Recent developments in Monte Carlo Event Generators

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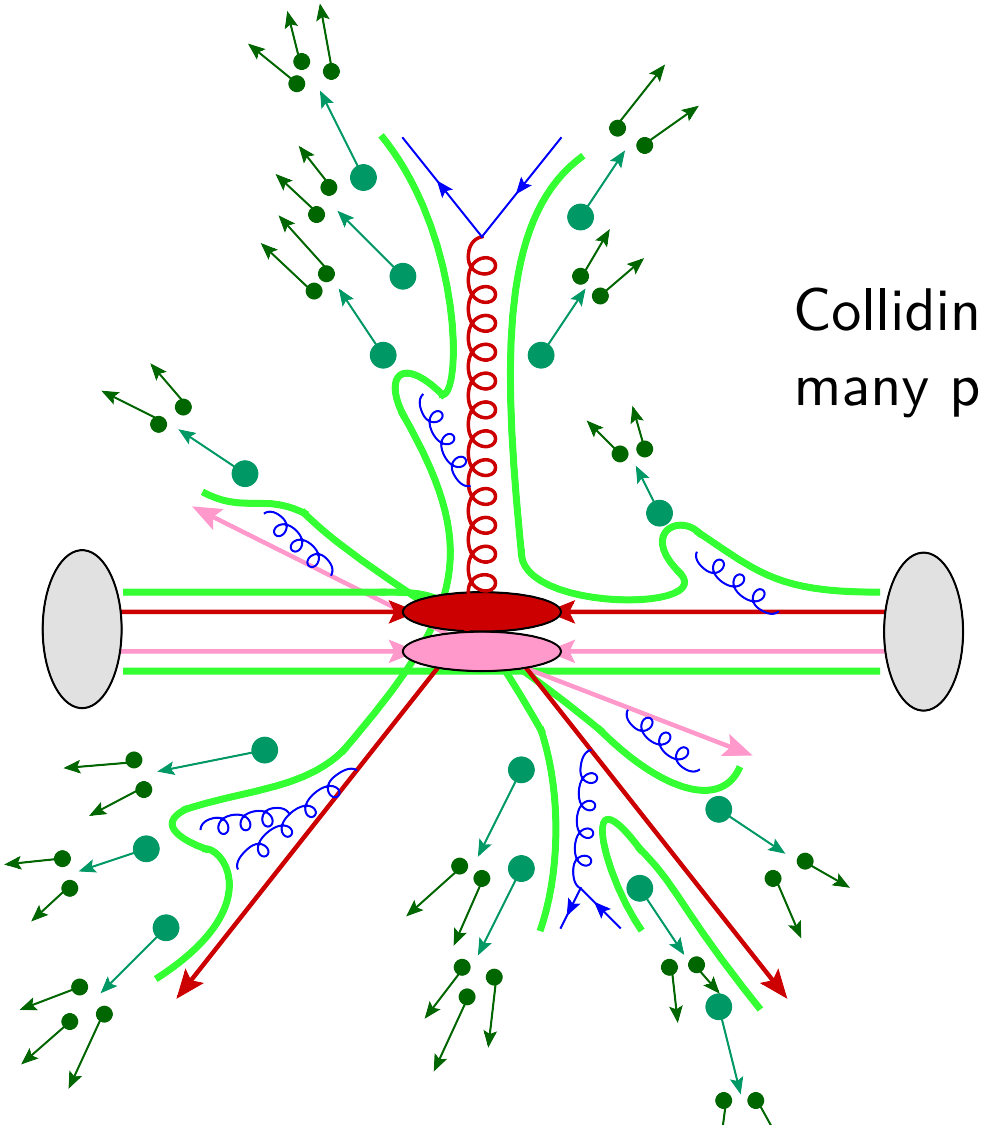
(with input from S. Frixione, R Frederix, J. Bellm, I. Helenius, C. Rasmussen, S. Höche, M. Schönherr, E. Re)

Image credits: easyrollerdice.com

Accurate pseudodata from theory tools → better analyses of backgrounds, better analyses of signals

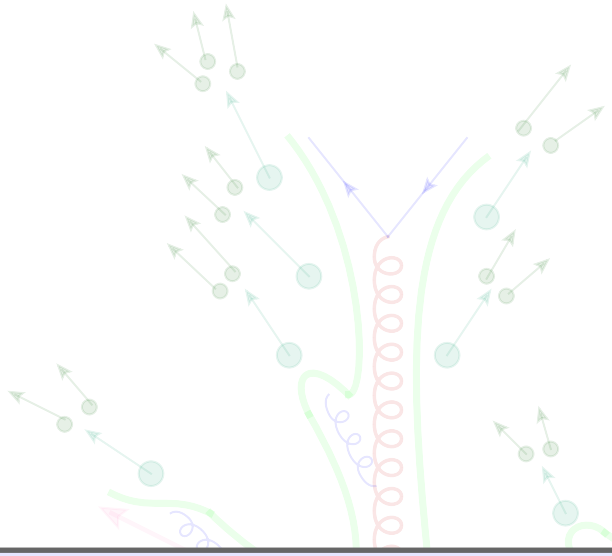


Colliding composite objects kick-starts many processes:

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

Accurate Monte Carlo predictions

Accurate pseudodata from theory tools → better analyses of backgrounds, better analyses of signals



Colliding composite objects kick-starts many processes:

hard scattering

Good theory tools should be universal, i.e. allow
...precision measurements of the emergence of jets, hadrons & new physics
...to obtain stringent indirect bounds through precision calculations

→ General-purpose event generators like HERWIG, PYTHIA, SHERPA et al.

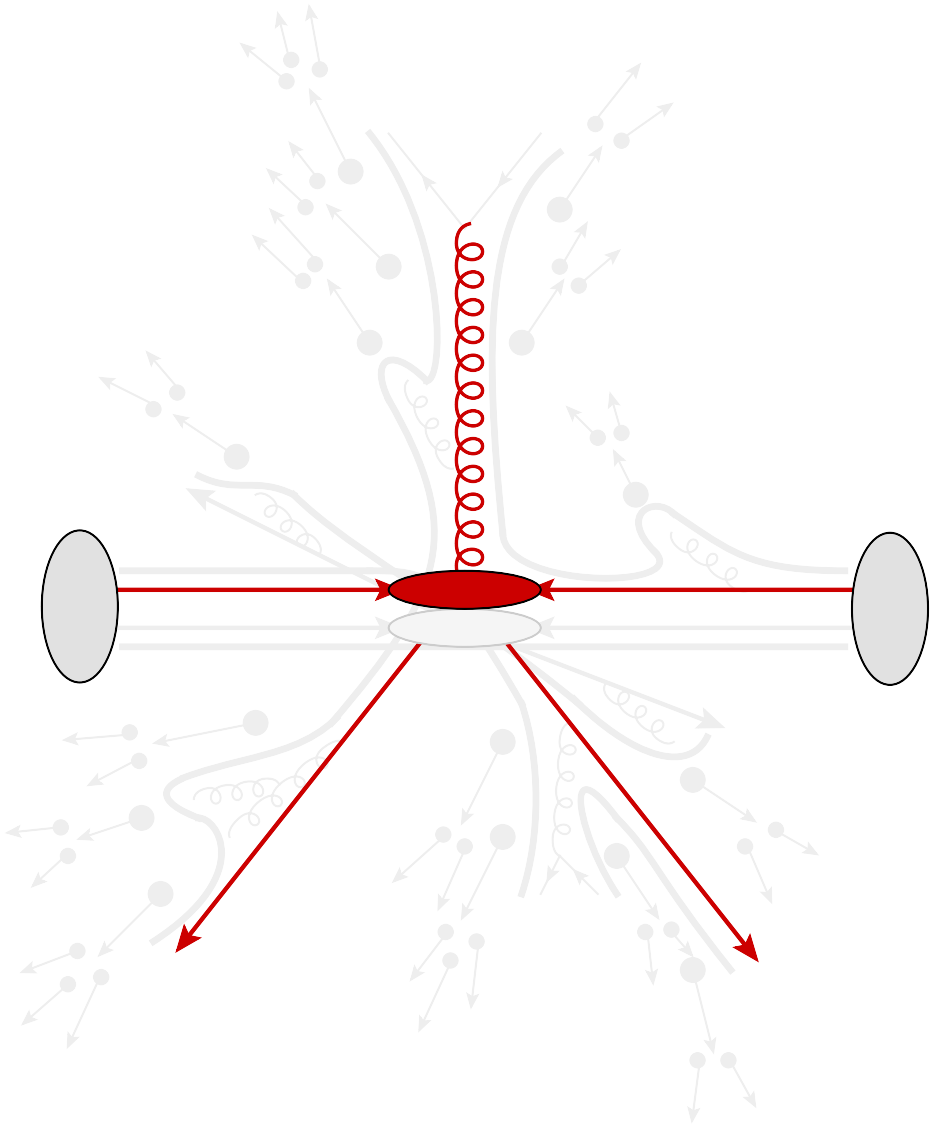
HERWIG, PYTHIA & SHERPA cheat sheet

	Inc. beams	*"Best" PQCD*	*pp MPI*	*Fragmentation*
HERWIG	ee, ep, pp, $\gamma x^{(*)}$	NLO+PS merged	Eikonal	Cluster
PYTHIA	ee, ep, pp, γx, pA, DM	NLO+PS merged	Interleaved	String
SHERPA	ee, ep, pp	NNLO+PS match	Traditional	Cluster

HERWIG7 news	PYTHIA8 news	SHERPA news
PQCD uncertainties, NLO merging, PS developments, new diffraction, new color reconnection	PS uncertainties, PS developments, improved elastic & diffractive cross sections, heavy ions and photons	PQCD uncertainties, PS developments, NLO merging w/ EW effects, massive 5F scheme.

...with important inputs from friends such as MadGraph, Openloops, Powheg-Box, aMC@NLO, Rivet, Professor...!

I) Hard scattering



Domain of fixed-order and precision calculations. Big community effort.
Here, focus on recent advances intertwined with "big three".

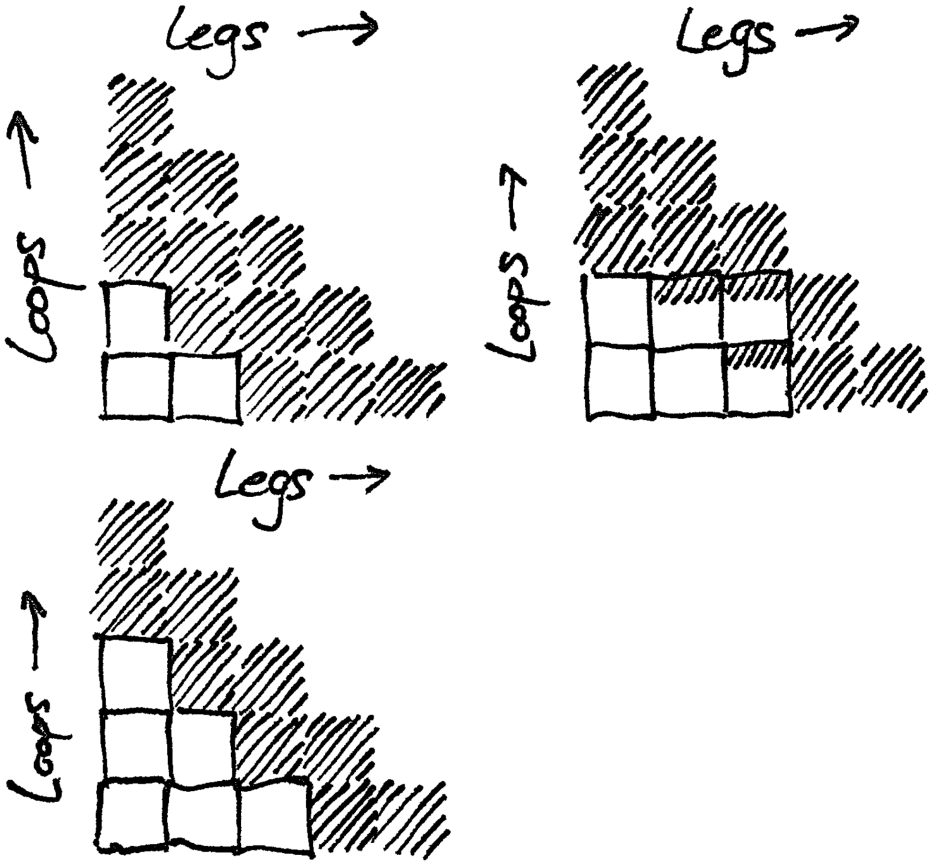
Hard scattering: Precision QCD in event generators

Many advances in precision QCD.

Multi-leg particularly important backgrounds.

Multi-loop allow precision indirect bounds.

Matching & merging combines calculations with each other and with subsequent parton shower.



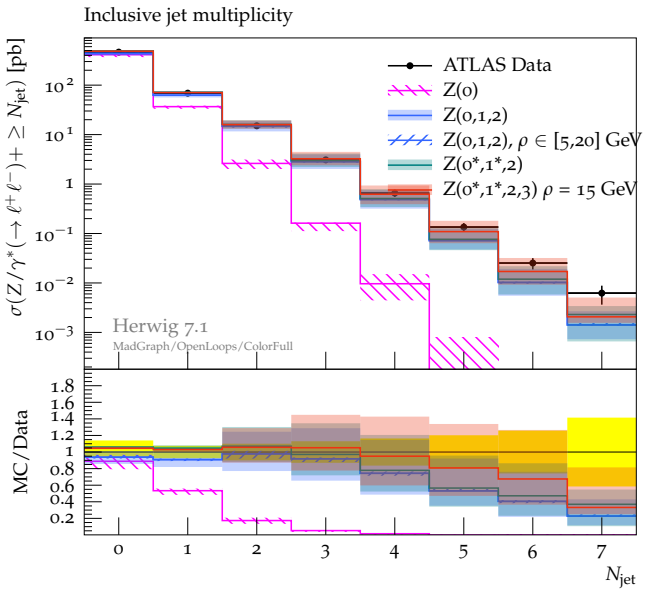
NLO+PS matching (MC@NLO, POWHEG) default for backgrounds, still developing for signals (automatic diagram subtraction for BSM resonances)

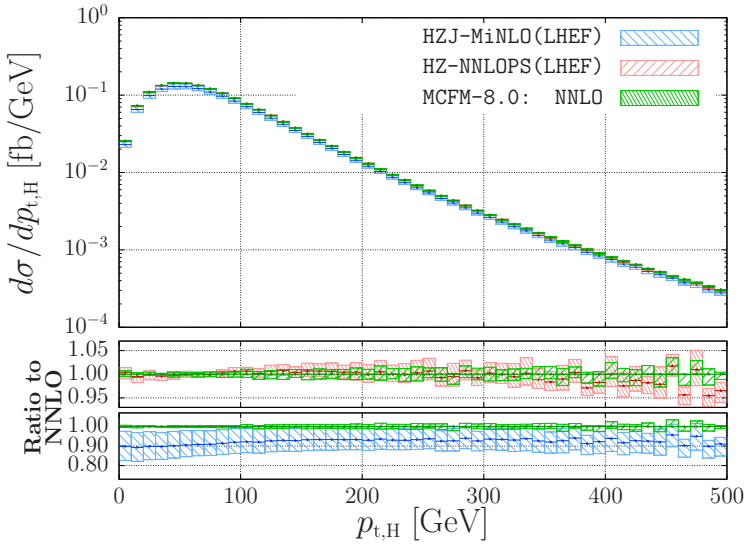
Hard scattering: precision QCD

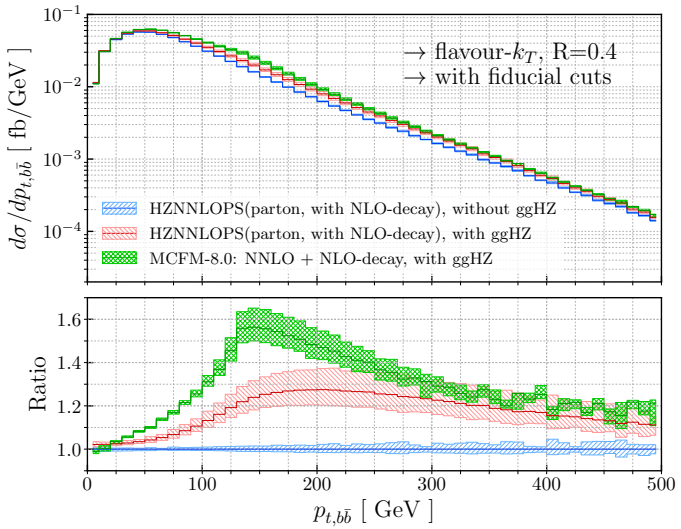
Plots from arXiv:1705.06700 and arXiv:1804.08141

NLO+PS merging is the state-of-the-art.
Available in SHERPA, PYTHIA, and in HERWIG7 (new in 2017!)

Impressive collection of color-singlet processes @ NNLO+PS matching frontier in POWHEG-BOX MINLO







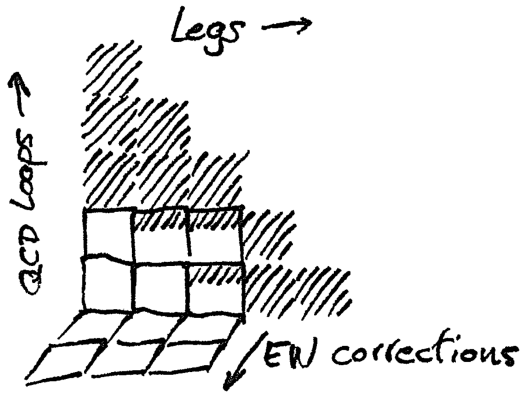
Matching recovers NNLO precision, but also allows to assess limitations!

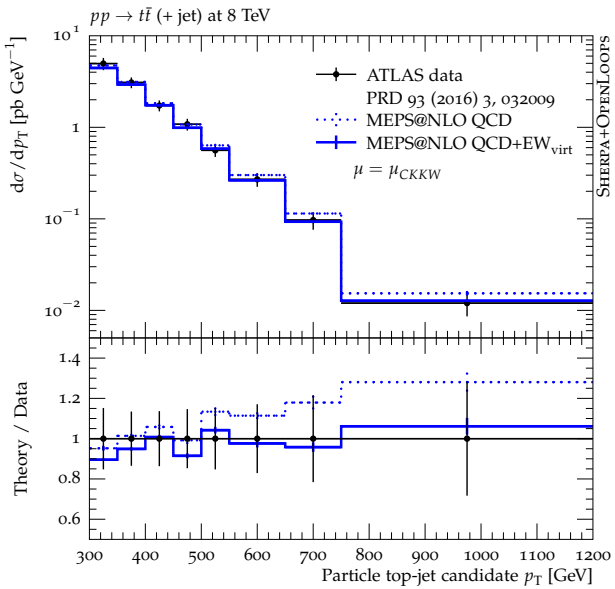
Hard scattering: Electroweak corrections

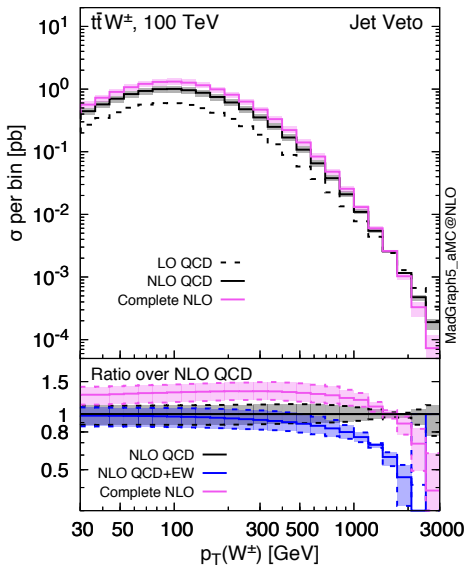
Plots from arXiv:1803.00950, arXiv:1711.02116, arXiv:1706.03522

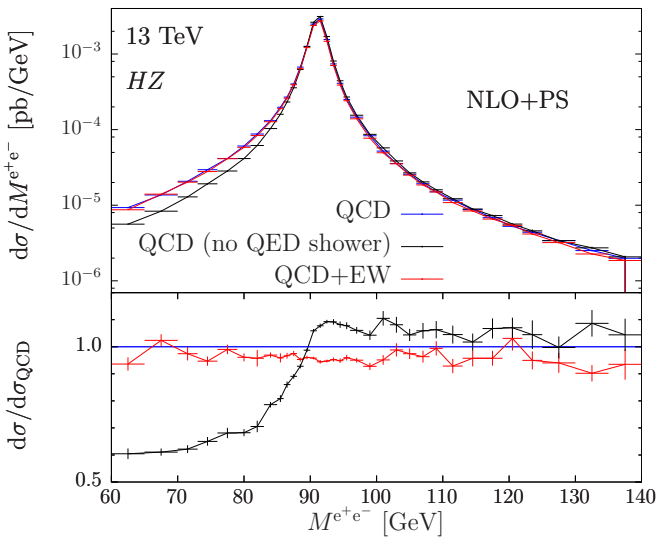
Size of NLO EW correction $\sim$ NNLO QCD, but with interesting observable dependence.

EW corrections can be combinated with PS similar to NLO QCD case.



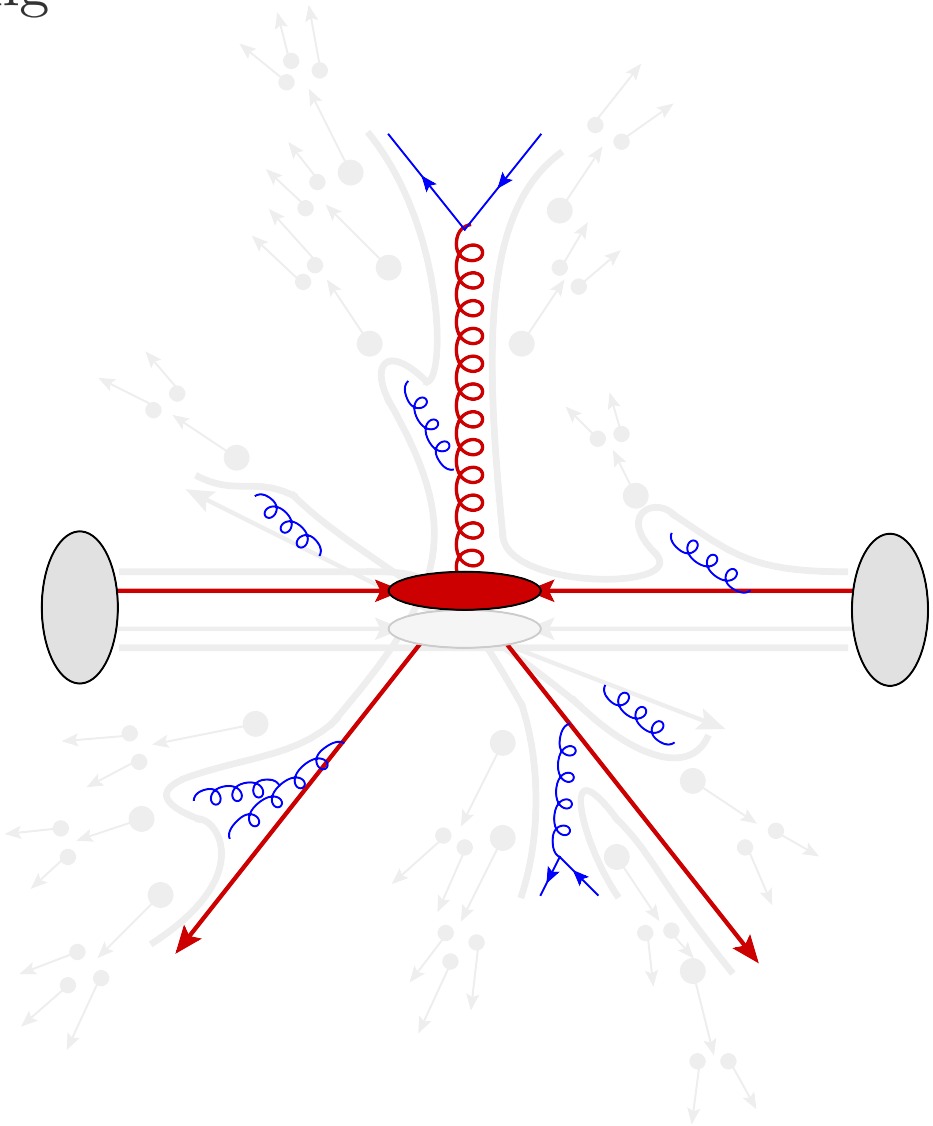






Important for even simple observables! Automation allows to assess formally subleading terms. Intense efforts. Many processes in SHERPA+OPENLOOPS & AMC@NLO

II) Parton showering



Crucial part of physics modeling, as required for jet structure and evolution. NLO+PS only as good as the PS $\rightarrow$ intense renewed activity.

Parton shower approximations

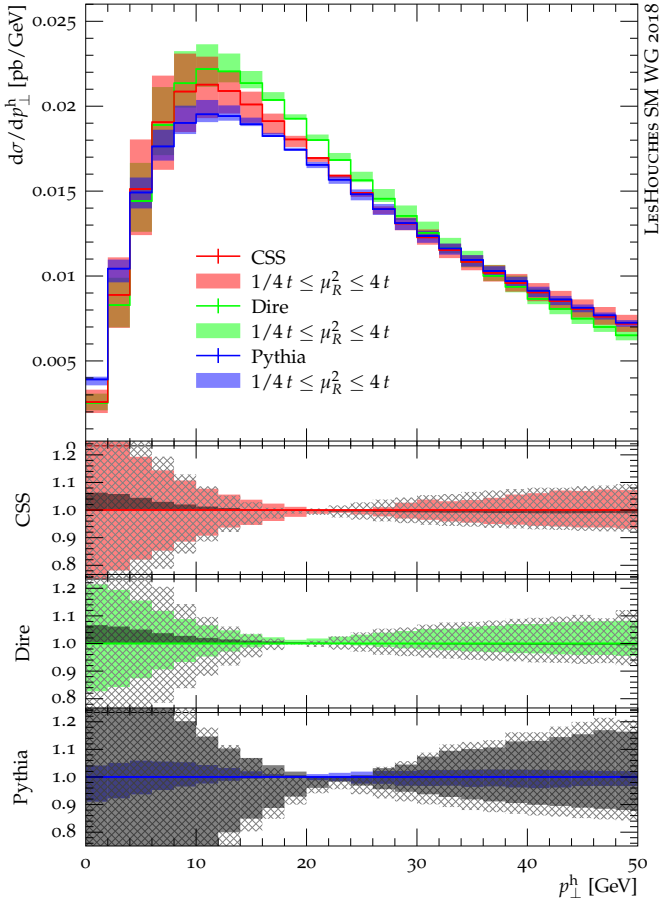
Plot from arXiv:1803.7977

PS aims at solving evolution equations

$$\frac{\mathrm{d}\, f_a(x,t)}{\mathrm{d}\ln t} = \sum_{b=q,g} \int_0^1 \frac{\mathrm{d}z}{z} \frac{\alpha_s}{2\pi} \left[P_{ab}(z)\right]_+ f_b\left(\frac{x}{z}, t\right)$$

by iteratively constructing new states distributed according to the evolution kernel $\left[P_{ab}(z)\right]_+$.

Current PS are spin-averaged, large-N_c & recover soft/collinear single real-emission pattern $\Rightarrow$ Large uncertainties.



Several groups working on defining "parton shower accuracy" (arXiv:1705.00742, arXiv:1705.08093, arXiv:1805.03757) and assess baselines (arXiv:1711.03497, arXiv:1805.09327)

Color states in dipole showers

Plot from arXiv:1801.06113

When improving the PS, we need sensible baselines. For example, showers that correctly treat the two leading color structures in $g \to gg$ splitting!

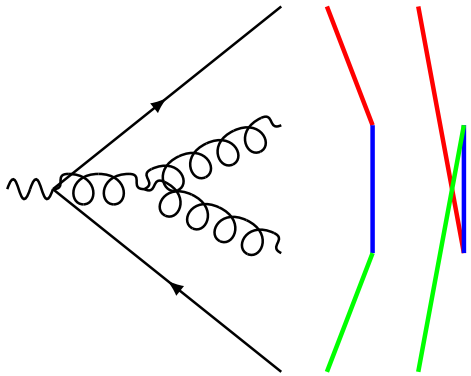
New implementation in HERWIG $\tilde{Q}$ shower. Color corrected through swapping with probability

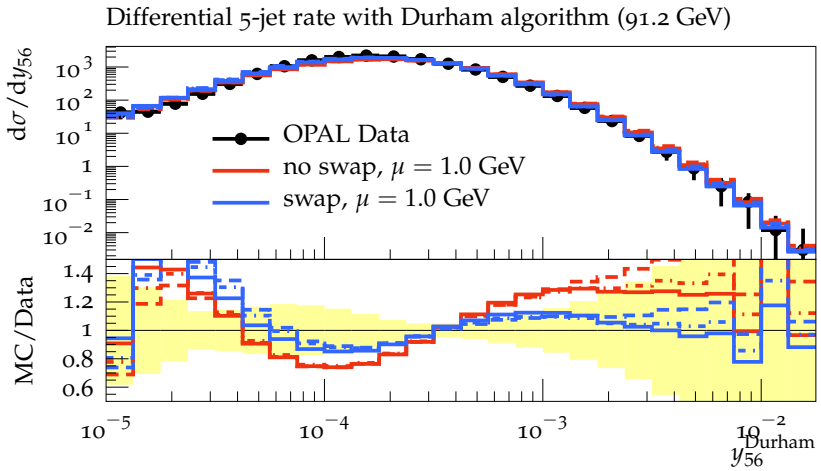
$$P_{swap} = \frac{w(1;3;2;4)}{w(1;2;3;4) + w(1;3;2;4)}$$

w taken from MG5. Can generalize to swapping ≥ 2 gluons.

$\to$ Systematic leading color?

Yields good data description.





To systematically define a sensible baseline, need to know the result beyond lowest order.

⇒ Work backwards after performing (N)NLO calculations: Define NLO evolution kernels as

$$\Delta_{\text{NLO}}(t_0, t_1) = e^{-\int_{t_1}^{t_0} \frac{dt}{t} \int d\tilde{z} \left[\left(\mathrm{V+I+C} \right)(\tilde{z}) \mathcal{O}(\Phi_B) + \int \mathrm{d}\Phi_{+1} (\mathrm{R-S})(\tilde{z}, \Phi_{+1}) \mathcal{O}(\Phi_R) \right]}$$

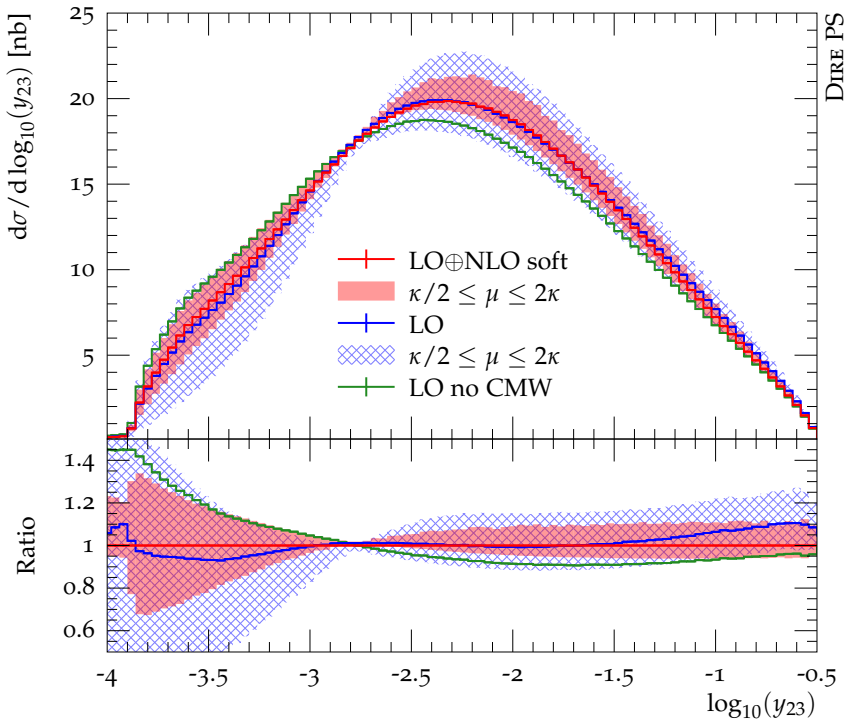
i.e. fully local NLO calculation in exponent of Sudakov factor.
Then derive LO shower from requirement of fully local subtraction.

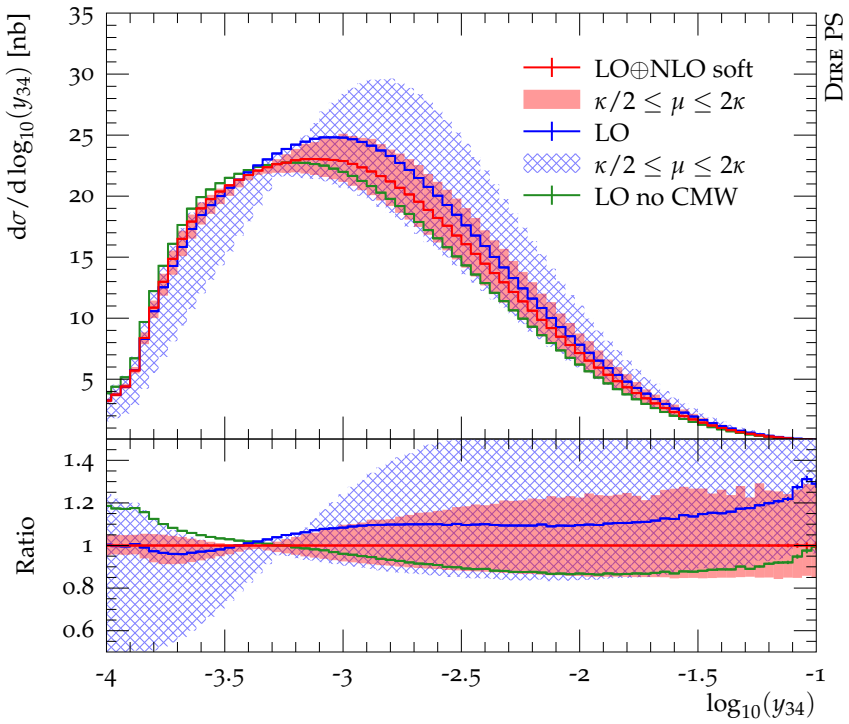
⇒ Exciting developments in VINCIA arXiv:1611.00013; DEDUCTOR arXiv:1705.00742; DIRE arXiv:1705.08093, arXiv:1805.03757

See arXiv:1705.08093, arXiv:1805.03757

Lessons from performing NLO calculation

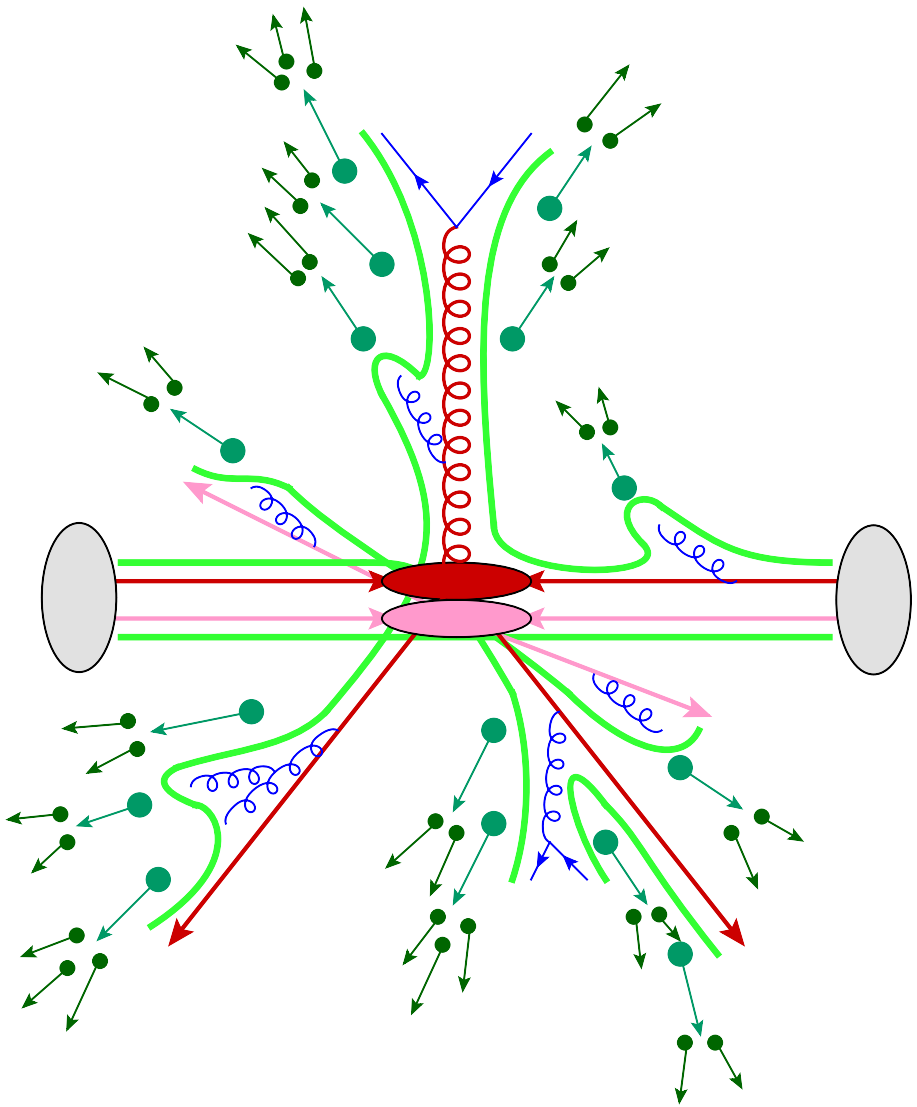
- *Triple coll. sectors require spin correlations in LO PS. Small effect.*
- *Double soft sectors require color correlations in LO PS. Small effect.*
- *4-mom. shifts from on-shell int. states has to be compensated.*
- *Recoil compensation & genuine NLO correction almost balance out.*





⇒ Realistic uncertainties. Implemented for SHERPA and PYTHIA.

III) Semi-soft and non-perturbative effects

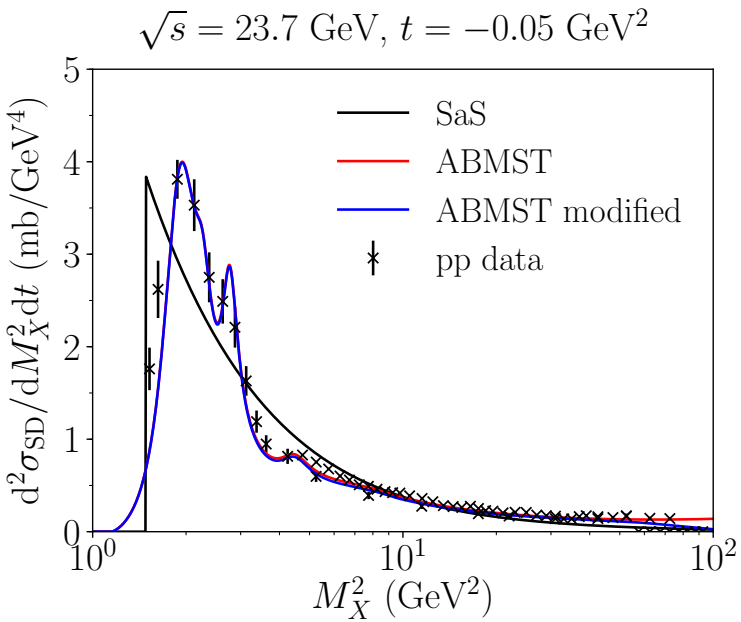


Non-perturbative models needed to describe the bulk of cross sections at LHC and beyond & offer exciting insights into emergent phenomena.

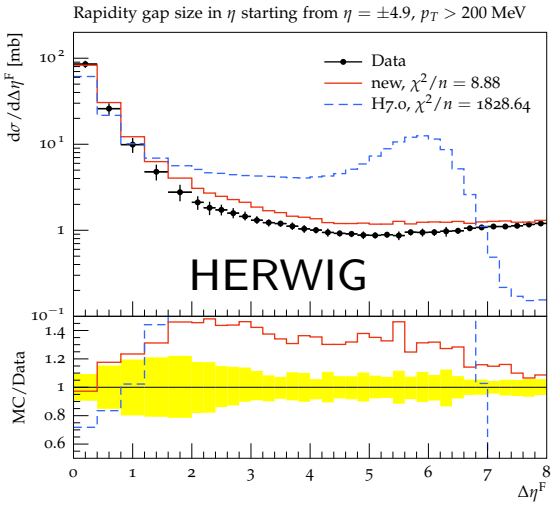
Total, elastic and diffractive cross-sections

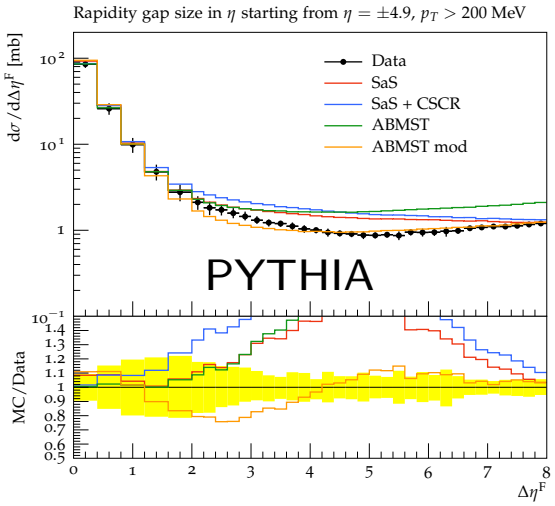
Plots from arXiv:1804.10373 and arXiv:1612.04701

PYTHIA: Difficult to describe all LHC data w/ old single Pomeron exchange model.
$\Rightarrow$ Total + elastic σ updated to two modern parametrizations (ABMST, COMPAS w/ ≥ 4 exchanges).



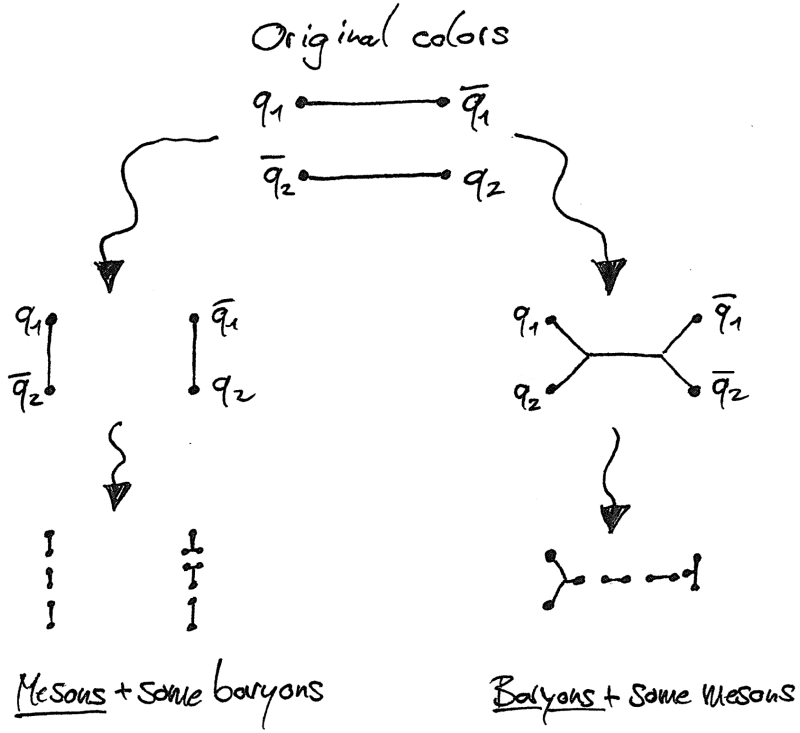
HERWIG: Now includes diffraction for the first time + includes new soft particle production (multiperipheral) model.





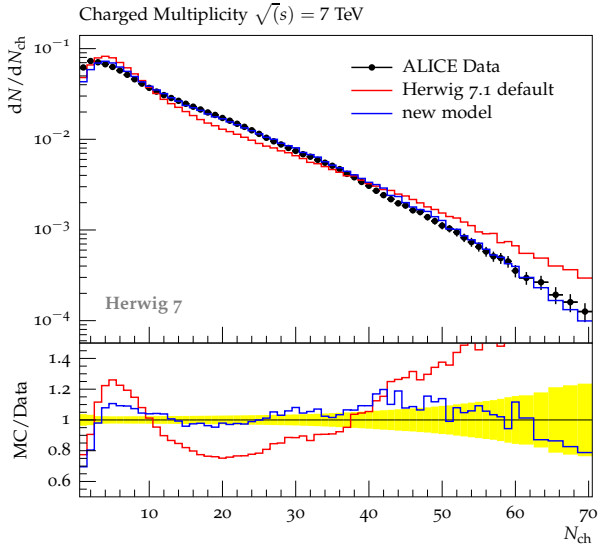
Color reconnection

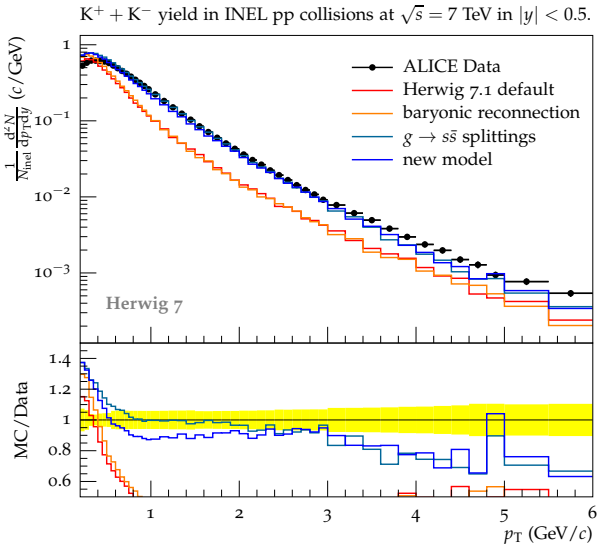
Plots from arXiv:1710.10906

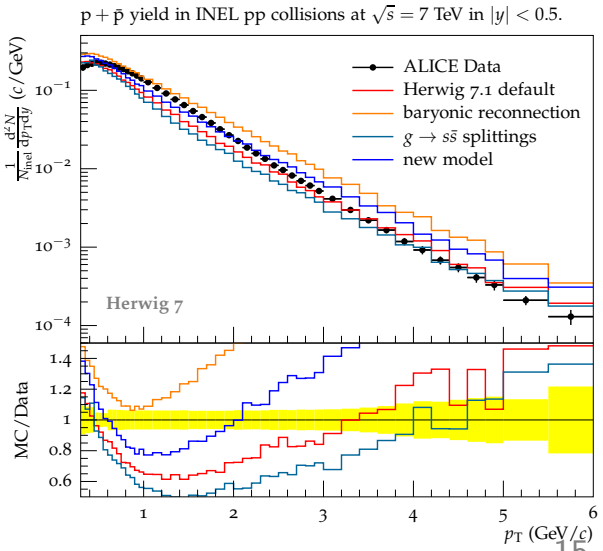


Hadrons are formed from color potentials between low-energy partons. Data prefers non-perturbative color rearrangement.

Herwig model now includes baryonic reconnection component & non-perturbative $g \to s\bar{s}$.



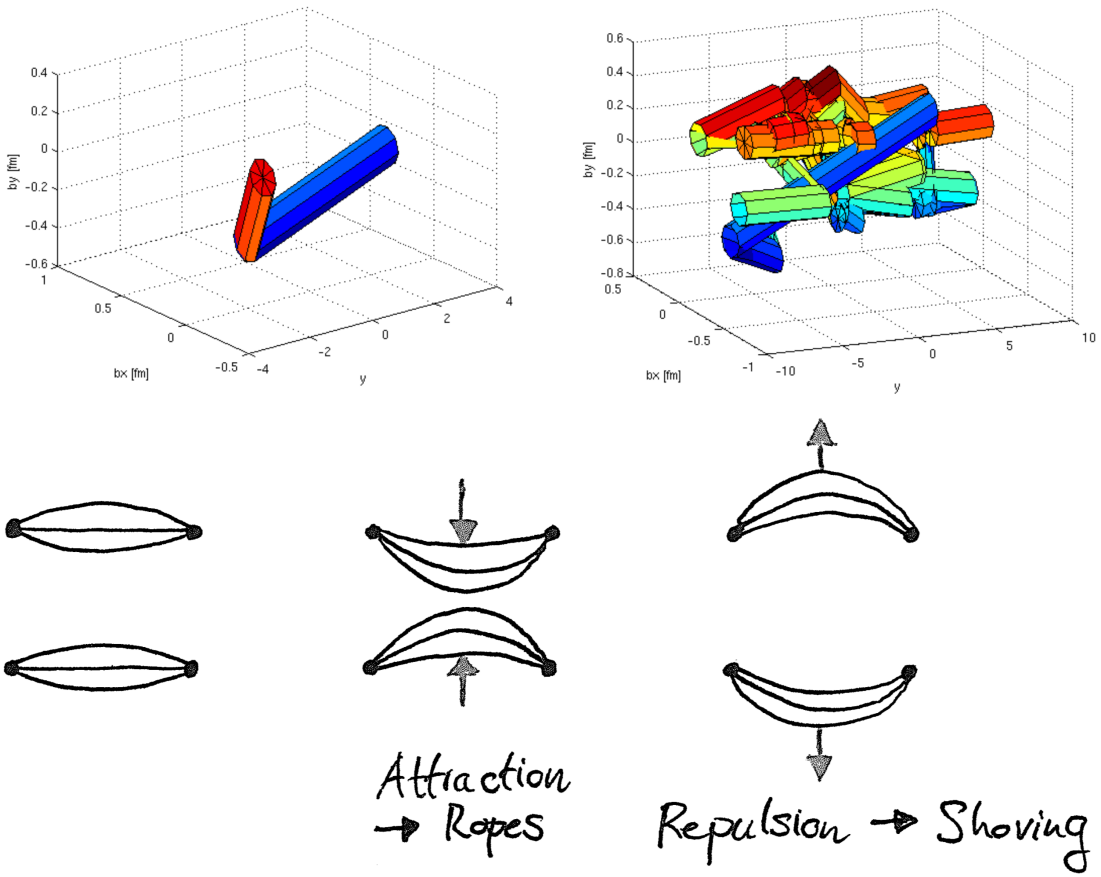




Collisions at LHC are packed densely with color.

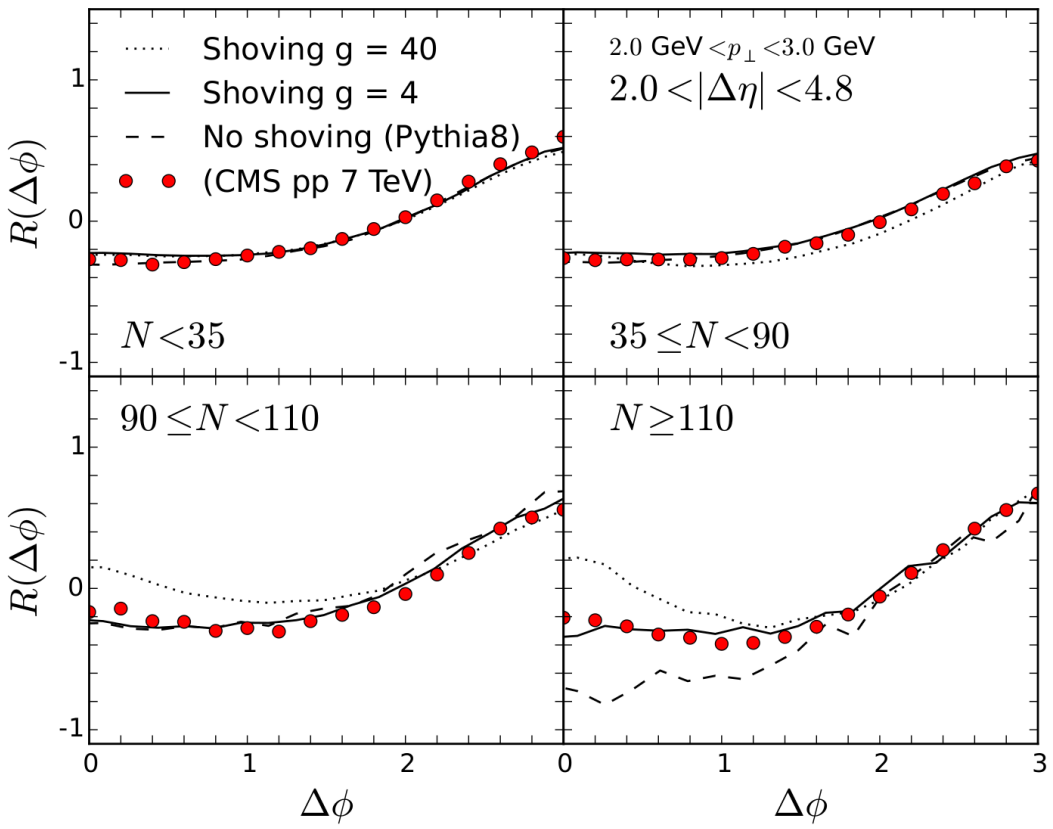
CR mimics collective effects, but not dynamics.

Model string interactions
$\rightarrow$ Microscopic model of collectivity!



Collective effects

Plots from arXiv:1710.09725



In 2010, CMS measured long-range azimuthal multiplicity correlations.
Repulsive string interactions can reproduce the "ridge" in CMS pp data with only one parameter on top of PYTHIA.
(plans in combination with heavy ions in PYTHIA $\rightarrow$ Gustafson)

IV) Summary

- Improving the fixed-order **perturbative precision** of event generators:
  Many color-singlet processes described at NNLO+PS with MINLO
  Inclusion of NLO EW effects in full swing in AMC@NLO and SHERPA
- Interesting developments in defining **shower at higher order**:
  Treatment of subleading color relevant, even for leading-color PS
  Can systematically correct PS through fully differential NLO calculation in exponent.
- Continuous improvements of **non-perturbative physics**:
  Improved models of complete cross section and photoproduction.
  More sophisticated color reconnection models.
  Exciting new ideas in modelling of collectivity (in pp and heavy-ion)

Apologies for omitting

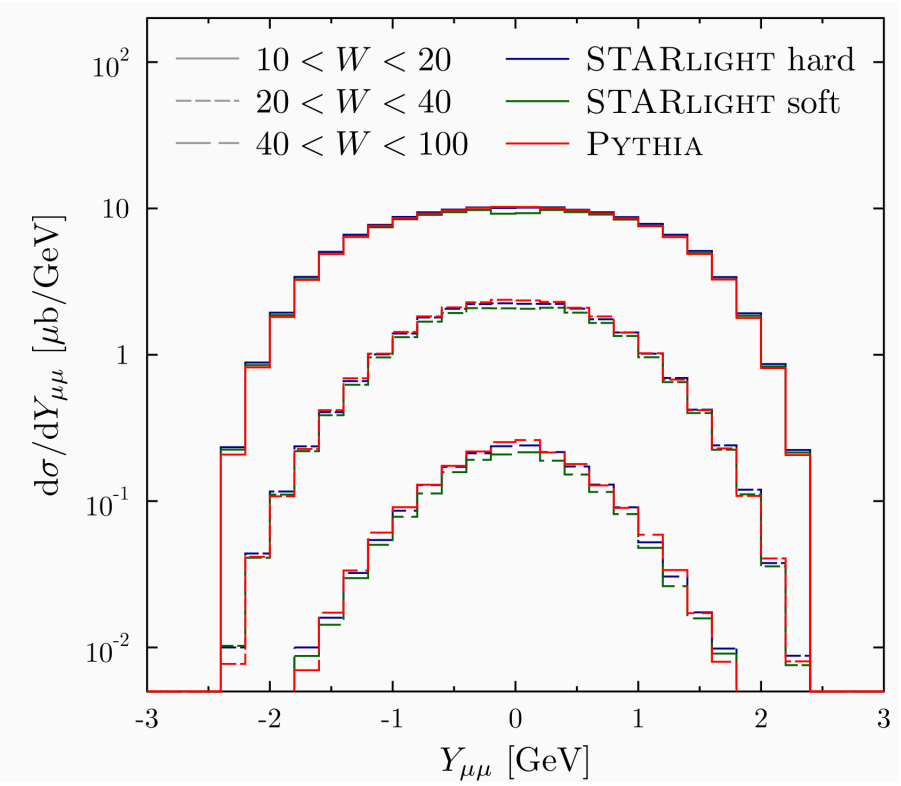
- Helicity showers for VINCIA LHC (arXiv:1708.01736)
- New dipole-like ISR for PYTHIA (arXiv:1710.00391)
- Advanced 5F massive scheme in SHERPA (arXiv:1712.06832, talk by Napoletano)
- Parton showers and non-global logarithms (arXiv:1803.07045, arXiv:1802.08531)
- Threshold logarithms in DEDUCTOR (arXiv:1711.02369)
- Improvements in treatment of heavy resonances in POWHEG-BOX-RES (arXiv:1801.03944, arXiv:1802.00426 & more, talks by Nason & Pozzorini)
- Combining high-energy resummation with DGLAP within HEJ + PYTHIA (arXiv:1712.00178)
- $\gamma\gamma$ collisions (arXiv:1510.05900) and new heavy-ion machinery in PYTHIA (arXiv:1607.04434, talk by Gustafson)
- More about EW corrections (talk by Zaro)

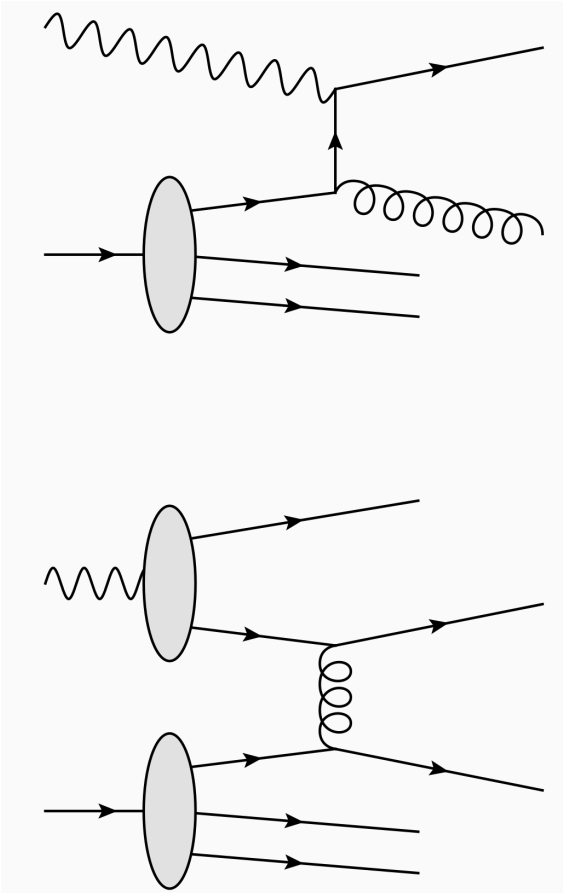
...and many more

Ultra-peripheral collisions

Figures by I. Helenius, based on arXiv:1510.05900

Incoming photons from p, A, ℓ beams can also have non-perturbative structure.
$\Rightarrow$ Important for $Q^2 \to 0$ piece of DIS, future $\ell\ell$ colliders, ultra-peripheral AA collisions.





Implemention in PYTHIA promising.