Theoretical uncertainties of monojet signatures from compressed-mass-spectrum

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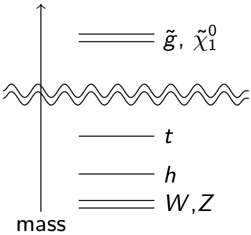
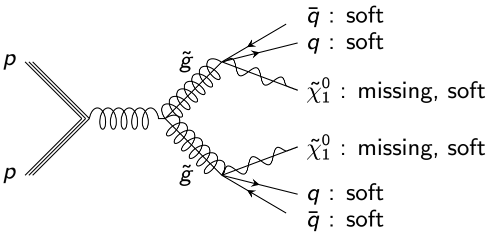
Work in progress.

Compressed-mass-spectrum scenarios

Compressed-mass-spectrum scenarios:

- New BSM particles have masses within a small mass gap and a stable BSM particle in their decay chain
- Remnent of new particle decay is hard to detect: either soft (mass gap is too small) or invisible
- Less constrained scenario from direct observation of decay product of new particle



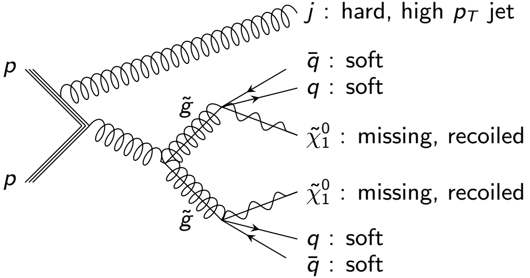


Those soft signals are hard to observe because of other large QCD activity. Still, there is a way to observe signals from this process at LHC.

Monojet signature from compressed-mass-spectrum scearios

Comparing to SM processes, this BSM process have more higher energy scale. Hence BSM process can be more radiative and have more chance of having a hard initial state radiation.

	energy scale
SM process	$\lesssim m_{\mathrm{EW}}$
BSM process	$\gtrsim m_{\tilde{g}}$

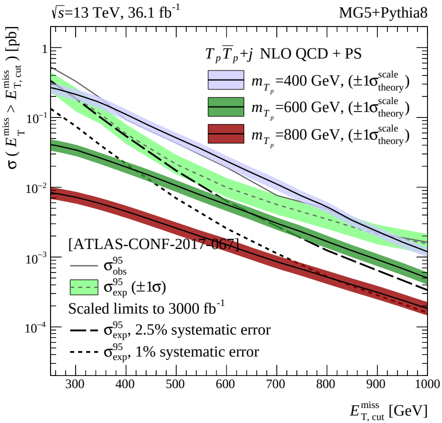


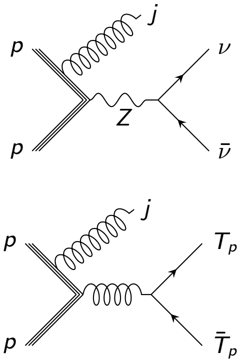
Therefore, whole system can be recoiled and there could be significant amount of event with high p_T jet + missing transverse energy, i.e. monojet channel.

What we could achieve from monojet study?

Monojet is a primitive channel but it is robust also. Possible achievements are:

- New physics discovery: check SM background only hypothesis vs background + BSM signal hypothesis





Understanding background and signal uncertainty is important to push down exclusion limit and discover new physics. If systematic error can be reduced from 2.5% to 1%, we can access mass $\sim$ 100 GeV more for new particle search

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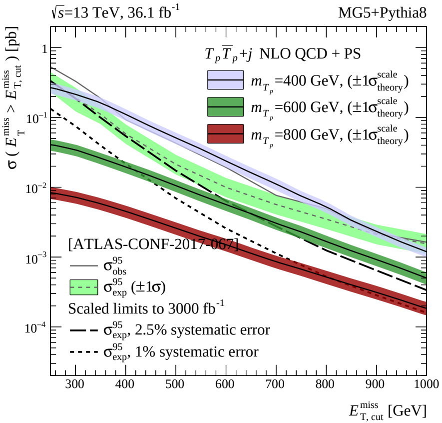


	energy scale
SM process	$\lesssim m_{\rm EW}$
BSM process	$\gtrsim m_{\tilde g}$

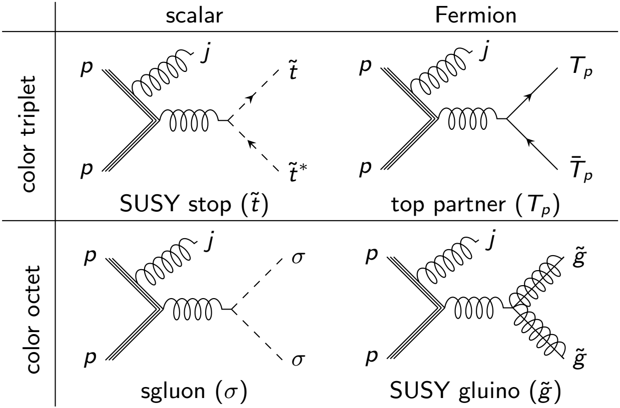
	13 TeV $\to$ 27 TeV XS change
SM BKG	$\times 11$, $p_T^{j_1} > 1.2$ TeV
	$\times 9$, $p_T^{j_1} > 800$ GeV
	$\times 5$, $p_T^{j_1} > 600$ GeV
T_p, 600 GeV	$\times 25$, $p_T^{j_1} > 800$ GeV
$\tilde g$, 1 TeV	$\times 37$, $p_T^{j_1} > 800$ GeV

Since background is getting dominated by systematic error, increasing $\sqrt{s}$ of pp collision could help pushing limit further down.

What we could achieve from monojet study?

Monojet is a primitive channel but it is robust also. Possible achievements are:

- New physics discovery: check SM background only hypothesis vs background + BSM signal hypothesis
- Properties of new particle: mass, spin and color?



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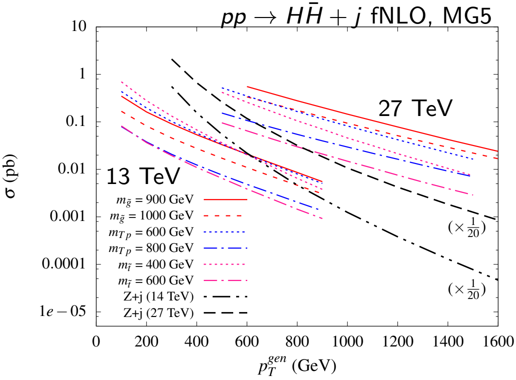
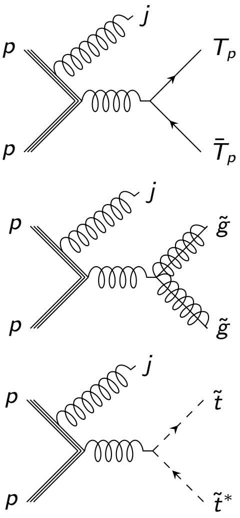
However, to fully resolve this hypothesis, we need to understand signal and background in high precision.

Monojet cross section for new particle disambiguation

Monojet can be used for distinguishing new particle hypotheses also.





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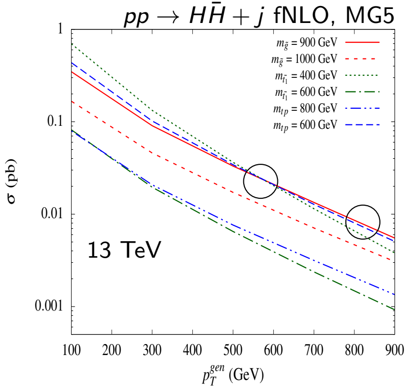
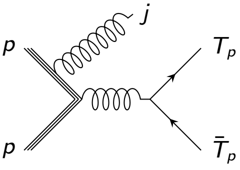
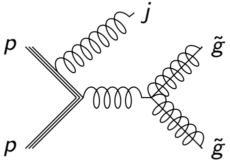
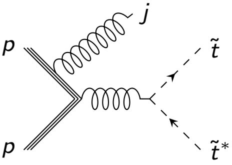


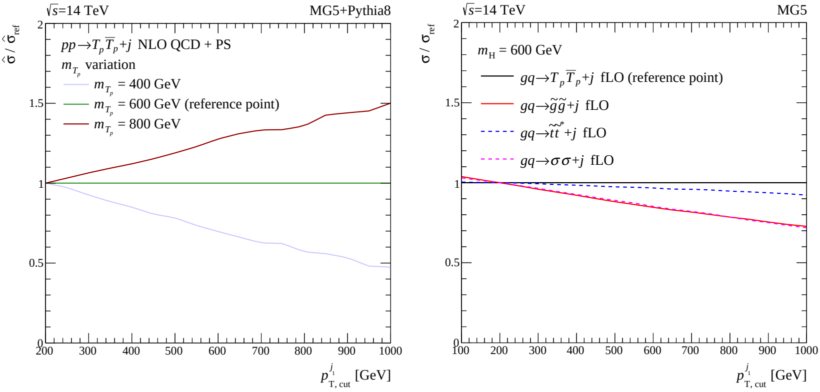






For some hypothesis comparison, for example: overlapping scalar top partner and Fermionic top partner lines, difference is very mild so we need high precision calculation to resolve such hypotheses precisely.

Monojet cross section for new particle disambiguation



In principle, we can distinguish BSM scenarios utilizing

- Overall normalization difference from BSM particle degree of freedom
- Energy scale of monojet
- Additional model dependent kinematical factor

To gather these information effectively, we need precise signal modelling.

NLO Monte-Carlo simulations

For precise study of signals, we performed NLO QCD Monte-Carlo simulations of 14 TeV pp collision with simplified models. To understand monojet behavior by QCD order, we organized simulation as followings:

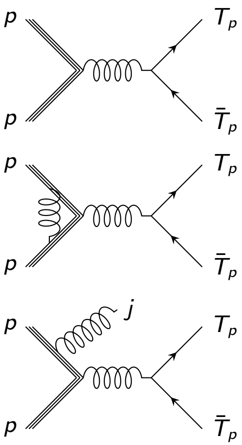
Fixed parton multiplicity at Born level

- Madgraph5_aMC@NLO+Pythia8:
  - $pp \to T_p \bar{T}_p$ (NLO QCD)
  - $pp \to T_p \bar{T}_p + j$ (NLO QCD)
  - $pp \to T_p \bar{T}_p + 2j$ (LO, MLM merged)

Multijet merged simulations

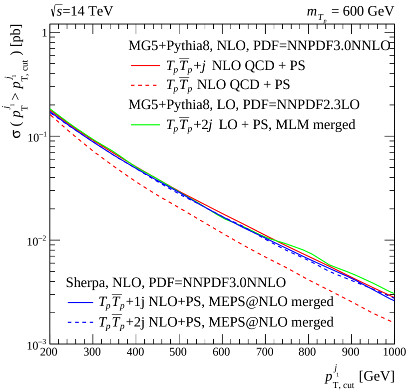
- Sherpa:
  - $pp \to T_p \bar{T}_p + j$ (NLO QCD, MEPS@NLO merged)
  - $pp \to T_p \bar{T}_p + 2j$ (NLO QCD, MEPS@NLO merged)

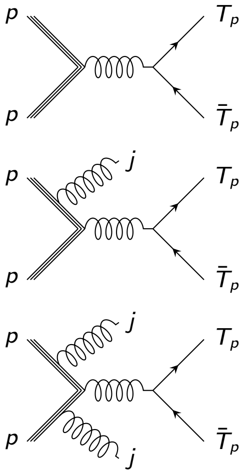
Let's focus on Fermionic top partner case for discussion of uncertainty.



A quick monojet p_T distribution check

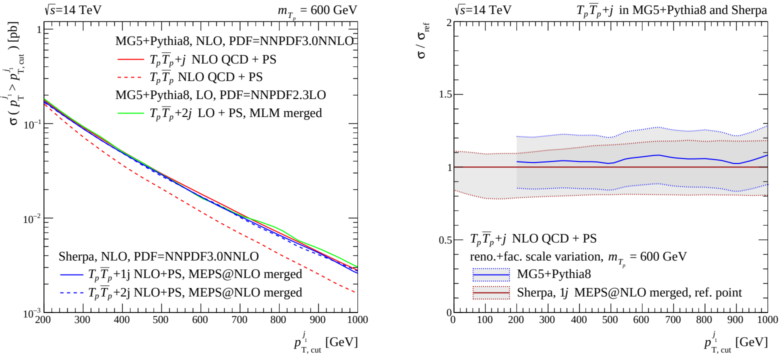
We reconstruct event at hadron level (without detector simulation) and check cross section of signals for leading jet $p_T > p_{T,cut}^{j_1}$ QCD order by order.





Briefly comparing between MG5 and Sherpa...

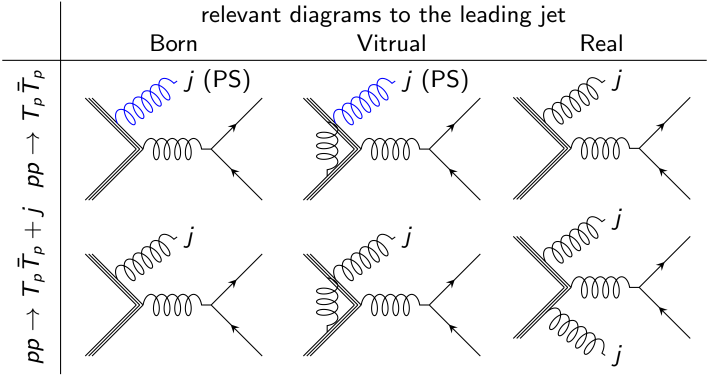
Comparsion between MG5 and Sherpa



Except $pp \rightarrow T_p \bar{T}_p$ NLO+PS, all cross section agrees each other witin 5%.
However, their uncertainty is different each other.
Furthermore, MEPS@NLO merged sample in Sherpa and unmerged sample in MG5 coincide each other after $p_T^{j_1} > 200 GeV$.
We can use simple MG5 setup for BSM monojet signature studies.

Shower and monojet

Since monojet signature is looking hard emission explicitly, it could be affected by parton shower depending on your setup. To remove the parton shower dependence, it's better to describe radiation using matrix element directly.



Double-counting in $pp \to T_p \bar{T}_p$ NLO+PS?

Shower and monojet

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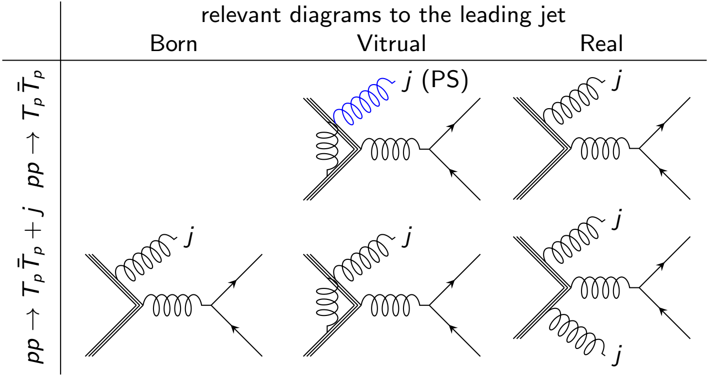
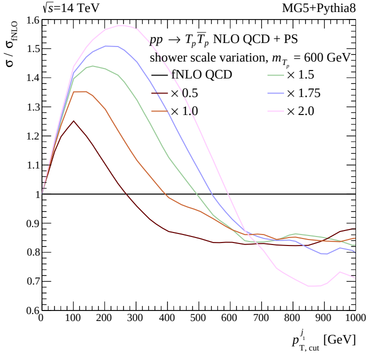
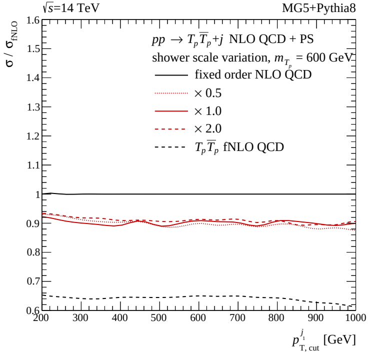


MC@NLO [Frixione, Webber, hep-ph/0204244] solves double-counting between Born and Real emission diagrams and removes PS dependence .

Shower scale variation and monojet

Still, there is a shower dependence remaining in virtual emission, there remains parton shower depenedence in $pp \to T_p \bar{T}_p$ NLO+PS. To remove the parton shower dependence, it's better to describe radiation using matrix element directly rather than using paton shower with dampening profile.





	$pp \to T_p \bar{T}_p$ NLO+PS	$pp \to T_p \bar{T}_p + j$ NLO+PS
PS reference scale (MG5)	$H_T/2$	$p_{\rm T}^{j_1}$ (k_T measure)

Scale uncertainty of finite order calculation

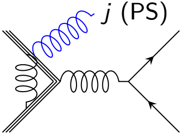
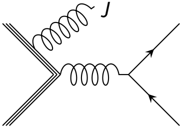
In a finite order perturbation theory, the observable we have calculated depends on scale parameter used for regulating singularities, such as

- Renormalization scale of couplings (α_S)
- Factorization scale of PDF

As we considering more higher order calculation, the scale dependence reduces. But we are doing finite order calculations, and hence, we need to estimate uncertainty form this calculation.

Scale uncertainty estimation: order-counting

In a leading jet p_T distribution, the scale uncertainty depends on QCD order and parton multiplicity. For $pp \to T_p \bar{T}_p$ NLO+PS,

	relevant diagrams to the leading jet		
	Born	Vitrual	Real
$pp \to T_p \bar{T}_p$			

In low p_T regime, Born, virtual and real emission contribute. Hence, the p_T distribution is NLO+PS precise.

process	schematic uncertainty of monojet p_T distribution	
	low p_T region	high p_T region
$pp \to T_p \bar{T}_p$ NLO+PS	NLO+PS	
$pp \to T_p \bar{T}_p + j$ NLO+PS		

Scale uncertainty estimation: order-counting

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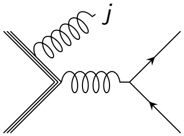
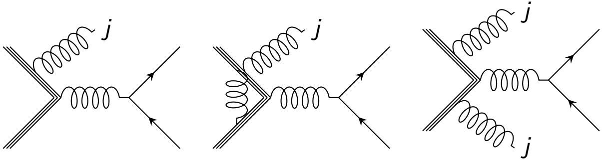
	relevant diagrams to the leading jet		
	Born	Vitrual	Real
$pp \to T_p \bar{T}_p$			

In high p_T regime, only real emission contribute since PS cannot push Born and virtual contribution here. Diagram is essentially $pp \to T_p \bar{T}_p + j$ at LO, hence, the p_T distribution is LO+PS precise.

process	schematic uncertainty of monojet p_T distribution	
	low p_T region	high p_T region
$pp \to T_p \bar{T}_p$ NLO+PS	NLO+PS	LO+PS
$pp \to T_p \bar{T}_p + j$ NLO+PS		

Scale uncertainty estimation: order-counting

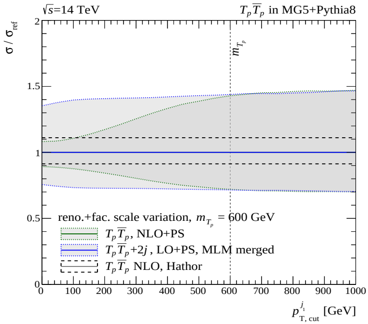
In a leading jet p_T distribution, the scale uncertainty depends on QCD order and parton multiplicity. For $pp \to T_p \bar{T}_p + j$ NLO+PS,

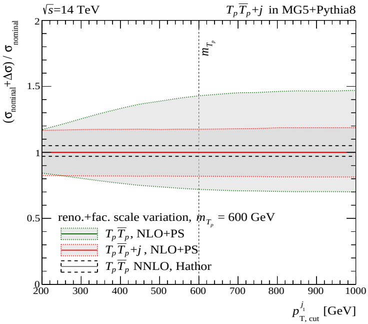
	relevant diagrams to the leading jet		
	Born	Vitrual	Real
$pp \to T_p \bar{T}_p + j$			

Born, virtual and real emission contribute everywhere. Hence, the p_T distribution is NLO+PS precise.

process	schematic uncertainty of monojet p_T distribution	
	low p_T region	high p_T region
$pp \to T_p \bar{T}_p$ NLO+PS	NLO+PS	LO+PS
$pp \to T_p \bar{T}_p + j$ NLO+PS	NLO+PS	NLO+PS

Scale uncertainty and monojet



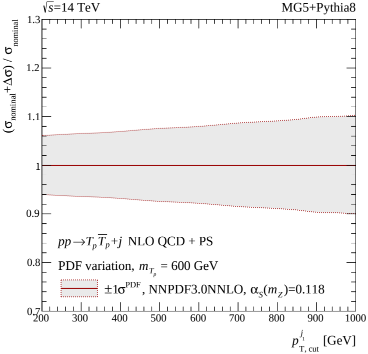


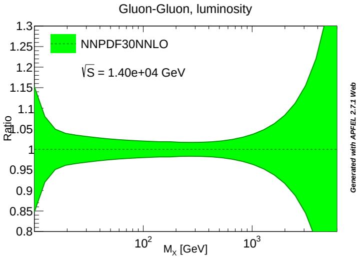
process	Uncertainty low p_T region	Uncertainty high p_T region
$pp \to T_p\bar{T}_p + 2j$ LO+PS	$\mathcal{O}(30 \sim 40\%)$	
$pp \to T_p\bar{T}_p$ NLO+PS	$\mathcal{O}(10\%)$	$\mathcal{O}(40\%)$
$pp \to T_p\bar{T}_p + j$ NLO+PS	$\mathcal{O}(10\%)$	
Rescaling NLO into NNLO	$\mathcal{O}(5\%)$	

Rescaling NLO cross section into NNLO can further reduce uncertainty by half.
Overall scale uncertainty can be under control near future.

PDF variation

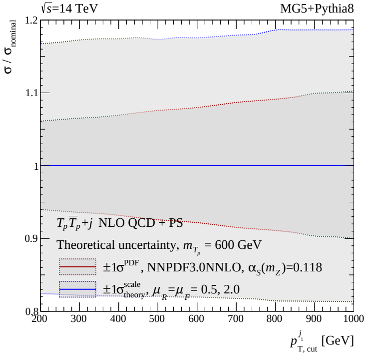
There is one more additional uncertainty in PDF: PDF variation. Parton distribution is basically fitted result of experimental data, and they have their own fitting uncertainty.





For moderate mass $m_{T_p} = 600$ GeV, $\sqrt{\hat{s}} \gtrsim 1200$ GeV, PDF variation is moderate, $\lesssim 10\%$. This error can be further reduced in future with more experiments.

Overall Uncertainty and Shape Uncertainty



Other than overall normalization, PDF variation affect shape of the leading jet p_T distribution more than scale variation.

Summary

- Monojet analysis is simple and robust channel for searching new physics with compressed-mass-spectrum.
- Each BSM hypotheses with compressed-mass-spectrum gives different monojet signature, such as normalization and shape, so we can use them for disntinguishing various BSM scenarios.
- This monojet signatures are prone to uncertainty, and hence, we need to use higher order correction to get better BSM scenario disambiguation.
- Still some works are in progress, stay tuned!