Precision Frontier at the LHC

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PHEP2018 @ IHEP

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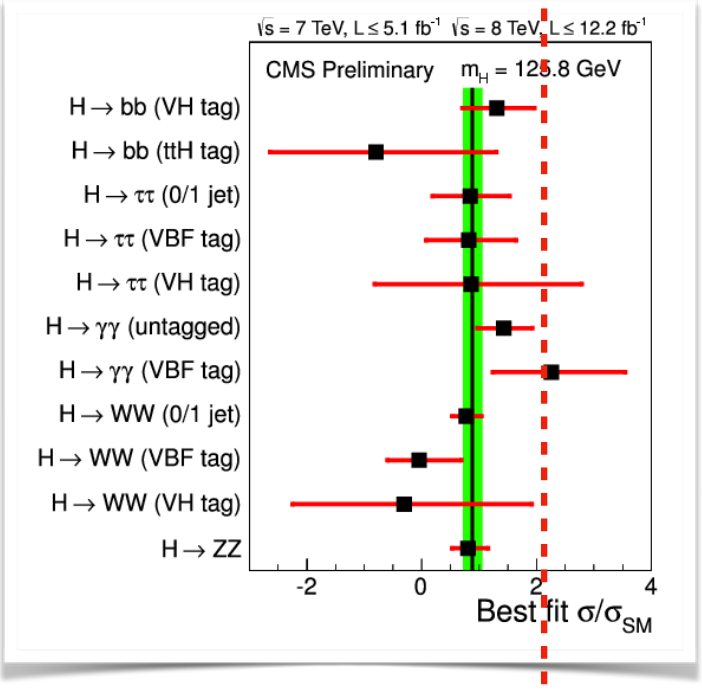
Outlines

- Why precision?
- Very very very brief overview of IR subtraction/slicing schemes
- Phenomenology - fixed order and resummation

Why Precision?



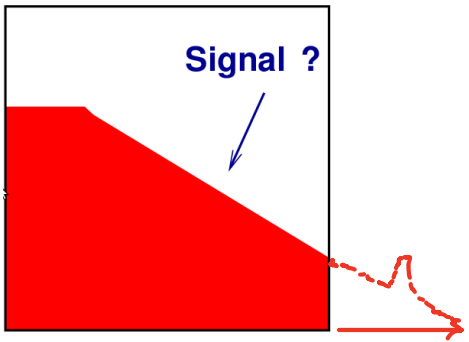
LO @ 8 TeV: 9.6 +/- 25% pb

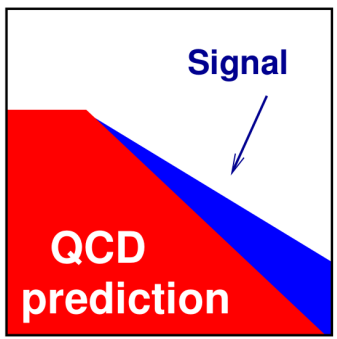
N3LO @ 8 TeV: 19.47 + .32% - 2.99% pb

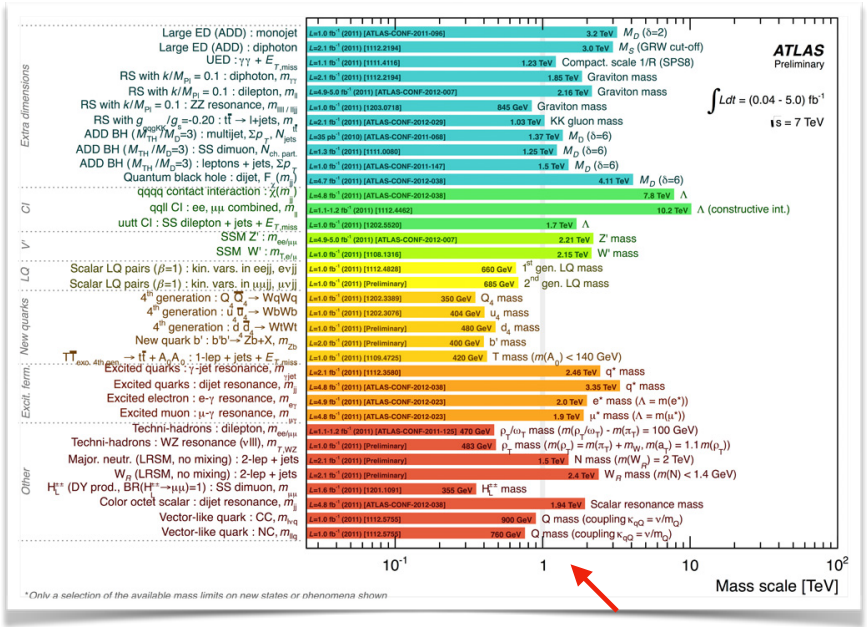
Anastasiou, Duhr, Dulat, Herzog, Mistlberger '15

If no higher order prediction is known

Why Precision?



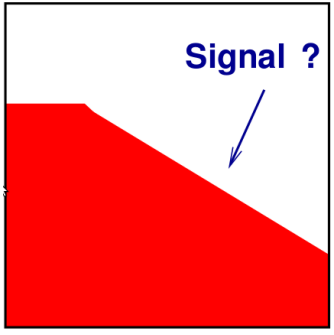


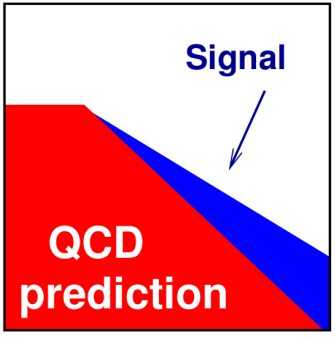


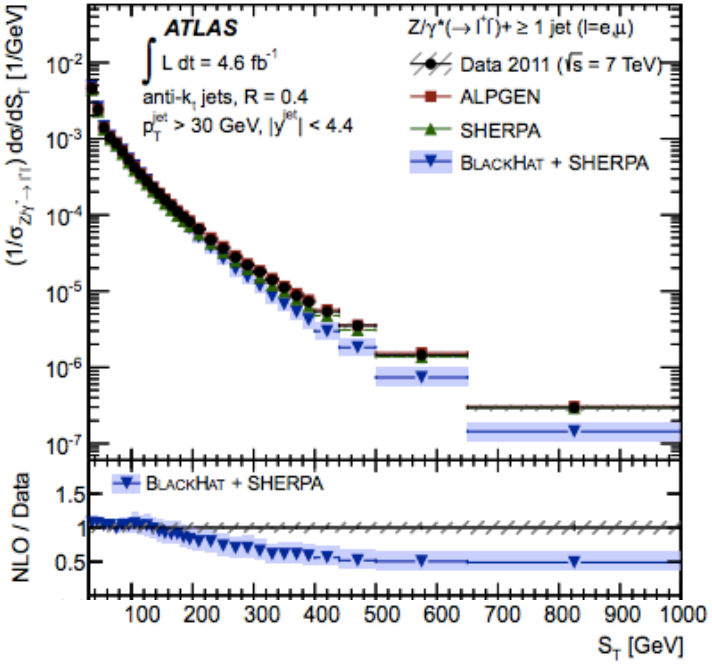
- Lower limits above 1 TeV now.
- New physics could be out of reach for current LHC
- Predicting the shape correctly will be crucial

New Physics = Data - SM predictions!!

Why Precision?



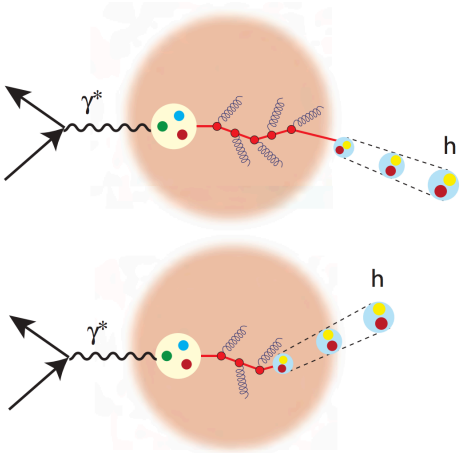




50% difference at high S_T

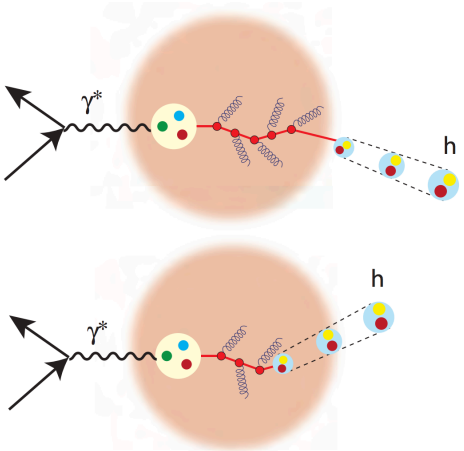
New Physics? Missing Higher order?

Why Precision?



- QCD itself is interesting, Heavy Ion, EIC ⋯
- Hard probe (perturbative) of nuclei internal structure (non-perturbative)
- To extract the non-perturbative information, we should know the hard part as accurate as possible

Why Precision?



- QCD itself is interesting, Heavy Ion, EIC ⋯
- Hard probe (perturbative) of nuclei internal structure (non-perturbative)
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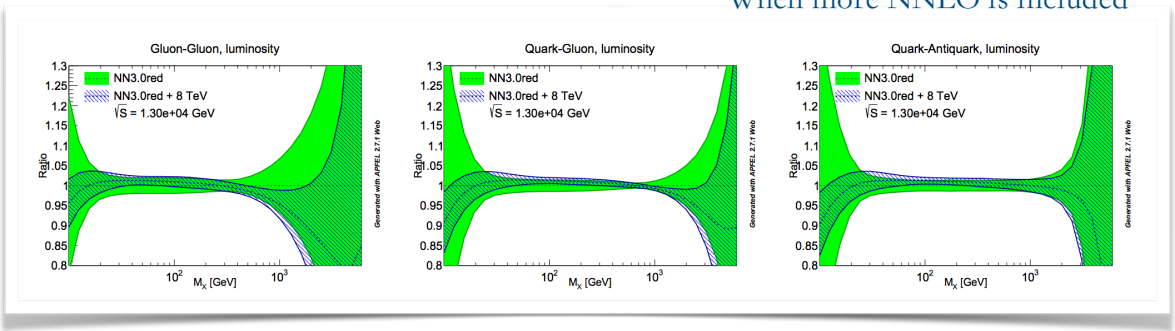
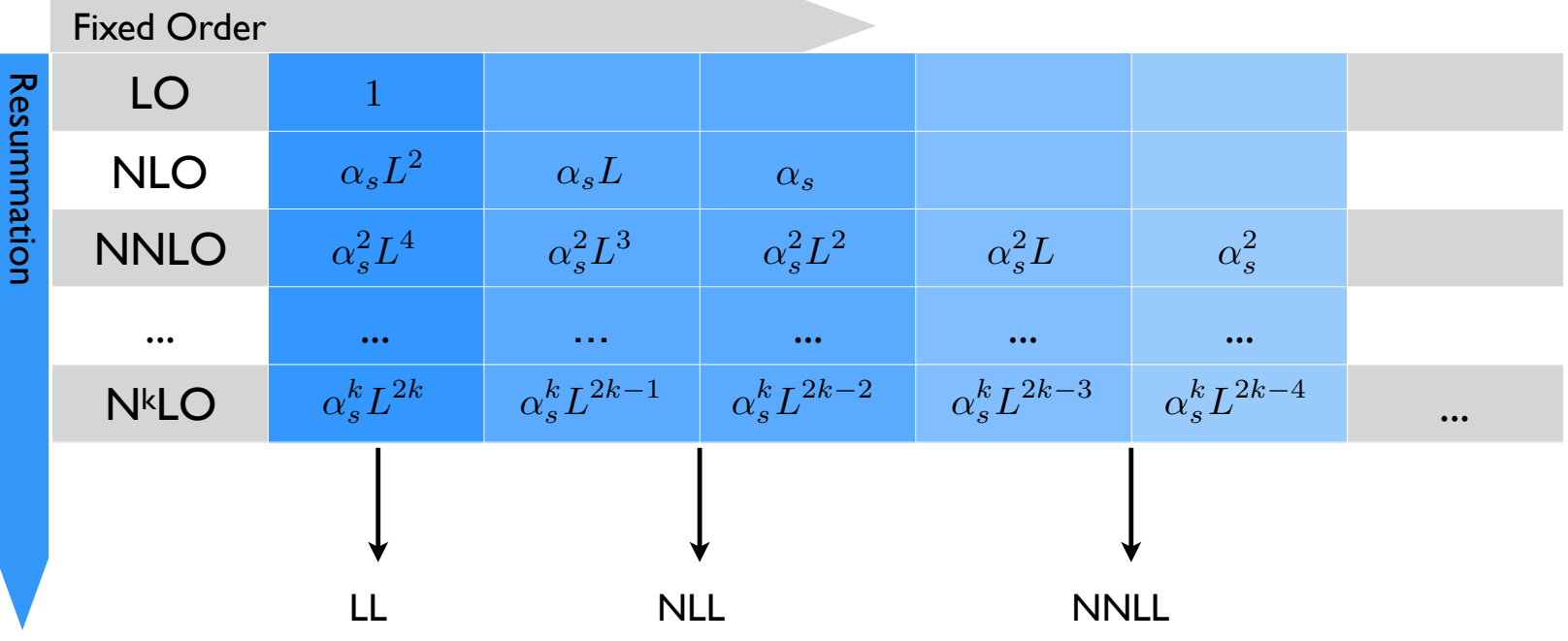
NNPDF30 extractions

When more NNLO is included

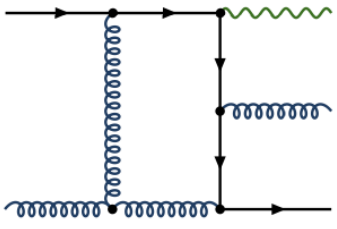


Will see later with more details

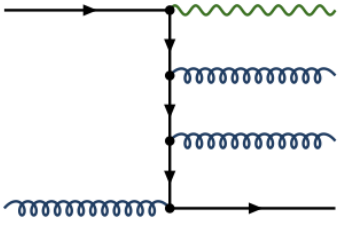
Precision (NLO, NNLO, N3LO ⋯ + Res.) is crucial



Not Just Loops



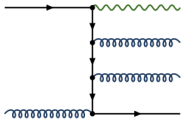
$$\int \mathrm{d}\Phi_3 \sum_{i=0}^{2} \frac{vr_i}{\epsilon^i}$$



$$\int \mathrm{d}\Phi_4 \, rr$$

- We are mostly interested in fully differential cross section
- IR poles occur in real emissions
- IR poles fully show up for degenerate (soft/collinear) states ONLY after integrating over phase space, with all kinds of exp. cuts, jet algorithms ⋯
- How to isolate for numerical evaluation?

Not Just Loops



$$= \int \mathrm{d}z \frac{f(z)}{z^{1+a\epsilon}}$$

Subtraction

$$\int \mathrm{d}z \frac{f(z) - f(0)}{z} + \int \mathrm{d}z z^{-1-a\epsilon} f(0)$$

Construct counter terms point-wise in the phase space

- Antenna subtraction — 2 Gehrmann, Glover
- STRIPPER + modifications — Czakon + …
- Projection to Born — Cacciari, et. al.

…

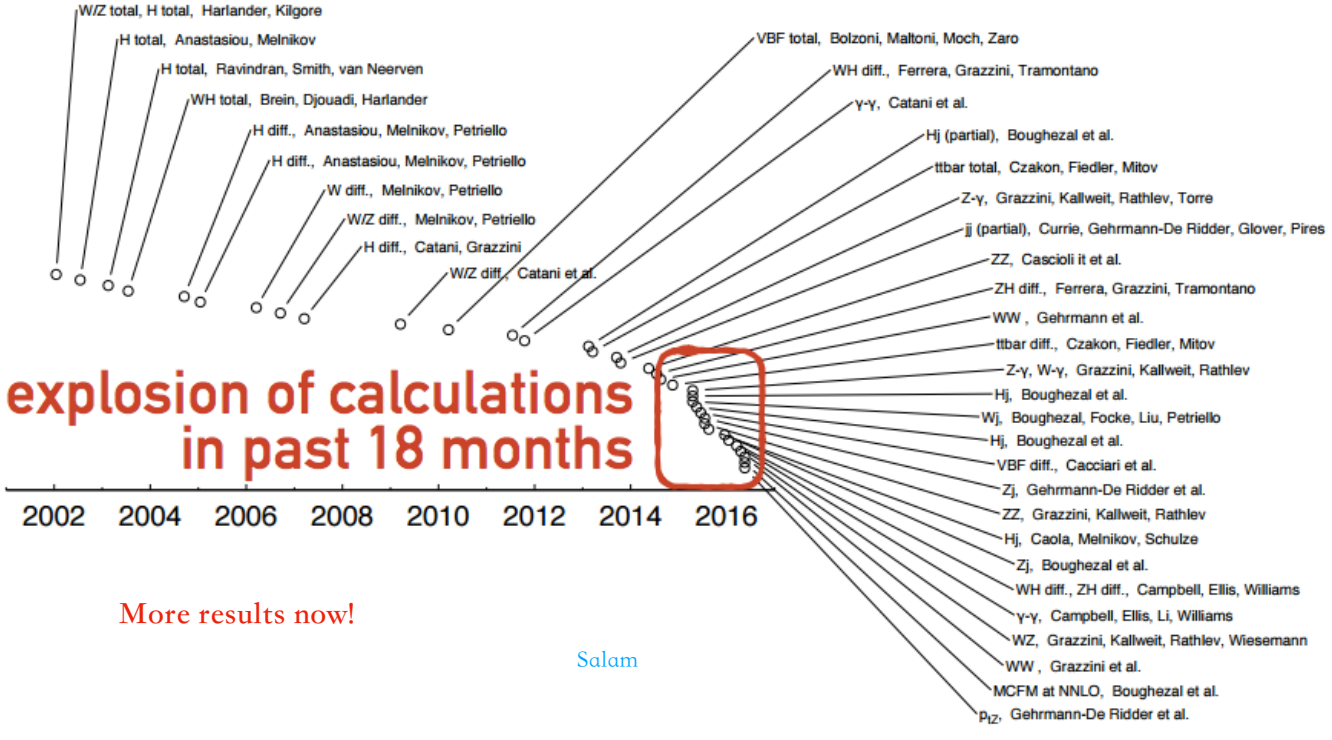
Slicing

$$\int \frac{f(z)}{z} \theta(z > z_0) - f(0) \frac{z_0^{-a\epsilon}}{a\epsilon} + \dots$$

A physical observable (z_0) to regulate all related IR singularities

- qT-subtraction — Catani, Grazzini
- Inclusive jet mass — Gao, Li, Zhu
- N-jettiness subtraction — Boughezal, et. al.

Phenomenology



More results now!

Salam

Phenomenology

process		known		desired
$pp \to H$	σ	$\mathrm{N^3LO_{HEFT}}+\mathrm{N^2LO_{QCD}}\left(\frac{1}{m_t^6}\right)$		
	$\mathrm{d}\sigma$	$\mathrm{NLO_{EW}}$	$\mathrm{d}\sigma$	$\mathrm{N^3LO_{HEFT}}+\mathrm{N^2LO_{QCD}}$
	$\mathrm{d}\sigma$	$\mathrm{N^2LO_{HEFT}}+\mathrm{NLO_{QCD}}+\mathrm{PS}$		$+\mathrm{NLO_{EW}}+\mathrm{N^{(1,1)}LO_{QCD\times EW}}$
$pp \to H+j$	$\mathrm{d}\sigma$	$\mathrm{N^2LO_{HEFT}}$	$\mathrm{d}\sigma$	$\mathrm{N^2LO_{HEFT}}+\mathrm{NLO_{QCD}}+\mathrm{NLO_{EW}}$
	$\mathrm{d}\sigma$	$\mathrm{NLO_{EW}}$		
$pp \to H+2j$	$\mathrm{d}\sigma$	$\mathrm{NLO_{HEFT}}+\mathrm{LO_{QCD}}$	$\mathrm{d}\sigma$	$\mathrm{N^2LO_{HEFT}}+\mathrm{LO_{QCD}}+\mathrm{NLO_{EW}}$
	$\mathrm{d}\sigma$	$\mathrm{N^2LO_{QCD}}(\mathrm{VBF^*})$	$\mathrm{d}\sigma$	$\mathrm{N^2LO_{QCD}}(\mathrm{VBF})+\mathrm{NLO_{EW}}(\mathrm{VBF})$
	$\mathrm{d}\sigma$	$\mathrm{NLO_{EW}}(\mathrm{VBF})$		
$pp \to H+3j$	$\mathrm{d}\sigma$	$\mathrm{NLO_{HEFT}}$	$\mathrm{d}\sigma$	$\mathrm{NLO_{QCD}}+\mathrm{LO_{QCD}}+\mathrm{NLO_{EW}}$
	$\mathrm{d}\sigma$	$\mathrm{NLO_{EW}}$		
$pp \to H+V$	$\mathrm{d}\sigma$	$\mathrm{N^2LO_{QCD}}$	$\mathrm{d}\sigma$	$\mathrm{N^2LO_{QCD}}+\mathrm{NLO}_{gg\to HV}+\mathrm{NLO_{EW}}$
$pp \to HH$	$\mathrm{d}\sigma$	$\mathrm{N^2LO_{HEFT}}$	$\mathrm{d}\sigma$	$\mathrm{N^2LO_{HEFT}}+\mathrm{NLO_{QCD}}+\mathrm{NLO_{EW}}$
	$\mathrm{d}\sigma$	$\mathrm{NLO_{QCD}}$		
$pp \to H+t\bar{t}$	$\mathrm{d}\sigma$	$\mathrm{NLO_{QCD}}$	$\mathrm{d}\sigma$	$\mathrm{NLO_{QCD}}+\mathrm{NLO_{EW}}$
	$\mathrm{d}\sigma$	$\mathrm{NLO_{EW}}$		
$pp \to H+t$ $pp \to H+\bar{t}$	$\mathrm{d}\sigma$	$\mathrm{NLO_{QCD}}$	$\mathrm{d}\sigma$	$\mathrm{NLO_{QCD}}+\mathrm{NLO_{EW}}$

More results now!

Phenomenology

process	known		desired	
$pp \to V$	σ	$\mathrm{N^3LO_{QCD}}(z \to 0)$		
	$\mathrm{d}\sigma$	$\mathrm{N^2LO_{QCD}}$	$\mathrm{d}\sigma$	$\mathrm{N^3LO_{QCD}} + \mathrm{N^2LO_{EW}}$
	$\mathrm{d}\sigma$	$\mathrm{NLO_{EW}}$		$+ \mathrm{N^{(1,1)}LO_{QCD\times EW}}$ + decays
	$\mathrm{d}\sigma$	$\mathrm{N^{(1,1)}LO_{QCD\times EW}}$		
$pp \to VV'$	$\mathrm{d}\sigma$	$\mathrm{N^2LO_{QCD}}$ + decays	$\mathrm{d}\sigma$	$\mathrm{N^2LO_{QCD}} + \mathrm{NLO_{EW}}$+ decays
	$\mathrm{d}\sigma$	$\mathrm{NLO_{EW}}$		
$pp \to V + j$	$\mathrm{d}\sigma$	$\mathrm{N^2LO_{QCD}}$	$\mathrm{d}\sigma$	$\mathrm{N^2LO_{QCD}} + \mathrm{NLO_{EW}}$+ decays
$pp \to V + 2j$	$\mathrm{d}\sigma$	$\mathrm{NLO_{QCD}}$+ decays	$\mathrm{d}\sigma$	$\mathrm{N^2LO_{QCD}} + \mathrm{NLO_{EW}}$+ decays
	$\mathrm{d}\sigma$	$\mathrm{NLO_{EW}}$+ decays		
$pp \to VV' + 1, 2j$	$\mathrm{d}\sigma$	$\mathrm{NLO_{QCD}}$+ decays	$\mathrm{d}\sigma$	$\mathrm{NLO_{QCD}}$+ $\mathrm{NLO_{EW}}$+ decays
	$\mathrm{d}\sigma$	$\mathrm{NLO_{EW}}$		
$pp \to VV'V''$	$\mathrm{d}\sigma$	$\mathrm{NLO_{QCD}}$	$\mathrm{d}\sigma$	$\mathrm{NLO_{QCD}}$+ $\mathrm{NLO_{EW}}$+ decays
	$\mathrm{d}\sigma$	$\mathrm{NLO_{EW}}$		
$pp \to \gamma\gamma$	$\mathrm{d}\sigma$	$\mathrm{N^2LO_{QCD}}$	$\mathrm{d}\sigma$	$\mathrm{N^2LO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to \gamma\gamma + j$	$\mathrm{d}\sigma$	$\mathrm{NLO_{QCD}}$	$\mathrm{d}\sigma$	$\mathrm{N^2LO_{QCD}} + \mathrm{NLO_{EW}}$

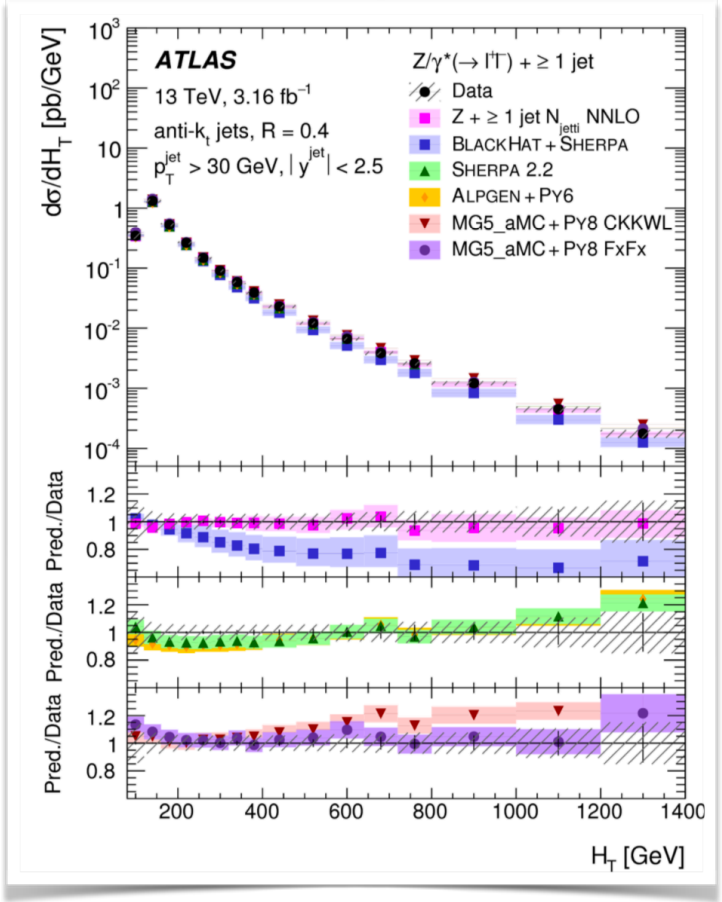
More results now!

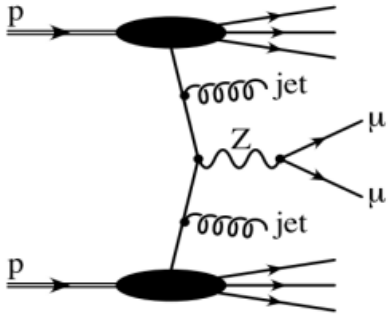
Phenomenology

process	known		desired	
$pp \to t\bar{t}$	$d\sigma$	N^2LO_{QCD}		
	$d\sigma$	NLO_{QCD}+ decays	$d\sigma$	N^2LO_{QCD} + NLO_{EW}+ decays
	$d\sigma$	NLO_{EW}		
$pp \to t\bar{t} + j$	$d\sigma$	NLO_{QCD}+ decays	$d\sigma$	N^2LO_{QCD} + NLO_{EW}+ decays
	$d\sigma$	NLO_{EW}		
$pp \to t\bar{t} + 2j$	$d\sigma$	NLO_{QCD}+ on-shell decays	$d\sigma$	NLO_{QCD}+ NLO_{EW}+ decays
$pp \to t\bar{t} + V$	$d\sigma$	NLO_{QCD}	$d\sigma$	NLO_{QCD}+ NLO_{EW}+ decays
	$d\sigma$	NLO_{EW}		
$pp \to t/\bar{t}$	$d\sigma$	N^2LO_{QCD} (t-channel)	$d\sigma$	N^2LO_{QCD} + NLO_{EW}+ decays
$pp \to 2j$	$d\sigma$	N^2LO_{QCD}(gg,qq)	$d\sigma$	N^2LO_{QCD} + NLO_{EW}
	$d\sigma$	NLO_{EW}		
$pp \to j + \gamma$	$d\sigma$	NLO_{QCD}	$d\sigma$	N^2LO_{QCD} + NLO_{EW}
	$d\sigma$	NLO_{EW}		
$pp \to 3j$	$d\sigma$	NLO_{QCD}	$d\sigma$	N^2LO_{QCD} + NLO_{EW}

More results now!

Phenomenology





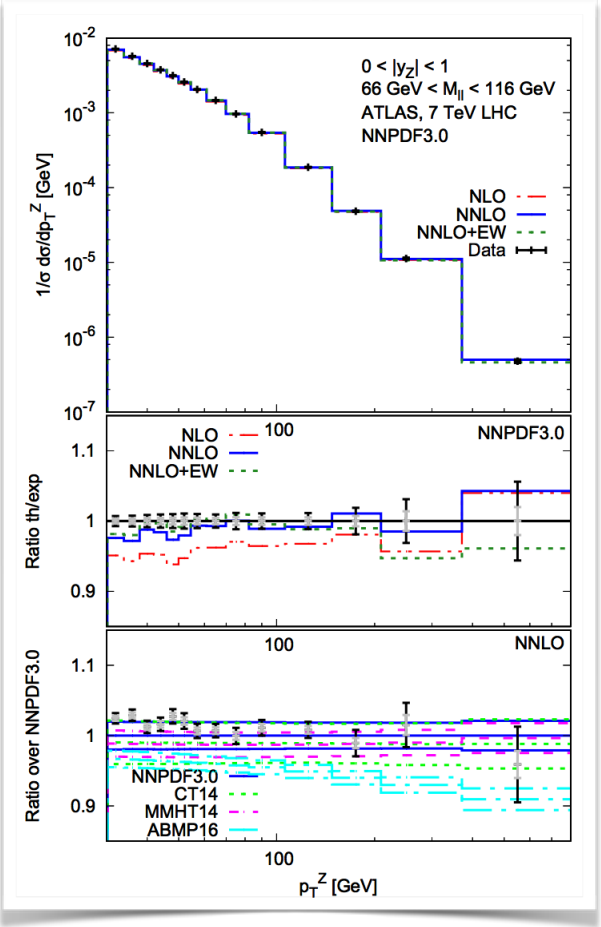
Z+jets H_T distribution

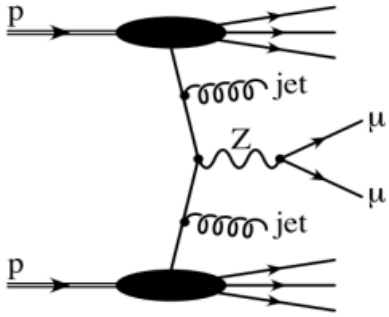
- common variable in beyond SM searches for heavy particles
- Irreducible background for new physics searches, e.g. dark matter, SUSY

NNLO recovers agreement with data by add on missing high orders.

Boughezal, et. al.

Phenomenology





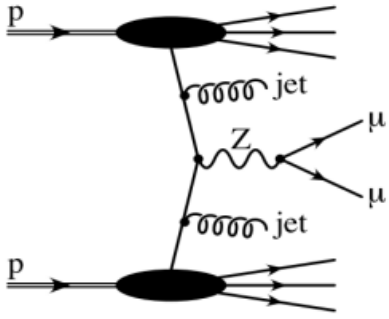
Z pT distribution

- Clean and very small exp. uncertainty ~ 1%
- therefore standard candle at the LHC

NNLO agrees much better than NLO.

Boughezal, et. al.

Phenomenology



	Before p_T^Z data	After p_T^Z data
$\sigma_{gg\to H}$ [pb]	48.22 ± 0.89 (1.8%)	48.61 ± 0.61 (1.3%)
σ_{VBF} [pb]	3.92 ± 0.06 (1.5%)	3.96 ± 0.04 (1.0%)

Z pT distribution

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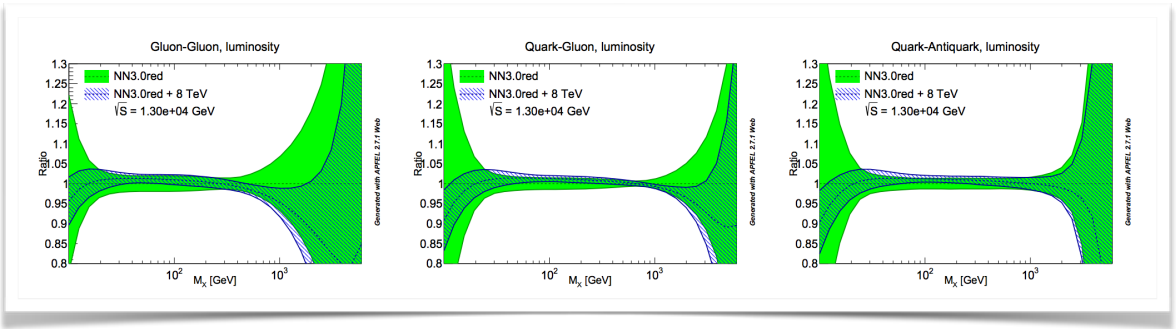


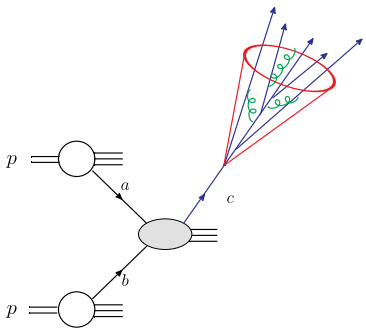
Error reduced by 30% when NNLO Z pT included

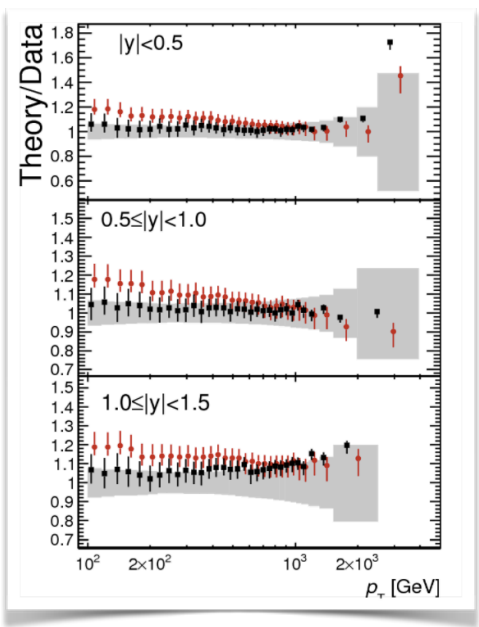
Boughezal, et. al.

Phenomenology

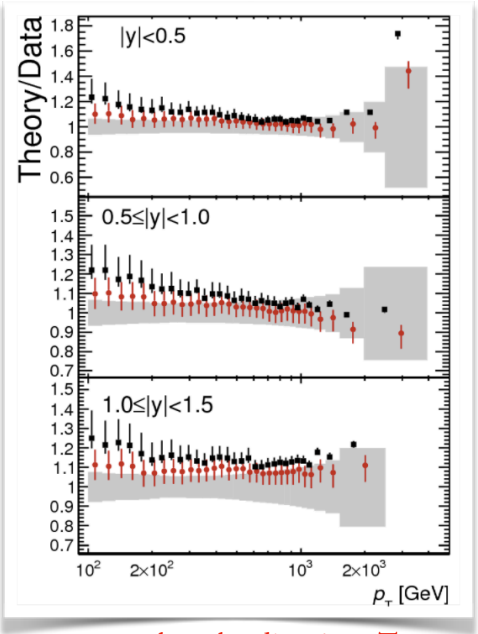
Single inclusive jet production

- Anther benchmark process at the LHC
- Related to new physics searches, PDF fitting ⋯





scale = individual jet pT



scale = leading jet pT

Fixed NLO or NNLO describes the data ?

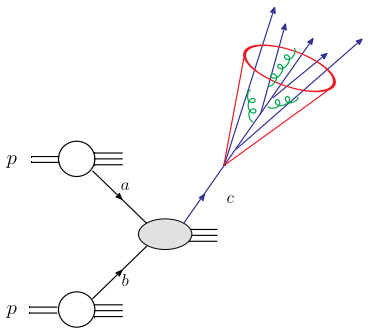
Depends on the scale choices

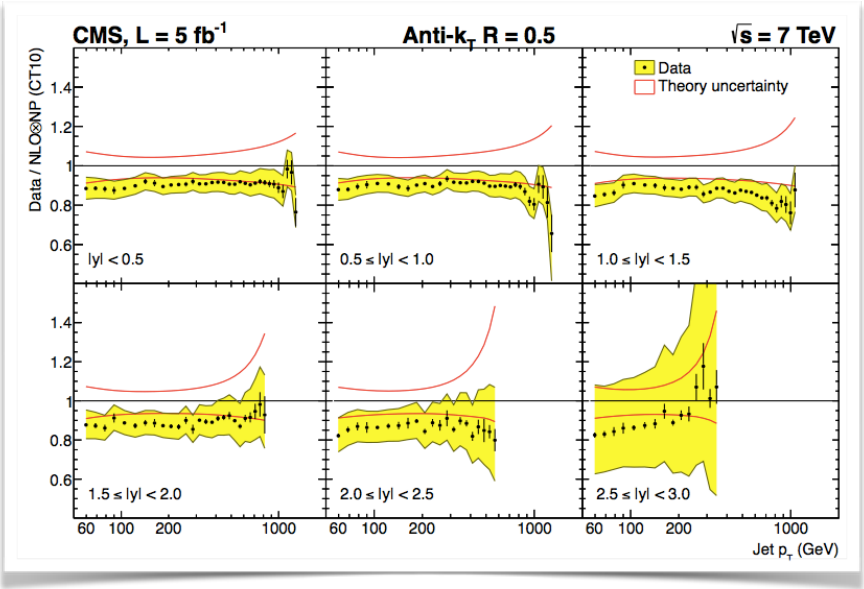
Currie, Glover, Pires

Phenomenology

Single inclusive jet production

- Anther benchmark process at the LHC
- Related to new physics searches, PDF fitting ⋯





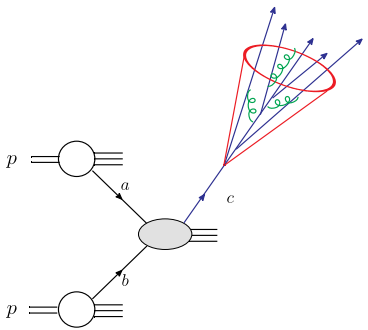
Fixed NLO or NNLO describes the data ?

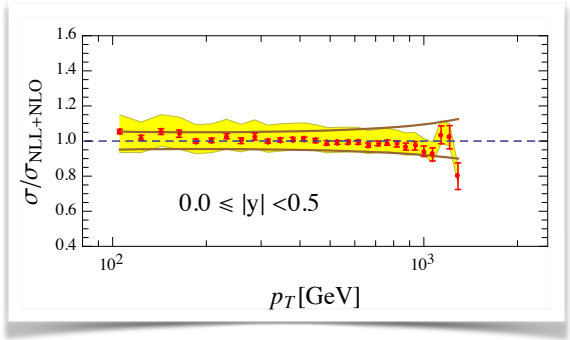
Systematic discrepancies

Phenomenology

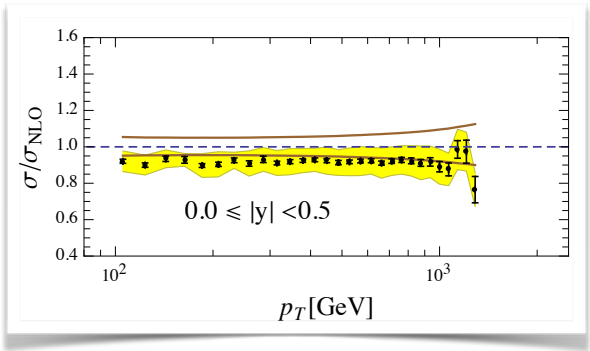
Single inclusive jet production

- Anther benchmark process at the LHC
- Related to new physics searches, PDF fitting ⋯





XL, Moch, Ringer



Fixed NLO or NNLO describes the data ?

Systematic discrepancies

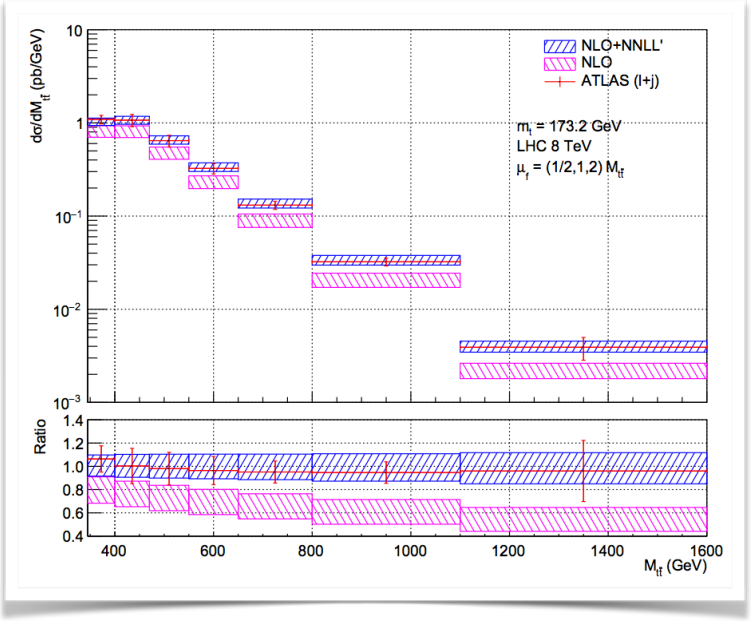
Fixed order is not everything

Resummation (small R) may help here

Phenomenology

t-tbar production

- Another example that resummation could help
- NLO + NNLL' (threshold)

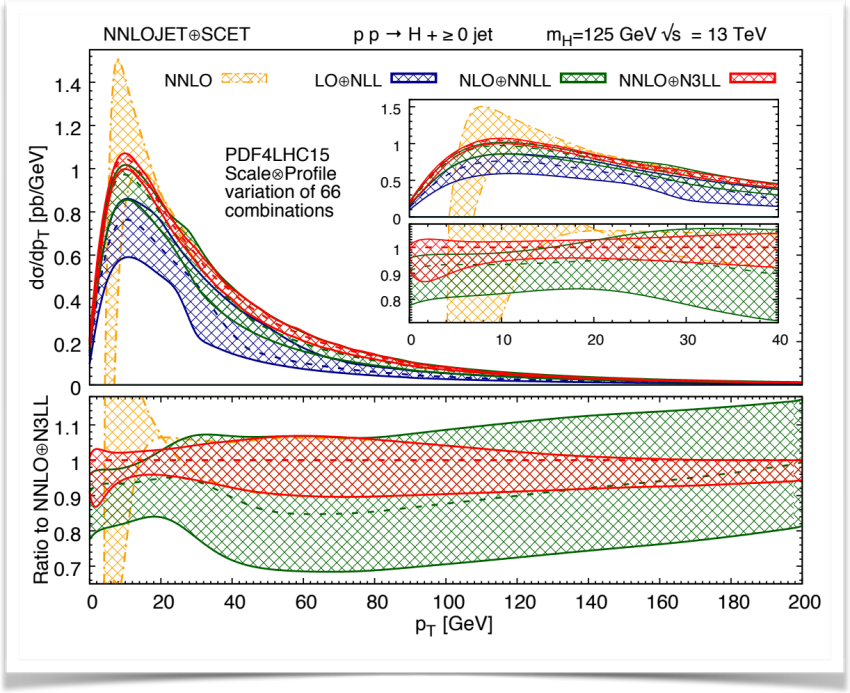


Pecjak, Scott, Wang, Yang

Phenomenology

Higgs production

- First result for NNLO + NNNLL at the LHC
- For small pT, resummation is crucial



Chen et. al.

Conclusions

- Precision is important (test QCD + new physics searches)
- We need to deal with both loop corrections and real emissions
- Now the frontier at the LHC is NNLO + beyond