

QCD in hadron collisions

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An exciting past 18 months

$t\bar{t}$ asymmetry

$W + \text{dijet}$ CDF anomaly

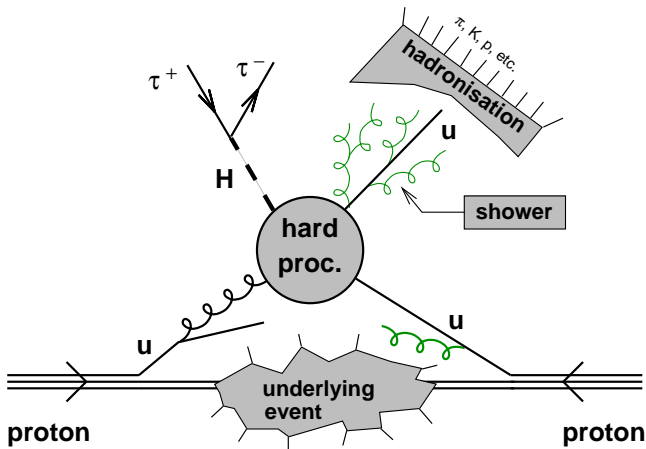
Exclusion of swathes of SUSY, etc.

Higgs Hints

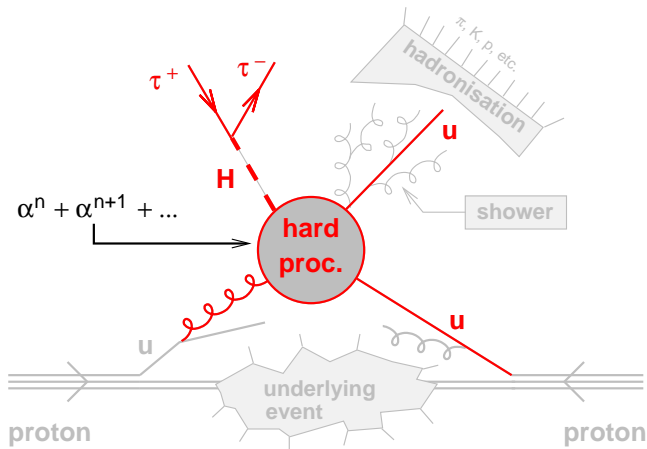
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This talk: examine recent collider-QCD developments and the role they're playing in some of these "headline" topics, as well as touch on some open problems

Some of what goes into collider predictions

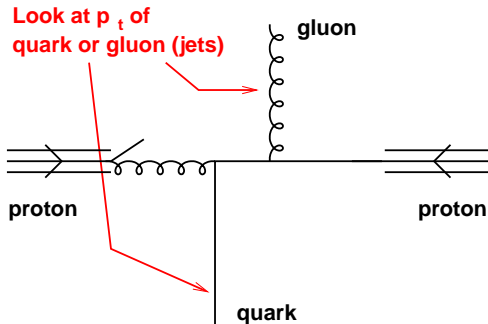
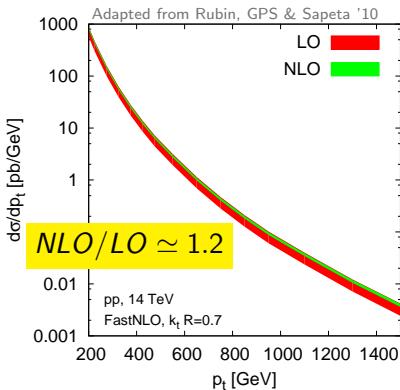


Some of what goes into collider predictions



The hard process is where we use pQCD expansion in α_s

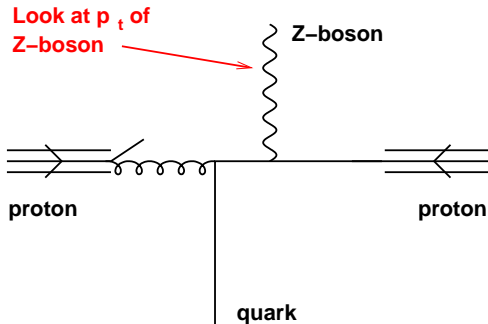
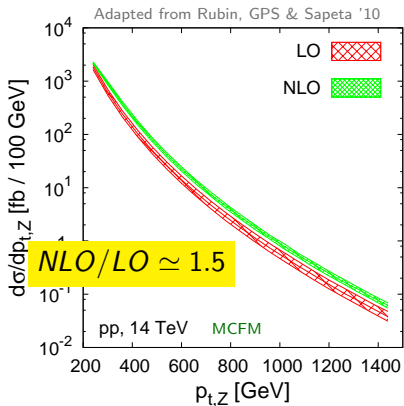
Consider LO, NLO and their ratio $K = \frac{\text{NLO}}{\text{LO}}$



K of 1.2 is compatible with being $1 + \mathcal{O}(\alpha_s)$

The hard process is where we use pQCD expansion in α_s

Consider LO, NLO and their ratio $K = \frac{\text{NLO}}{\text{LO}}$

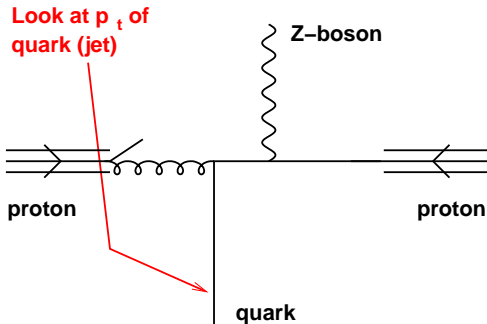
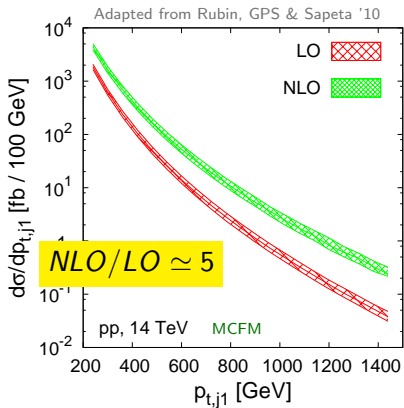


K of 1.5 is compatible with being $1 + C \times \alpha_s$, with quite large C

To date, no generalised understanding of size of C when in range 5 – 10

The hard process is where we use pQCD expansion in α_s

Consider LO, NLO and their ratio $K = \frac{\text{NLO}}{\text{LO}}$

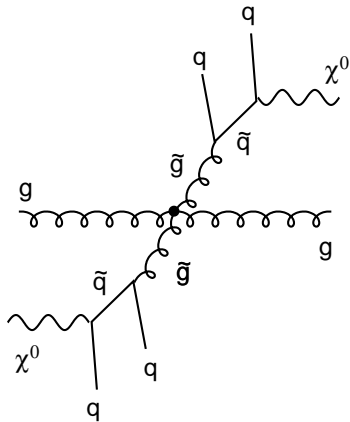


$1 + C\alpha_s \rightarrow K = 5 ?!!$ Often driven by new topologies

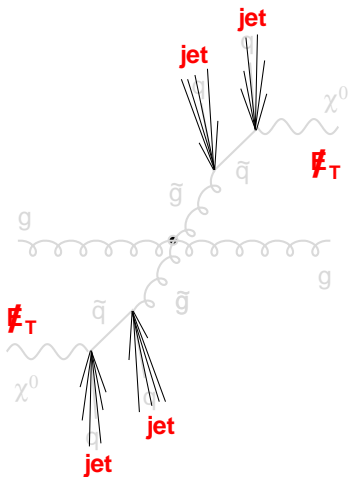
The NLO revolution

and one way it's being used

Signal

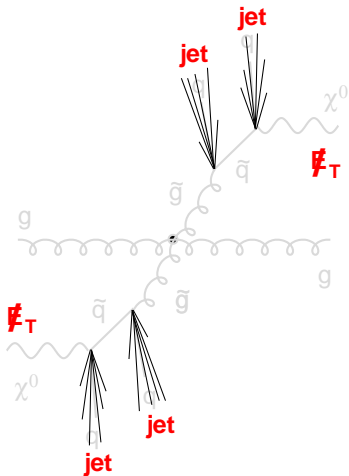


Signal

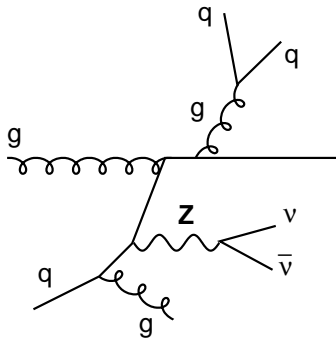


SUSY example: gluino pair production

Signal

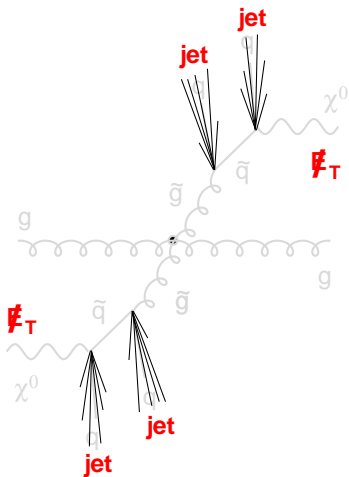


Background

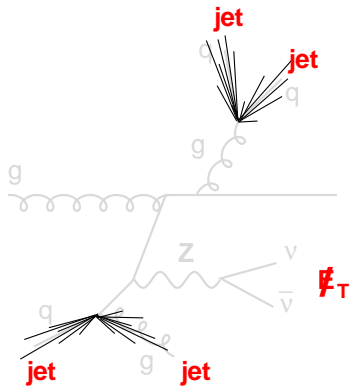


SUSY example: gluino pair production

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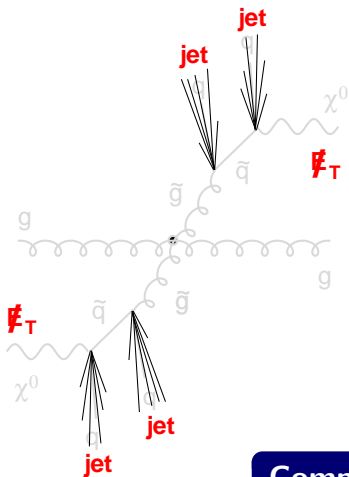


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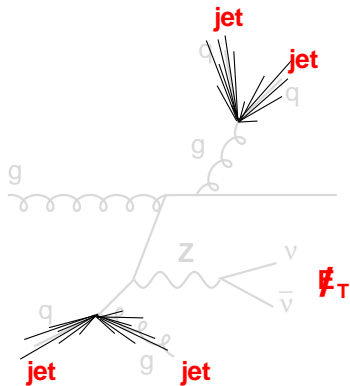


SUSY example: gluino pair production

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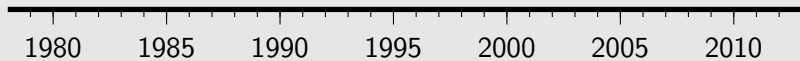


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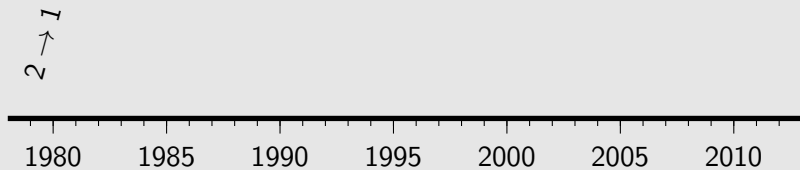


Complexity of NLO calculation determined by final-state multiplicity: a $2 \rightarrow 5$ process.

NLO timeline

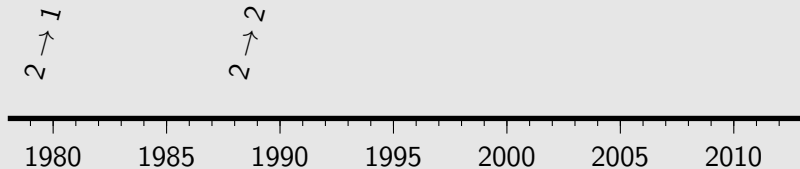


NLO timeline



1979: NLO Drell-Yan [Altarelli, Ellis & Martinelli]

NLO timeline

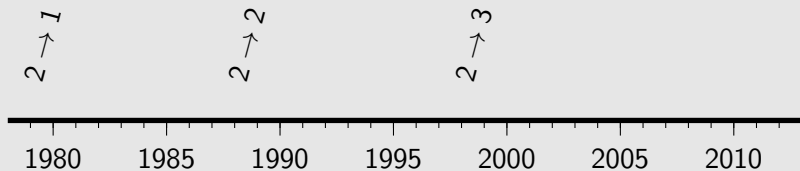


1987: NLO high- p_t photoproduction [Aurenche et al]

1988: NLO $b\bar{b}$, $t\bar{t}$ [Nason et al]

1993: dijets, V_j [JETRAD, Giele, Glover & Kosower]

NLO timeline



1998: NLO $Wb\bar{b}$ [MCFM: Ellis & Veseli]

2000: NLO $Zb\bar{b}$ [MCFM: Campbell & Ellis]

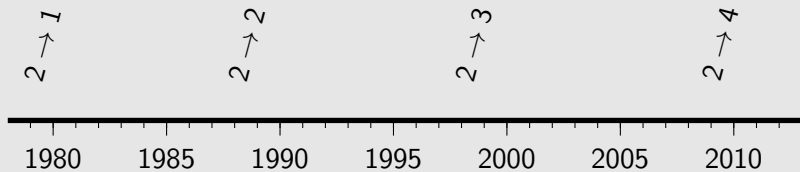
2001: NLO $3j$ [NLOJet++: Nagy]

...

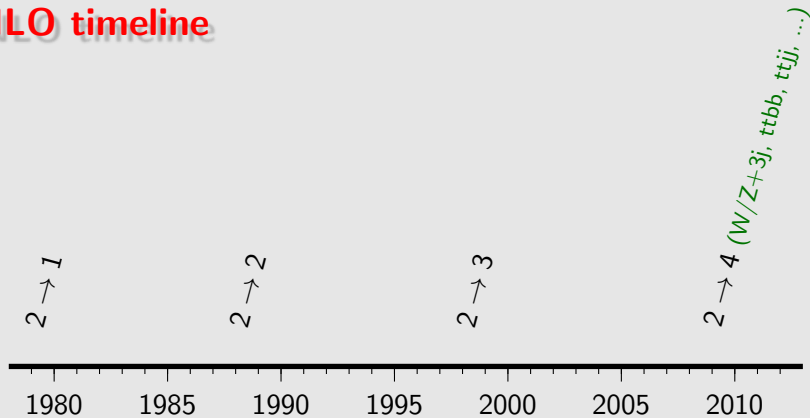
2007: NLO $t\bar{t}j$ [Dittmaier, Uwer & Weinzierl '07]

...

NLO timeline



NLO timeline



2009: NLO $W+3j$ [Rocket: Ellis, Melnikov & Zanderighi]

[unitarity]

2009: NLO $W+3j$ [BlackHat+Sherpa: Berger et al]

[unitarity]

2009: NLO $t\bar{t}b\bar{b}$ [Bredenstein et al]

[traditional]

2009: NLO $t\bar{t}b\bar{b}$ [HELAC-NLO: Bevilacqua et al]

[unitarity]

2009: NLO $q\bar{q} \rightarrow b\bar{b}b\bar{b}$ [Golem: Binoth et al]

[traditional]

2010: NLO $t\bar{t}jj$ [HELAC-NLO: Bevilacqua et al]

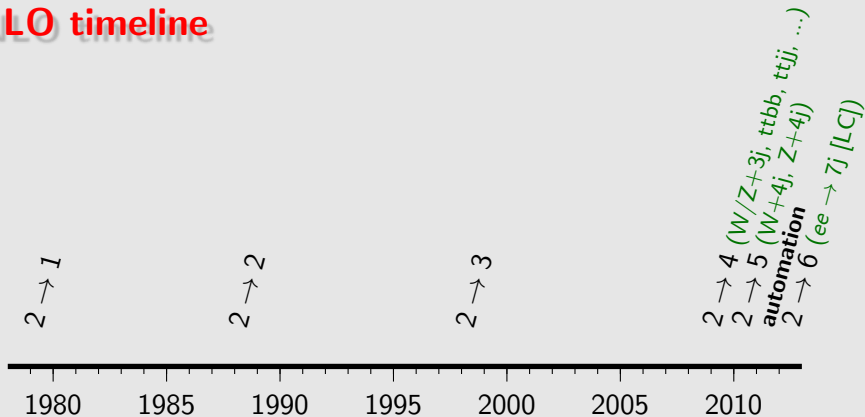
[unitarity]

2010: NLO $Z+3j$ [BlackHat+Sherpa: Berger et al]

[unitarity]

...

NLO timeline



2010: NLO $W+4j$ [BlackHat+Sherpa: Berger et al]

[unitarity]

2011: NLO $WWjj$ [Rocket: Melia et al]

[unitarity]

2011: NLO $Z+4j$ [BlackHat+Sherpa: Ita et al]

[unitarity]

2011: NLO $4j$ [BlackHat+Sherpa: Bern et al]

[unitarity]

2011: first automation [MadNLO: Hirschi et al]

[unitarity + feyn.diags]

2011: first automation [Helac NLO: Bevilacqua et al]

[unitarity]

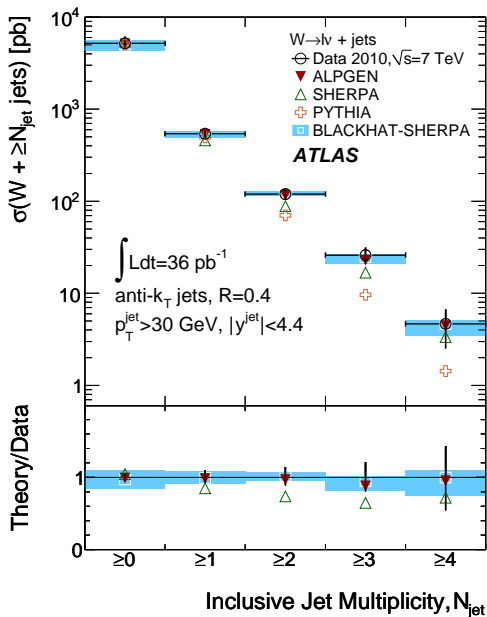
2011: first automation [GoSam: Cullen et al]

[feyn.diags(+unitarity)]

2011: $e^+e^- \rightarrow 7j$ [Becker et al, leading colour]

[numerical loops]

W + 0,1,2,3,4 jets @NLO



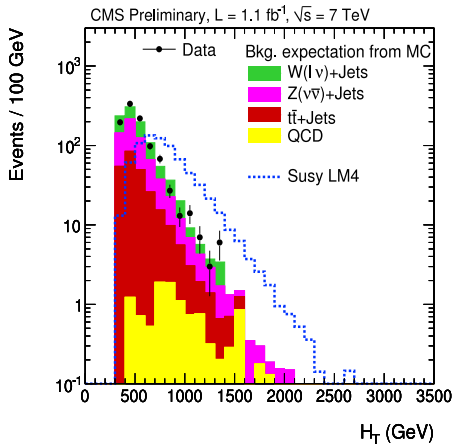
Technical revolution has gone hand-in-hand with LHC measurements of these complex processes.

Powerful validation of NLO approach.

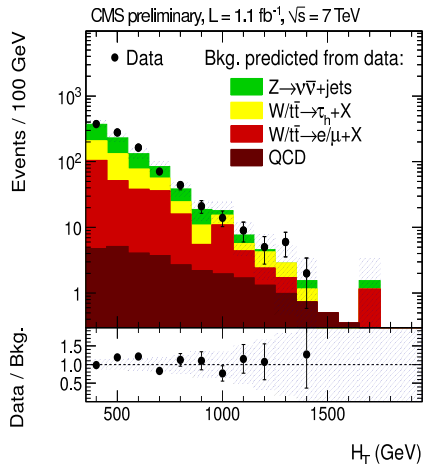
So do SUSY searches now just compare data to NLO?

Two plots from a CMS SUSY analysis

Data v. Monte Carlo backgrounds



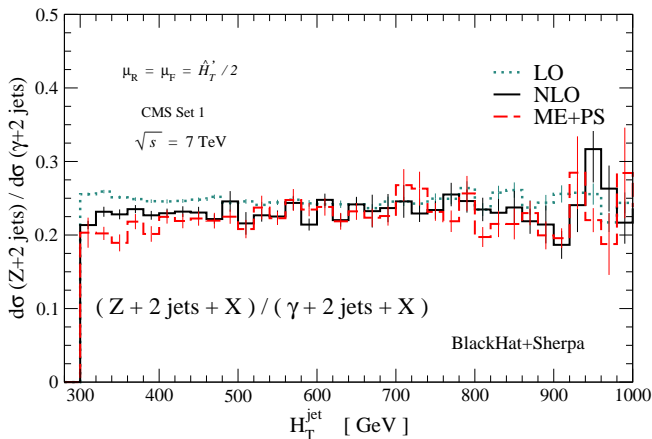
Data v. “data-driven” backgrounds



So where are the NLO predictions being used?

The CMS search did **not** estimate $Z+\text{jets}$ bkgd from NLO. Instead used

$$\frac{d\sigma^{Z+\text{jets}}}{dH_T} = \left(\frac{d\sigma^{\gamma+\text{jets}}}{dH_T} \right)_{\text{data}} \times \left(\frac{d\sigma^{Z+\text{jets}}}{dH_T} / \frac{d\sigma^{\gamma+\text{jets}}}{dH_T} \right)_{\text{NLO}}$$



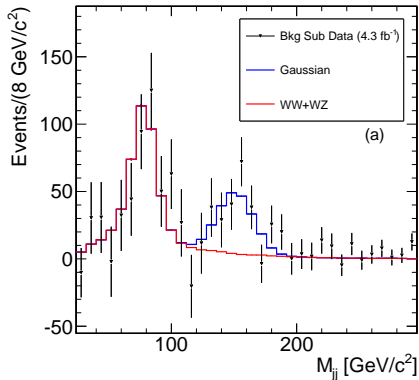
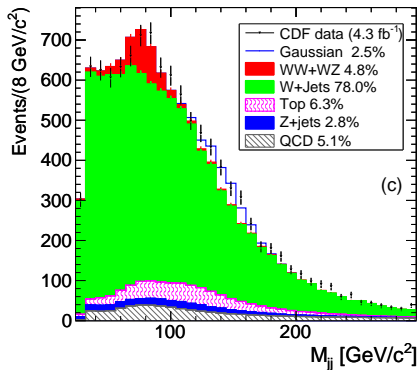
Example of widely used **data-driven** bkgd estimates

Combine best of theory knowledge with best of experimental knowledge.

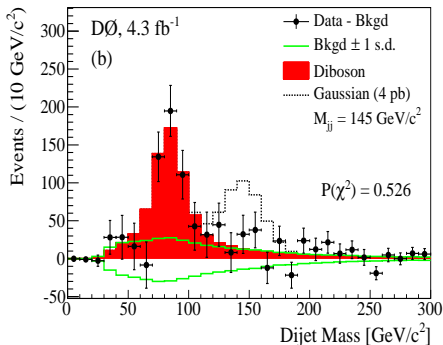
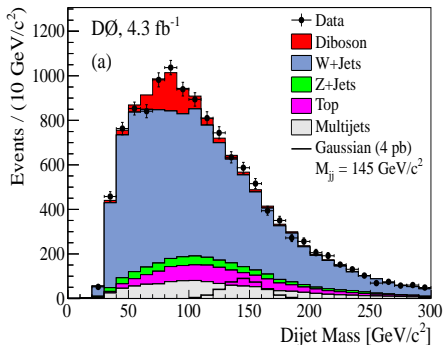
Merging NLO and showers

and the CDF $W + \text{dijet}$ anomaly

Remember the CDF W +dijet excess?



and the D0 W+dijet non-excess?



CDF and D0 data are **not** being compared to NLO (=W+partons):

They are “detector-level” data and can only be compared to hadron-level calculations + detector simulation.

In this case hadron-level = Alpgen \otimes Pythia

Perturbative expansion: for precision.

Parton Showers (PS): for realism;

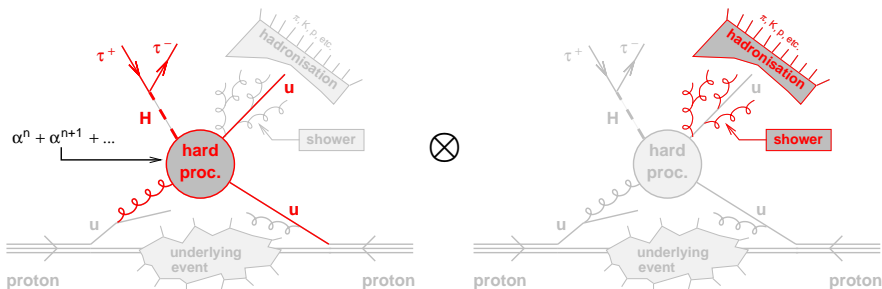
To combine them: must remove double counting

Tree-level (LO) + PS

Different tree-level multiplicities (W , $W+1j$, $W+2j$, etc.) get combined

MLM/CKKW: Alpgen+Pythia/Herwig, MadGraph, Sherpa, ...

Fully automated



NLO + PS — MC@NLO, POWHEG

Greater accuracy, but harder to perform than LO+PS:

NLO contains more physics than LO,
so more double-counting with parton shower

Less “available” than tree+PS: until recently,

- ↳ A single (low) multiplicity, e.g. W@NLO + PS
- ↳ Programmed manually for each process

Recently: move towards automation:

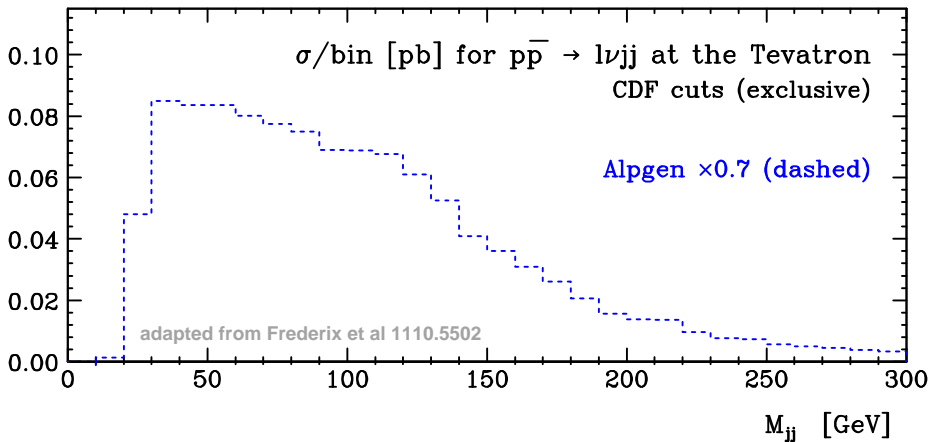
POWHEGBox: $t\bar{t}+\text{jet}$, W^+W^++2j , ...

aMC@NLO (MadLoop + auto MC@NLO): $W+2j$, $Z+2b$, ...

+ ideas for combining multiplicities, e.g. MENLOPS, ...

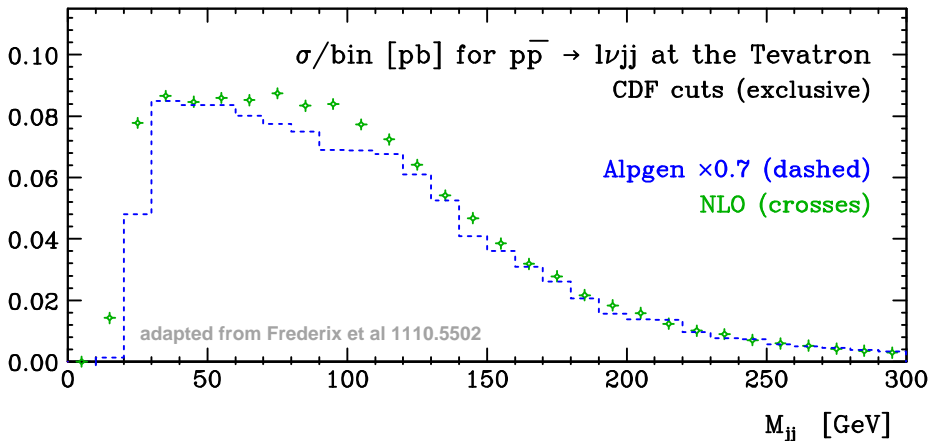
A key application of this progress has been to the W+dijet anomaly

CDF & DØ use Alpgen (scaled): tree level QCD + parton shower



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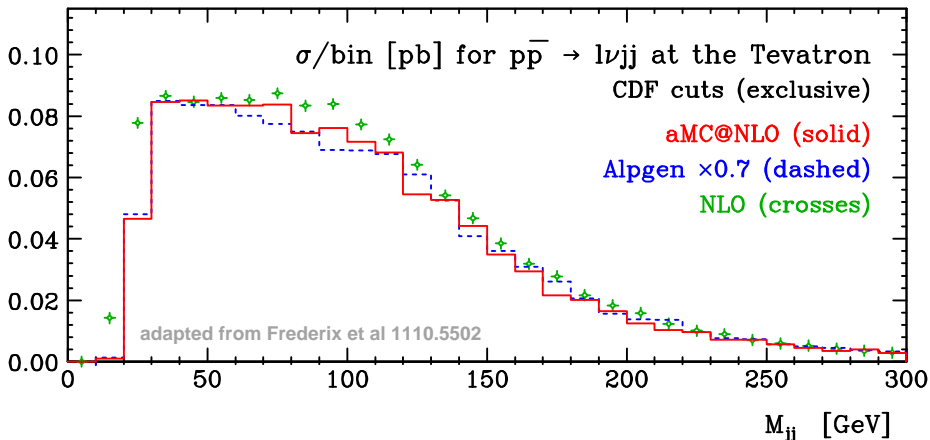
NLO has substantial shape differences: should we worry?

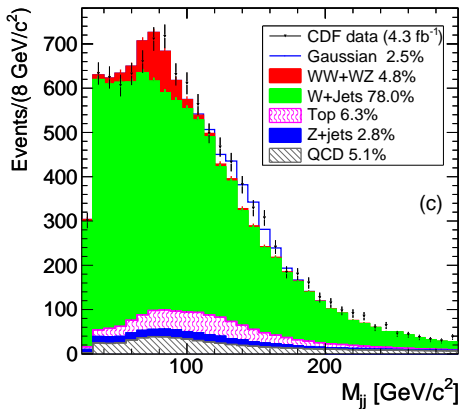


CDF & DØ use Alpgen (scaled): tree level QCD + parton shower

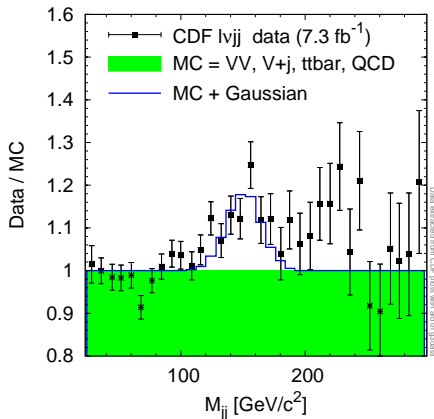
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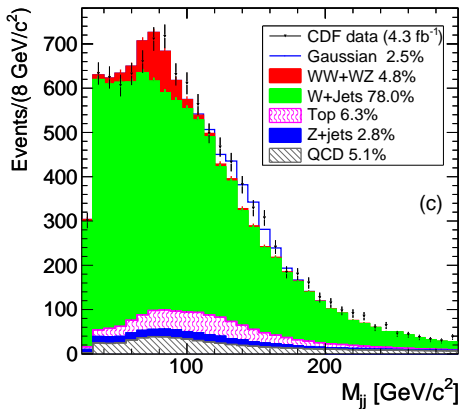
NLO + parton shower (aMC@NLO) is close to Alpgen
→ QCD under good control



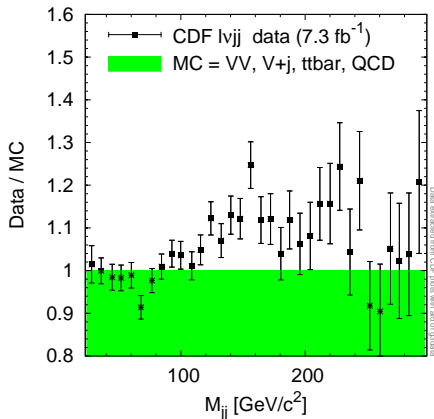


Instead of data – MC \Rightarrow **data/MC**

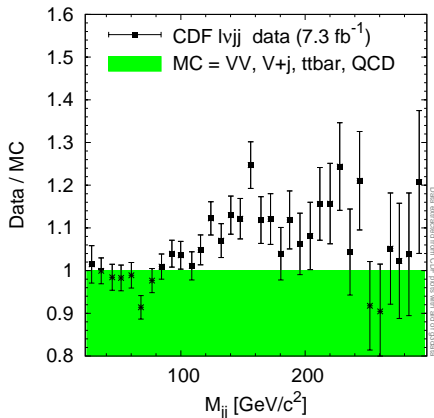
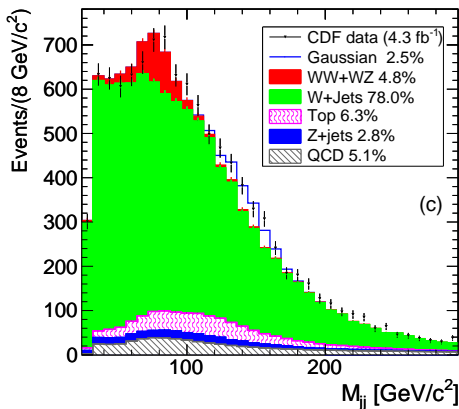




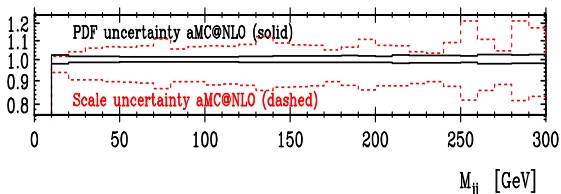
Instead of data – MC \Rightarrow **data/MC**



Instead of data – MC \Rightarrow **data/MC**



aMC@NLO
uncertainties: \rightarrow

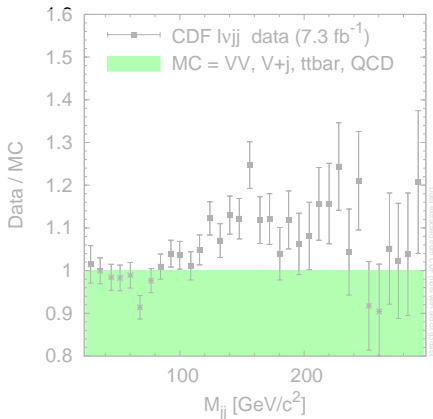
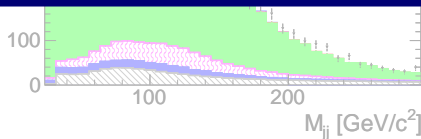


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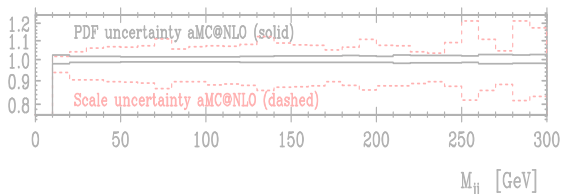


“Anomaly” is a 10% effect
(not clear it’s really a peak)

10% is clearly at limit
of NLO accuracy



aMC@NLO
uncertainties: \rightarrow



Going beyond limitations of NLO

[two of the options]

High precision — NNLO — is crucial for key processes, but not yet always available:

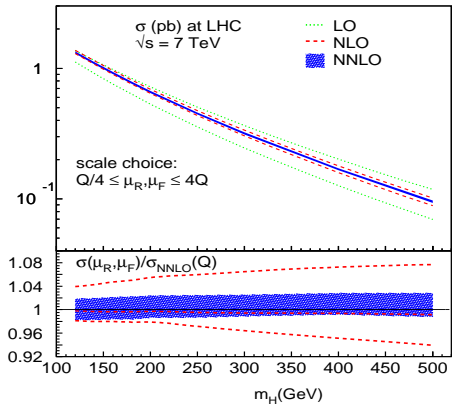
✓ $W, Z, \text{Higgs}, \gamma\gamma, \text{VBF}, VH$

✗ $VV, t\bar{t}, \text{inclusive jets, etc.}$

Important also to develop methods so that we're less sensitive to limits on our precision.

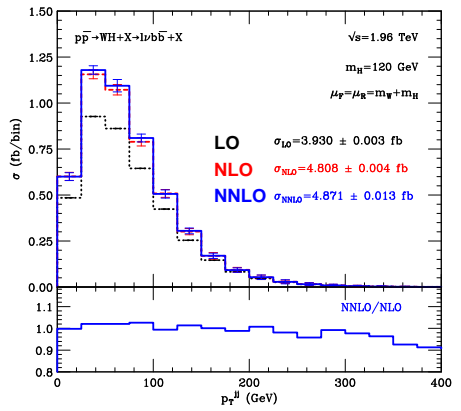
Generally by finding ways to distinguish signals from the background more efficiently, i.e. increasing S/B .

New in 2010: NNLO VBF \rightarrow H



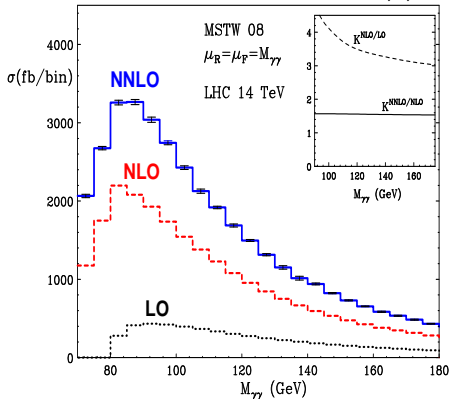
Bolzoni, Maltoni, Moch & Zaro

New in 2011: NNLO WH (differential)



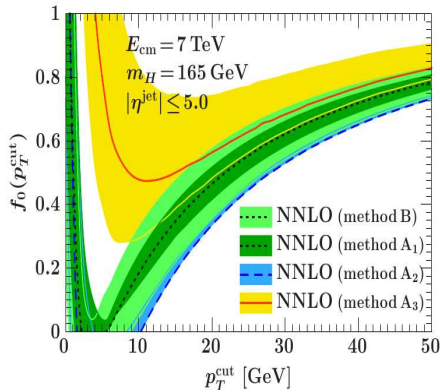
Ferrera, Grazzini & Tramontano

New in 2011: NNLO $\gamma\gamma$



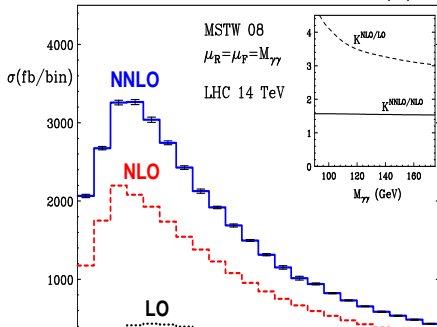
Catani et al

Higgs jet veto efficiency

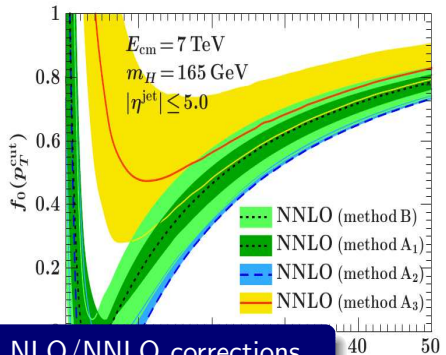


analyses by Stewart & Tackmann '12
 + Banfi, GPS & Zanderighi
 using FeHiP/HNNLO

New in 2011: NNLO $\gamma\gamma$



Higgs jet veto efficiency



Some key processes see large or giant NLO/NNLO corrections. Various techniques — threshold resummation, p_t resummation, LoopSim — can improve situation.

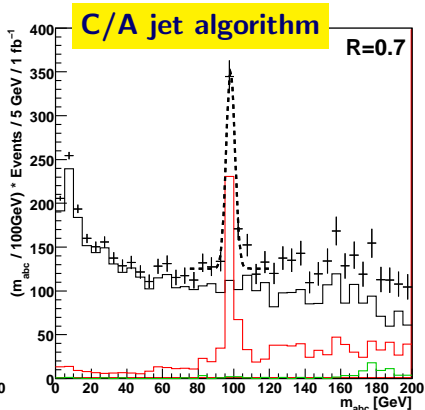
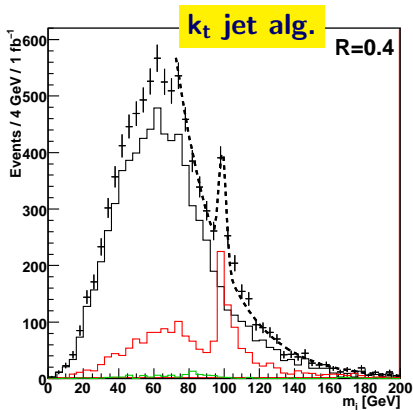
Still, can't help but wonder if we're missing something, especially in the $gg \rightarrow H$ case.

mann '12
 anderighi
 /HNNLO

Are we using all possible handles to analyse data?

A new sub-field has emerged, “Boost”, for finding boosted tops/Z/H/etc.

It's teaching us that there are many ways of looking at events, and QCD can educate us about the “best” ways.



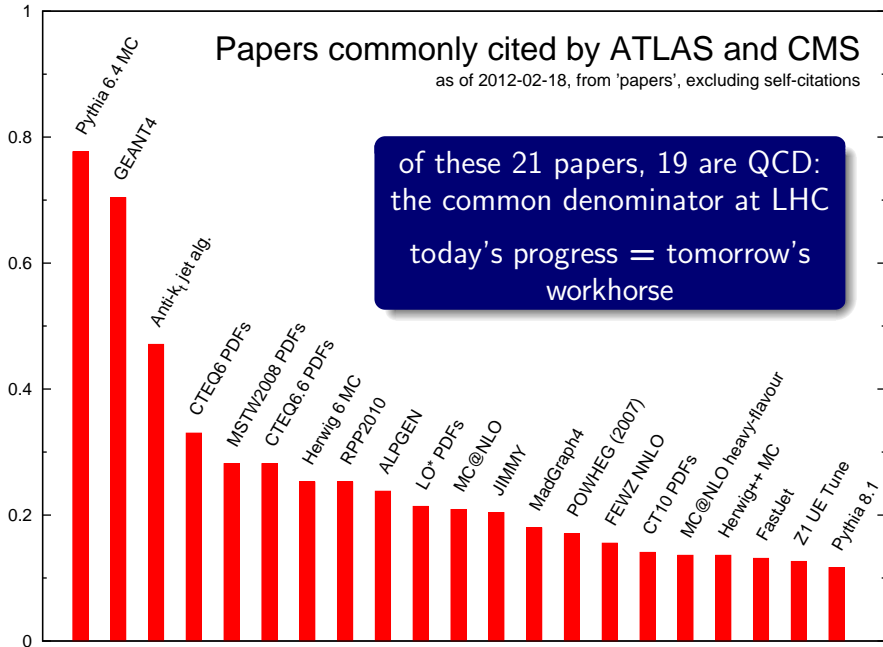
[Search for R-parity violating $\chi^0 \rightarrow qq\bar{q}$; Butterworth, Ellis, Raklev & GPS '09]

Closing

Papers commonly cited by ATLAS and CMS

as of 2012-02-18, from 'papers', excluding self-citations

fraction of ATLAS & CMS papers that cite them



of these 21 papers, 19 are QCD:
the common denominator at LHC
today's progress = tomorrow's
workhorse

Plot by GP Salam based on data from ATLAS, CMS and INSPIREHEP

EXTRAS

Traditional

Draw all Feynman diagrams with 1 loop. Work out formulae for them.

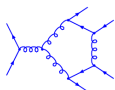
Work hard to reduce integrals to known forms (+ tricks).

Tree and one-loop contributions to $pp \rightarrow t\bar{t}b\bar{b} + X$

Ansgar Denner (PSI)



7 trees



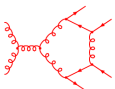
24 pentagons



8 hexagons



36 trees



114 pentagons

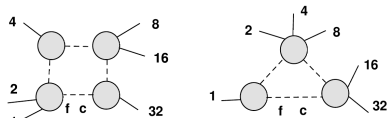


40 hexagons

Recursive/unitarity methods

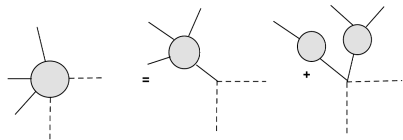
Assemble loop-diagrams from individual tree-level diagrams.

Build trees by sticking together simpler tree-level diagrams



Costas G. Papadopoulos (Athens)

Blobs are always tree-like objects



Traditional

Draw all Feynman diagrams with 1 loop. Work out formulae for them.

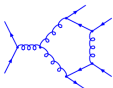
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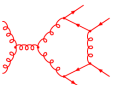
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Some main ideas:

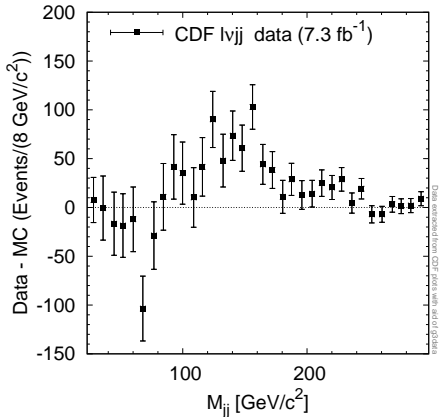
Bern, Dixon & Kosower '93
[sewing together trees]

Britto, Cachazo & Feng '04
[on-shell complex loop momenta]

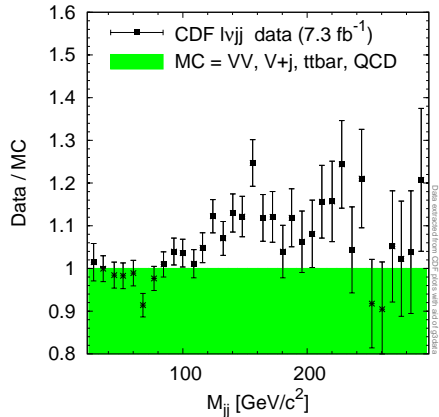
Ossola, Pittau & Papadopoulos '06
[handful of loop momentum choices give full amplitude]

CDF W_{jj} : difference wrt MC v. ratio to MC

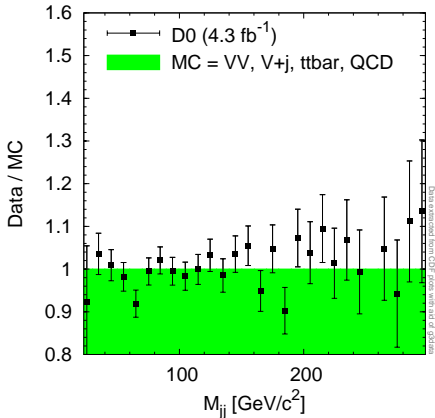
CDF difference



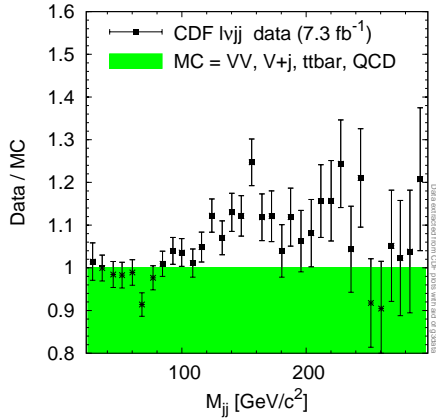
CDF ratio



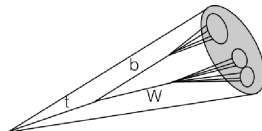
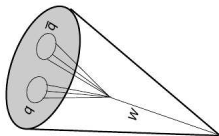
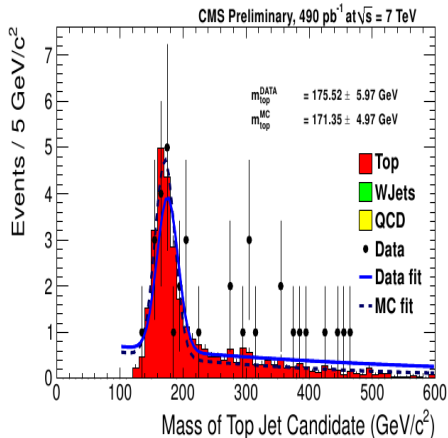
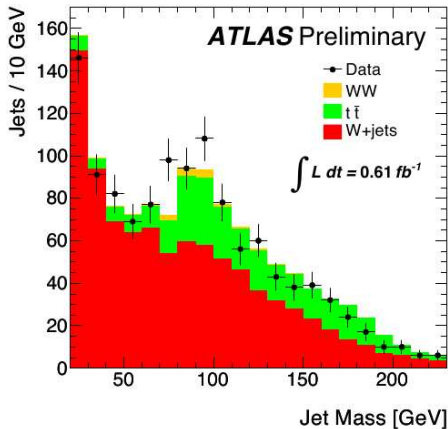
DØ ratio



CDF ratio



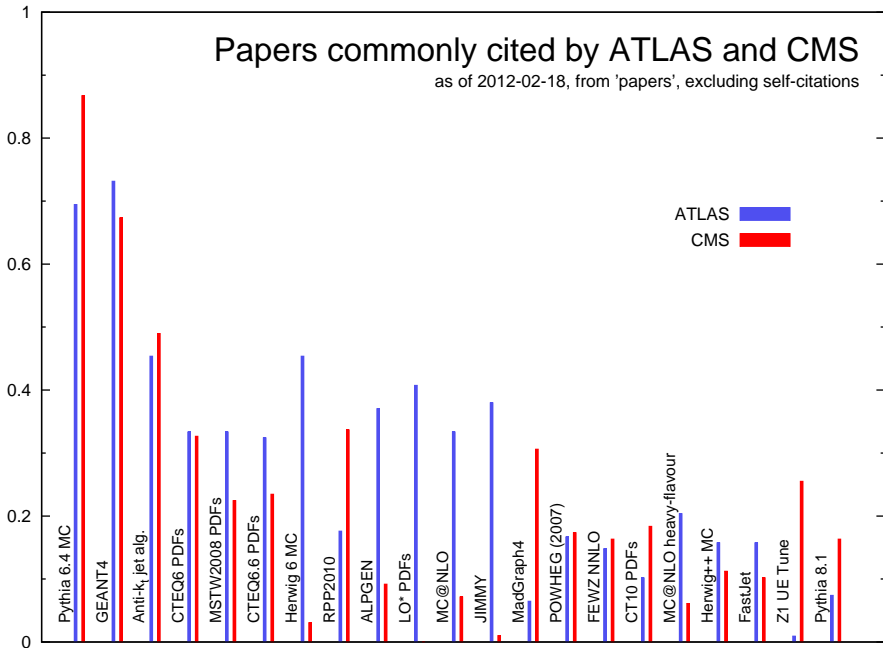
Experimental progress on boosted objects



Papers commonly cited by ATLAS and CMS

as of 2012-02-18, from 'papers', excluding self-citations

fraction of ATLAS & CMS papers that cite them



Plot by GP Salam based on data from ATLAS, CMS and INSPIREHEP