Perturbative QCD in hadron collisions

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An exciting past 24 months

Higgs(-like) discovery

$t\bar{t}$ asymmetry

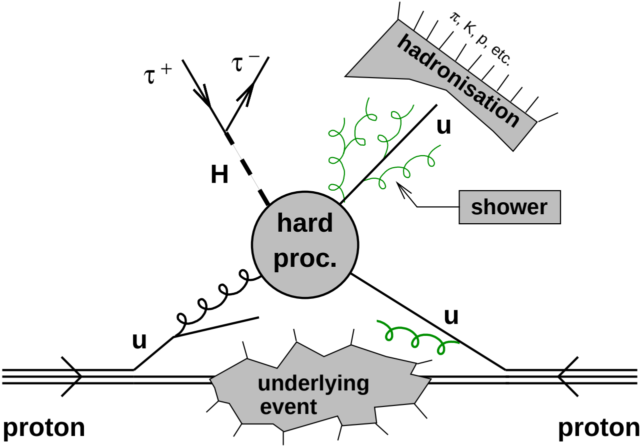
W + dijet CDF anomaly

Exclusion of swathes of SUSY, etc.

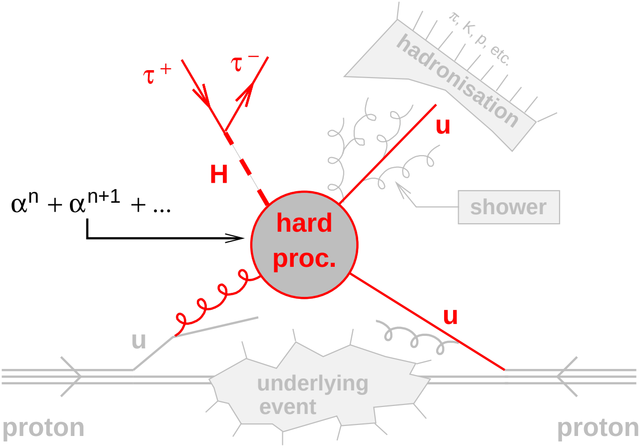
...

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

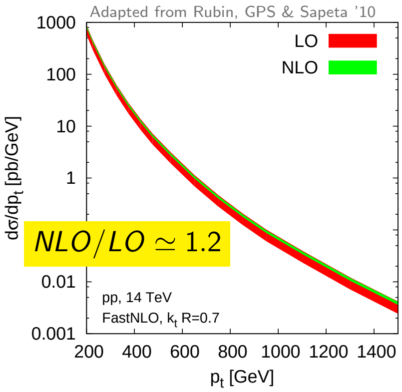


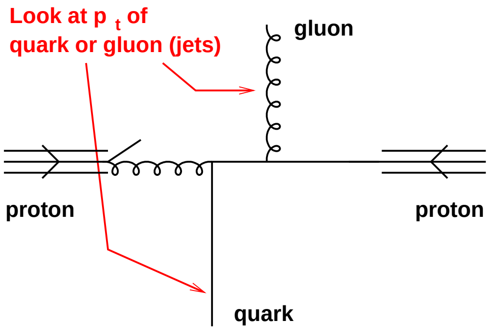
E.g. QCD corrections to $e^+e^- \to$ hadrons cross section:

$$R = 1 + 0.32\alpha_s + 0.14\alpha_s^2 - 0.41\alpha_s^3 - 0.82\alpha_s^4$$

keep in mind $\alpha_s(m_Z) \simeq 0.118$

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

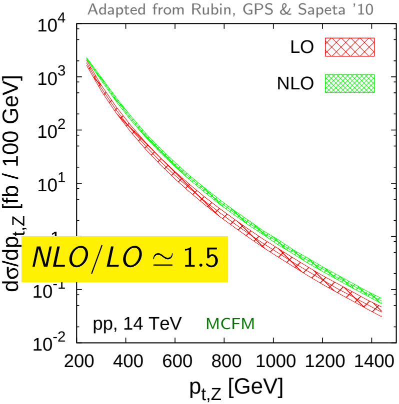




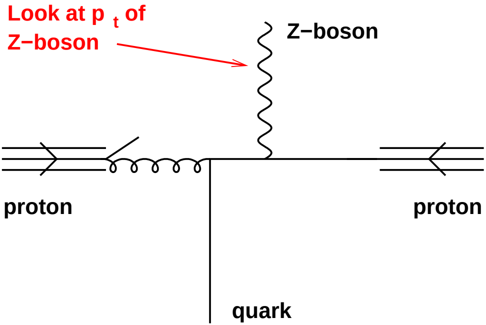
$1 + 2\alpha_s$ looks like a reasonable series

What it looks like at hadron colliders

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



$NLO/LO \simeq 1.5$



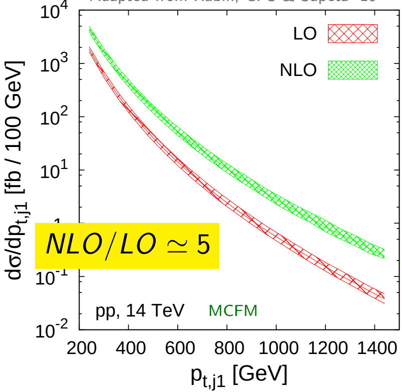
$1 + C \times \alpha_s$, with quite large $C \simeq 5$

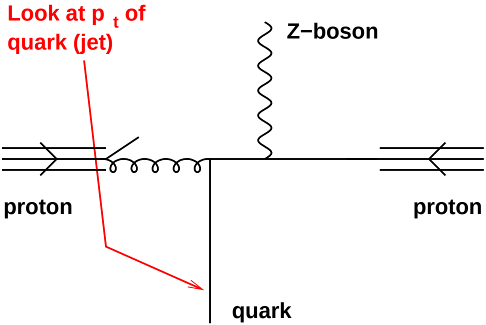
To date, no generalised understanding of size of C when in range $5 - 10$

What it looks like at hadron colliders

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

Adapted from Rubin, GPS & Sapeta '10



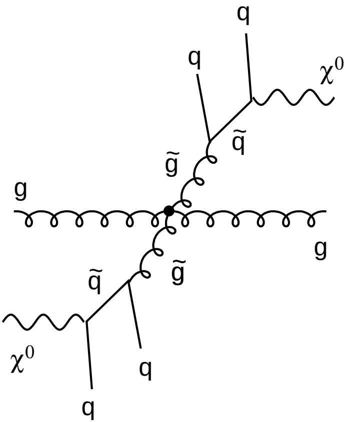


$1 + C\alpha_s \longrightarrow C = 50$?!! Often driven by new topologies

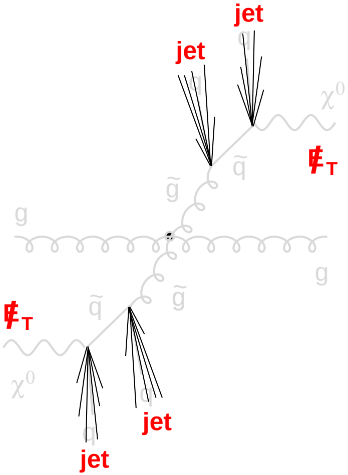
The NLO revolution

and one way it's being used

Signal

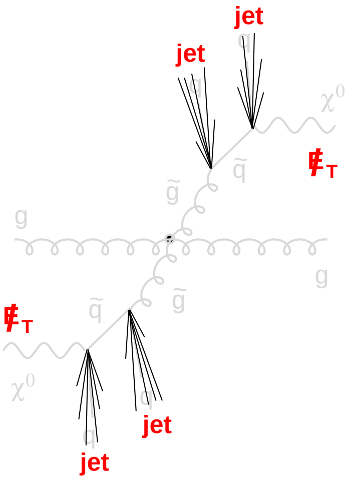


Signal

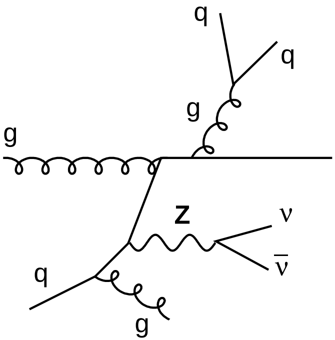

jet
jet
χ^0
$\not{E}_T$
$\tilde{q}$
$\tilde{g}$
g
g
$\tilde{g}$
$\tilde{q}$
$\not{E}_T$
χ^0
jet
jet

SUSY example: gluino pair production

Signal



Background



SUSY example: gluino pair production

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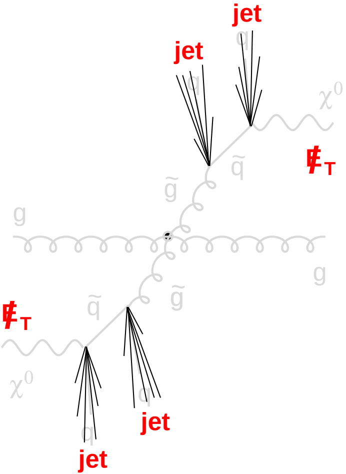
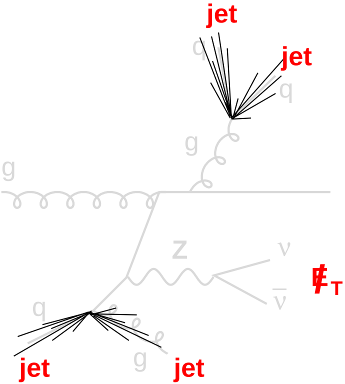


Background



SUSY example: gluino pair production

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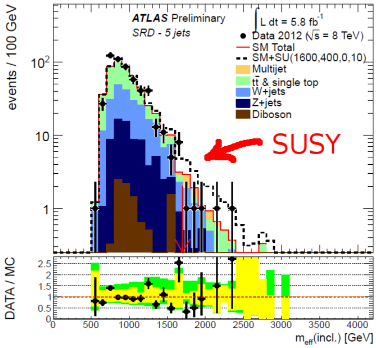
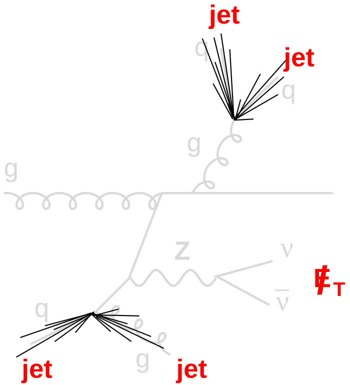


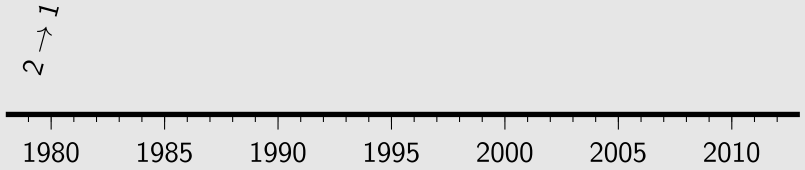
Background



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

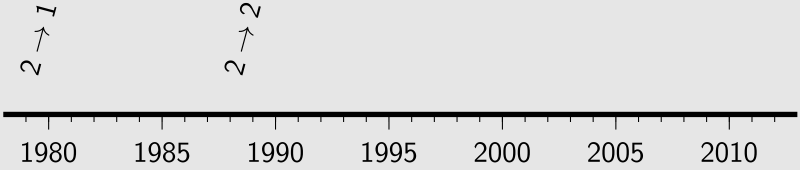
NLO timeline

NLO timeline



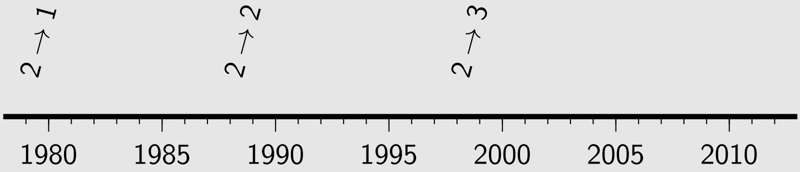
1979: NLO Drell-Yan [Altarelli, Ellis & Martinelli]
1991: NLO $gg \to$ Higgs [Dawson; Djouadi, Spira & Zerwas]

NLO timeline



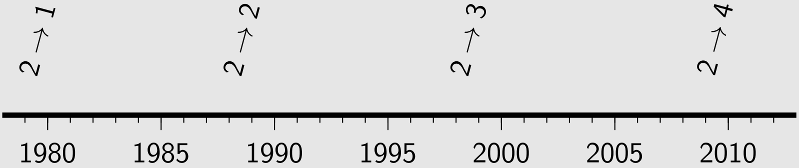
1987: NLO high-p_t photoproduction [Aurenche et al]
1988: NLO $b\bar{b}$, $t\bar{t}$ [Nason et al]
1988: NLO dijets [Aversa et al]
1993: Vj [JETRAD, Giele, Glover & Kosower]

NLO timeline

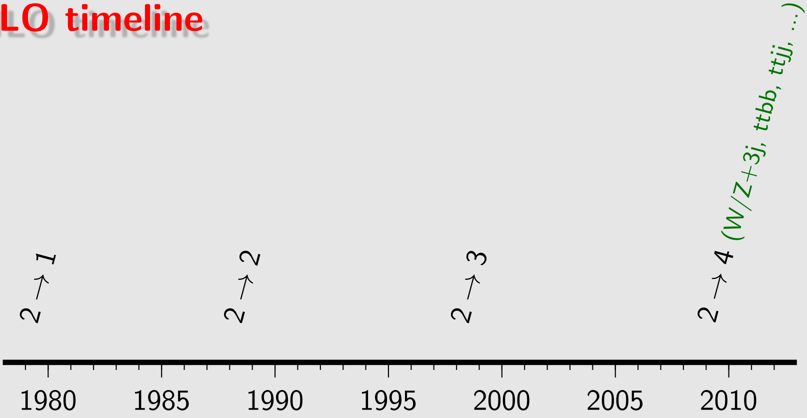


1998: NLO $Wb\bar{b}$ [MCFM: Ellis & Veseli]
2000: NLO $Zb\bar{b}$ [MCFM: Campbell & Ellis]
2001: NLO $3j$ [NLOJet++: Nagy]
...
2007: NLO $t\bar{t}j$ [Dittmaier, Uwer & Weinzierl '07]
...

NLO timeline

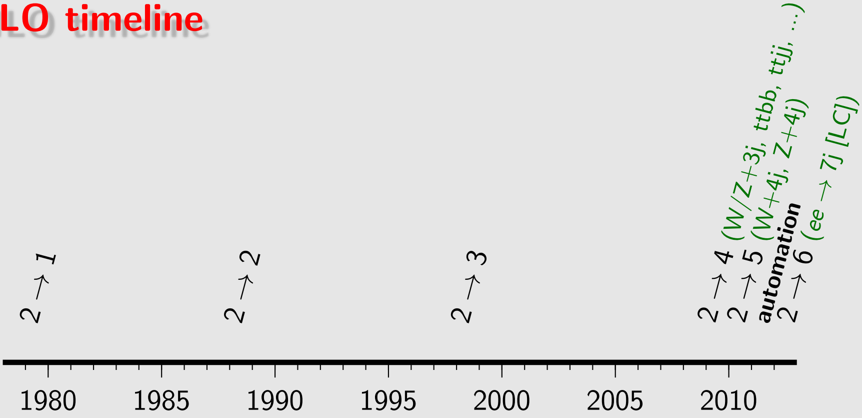


NLO timeline



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 $q\bar{q} \to b\bar{b}b\bar{b}$ [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]

2011/12: NLO $WWjj$ [Rocket: Melia et al; GoSaM+MadX Greiner et al] [unitarity]

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

2011/12: NLO $4j$ [BlackHat/NGluons+Sherpa: Bern et al; Badger et al] [unitarity]

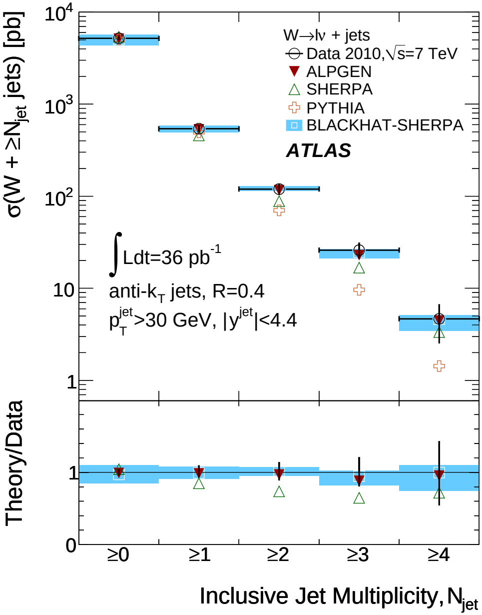
2011–: first automation [MadNLO: Hirschi et al] [unitarity + feyn.diags]

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

2011–: first automation [GoSam: Cullen et al] [feyn.diags(+unitarity)]

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

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

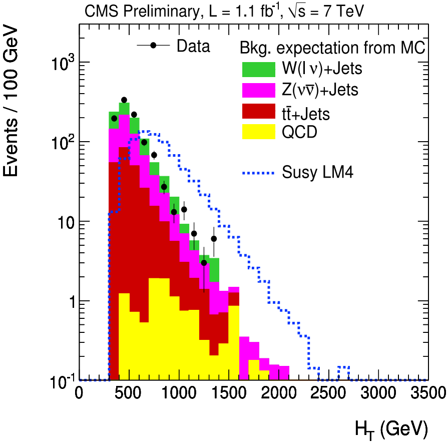


Technical revolution has gone hand-in-hand with LHC measurements of these complex processes.

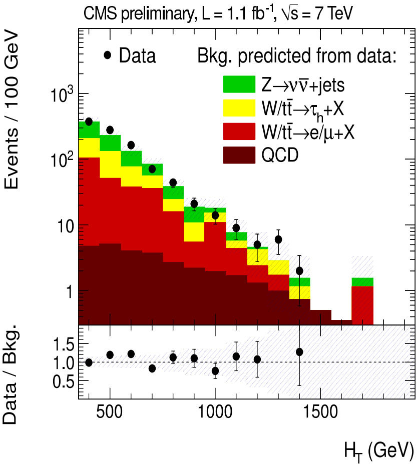
Powerful validation of NLO approach.

So do SUSY searches now just compare data to NLO?

Data v. Monte Carlo backgrounds



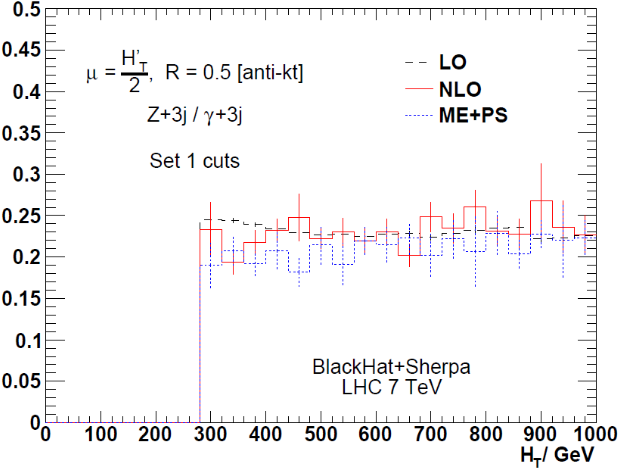
Data v. "data-driven" backgrounds



So where are the NLO predictions being used?

The CMS search did **not** estimate Z+jets bkgd from NLO. Instead used

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



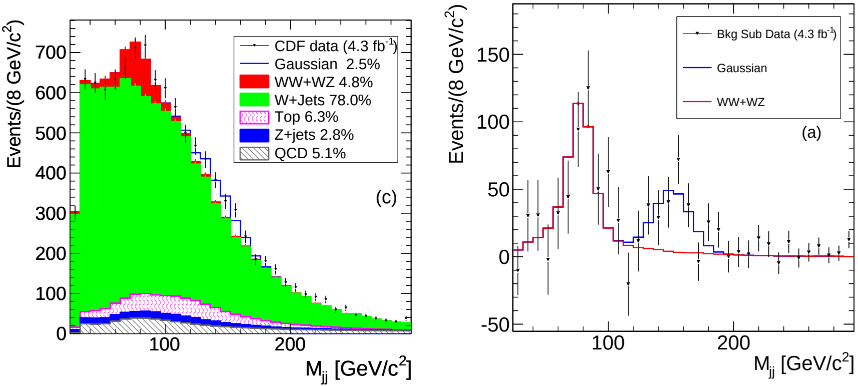
Example of widely used **data-driven** bkgd estimates

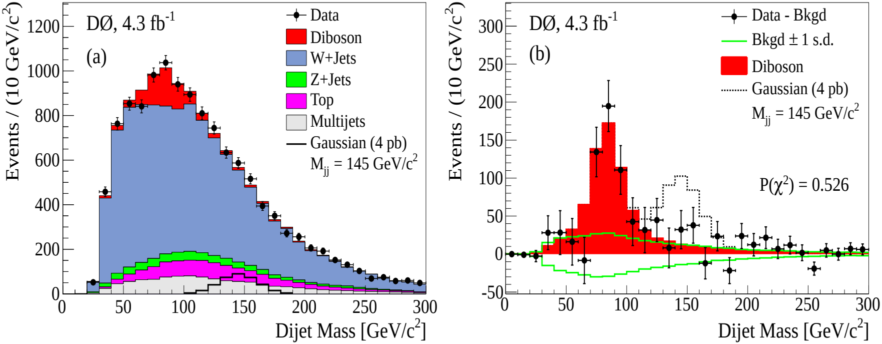
Combine best of theory knowledge with best of experimental knowledge.

Merging NLO and showers

and the CDF W + dijet anomaly

Remember the CDF W+dijet excess?





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

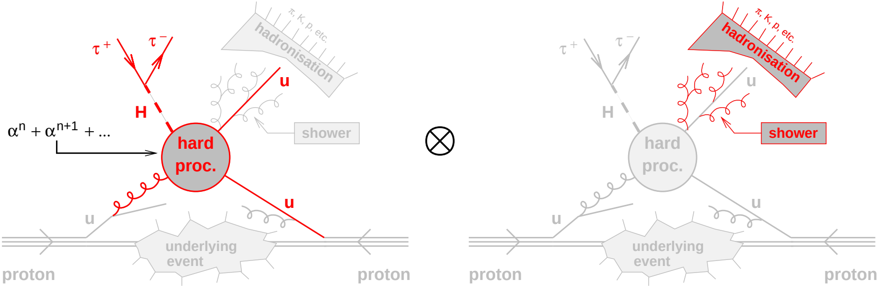
They are "detector-level" data and can only be compared to hadron-level calculations + detector simulation.

In this case hadron-level = Alpgen ⊗ Pythia

Perturbative expansion: for precision.
Parton Showers (PS): for realism;
To combine them: must remove double counting

Tree-level (LO) + PS

Different tree-level multiplicites (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

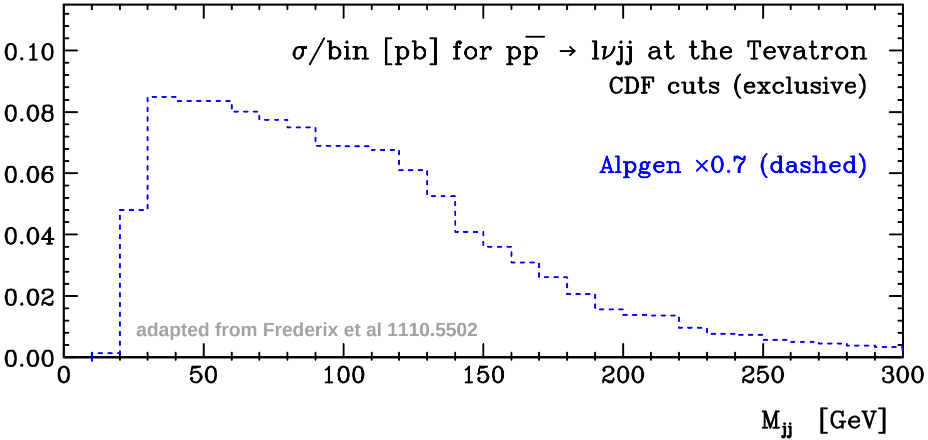
Recently: move towards automation:

POWHEGBox: $t\bar{t}$+jet, W^+W^++2j, ...
aMC@NLO (MadLoop + auto MC@NLO): W+2j, Z+2b, ...

+ ideas for combining multiplicities, extending their applicability
e.g. MENLOPS, MINLO, FxFx merging, Sherpa merging, UNLOPS, ...

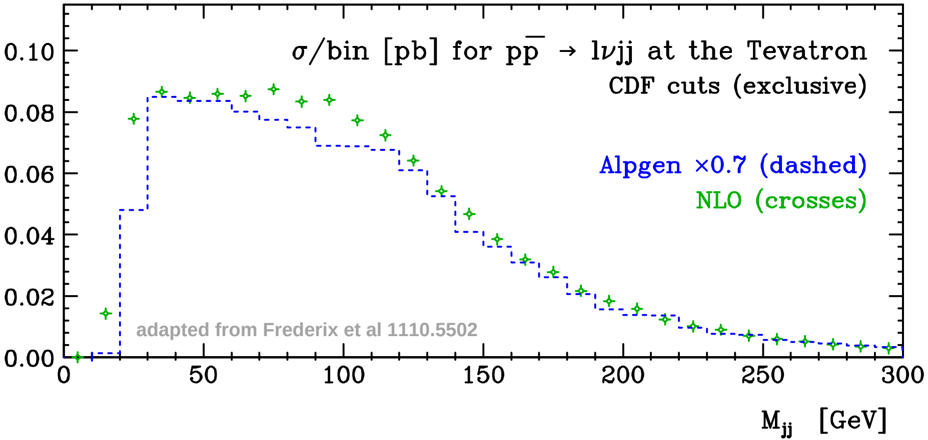
One application of this progress has been to the W+dijet anomaly

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



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

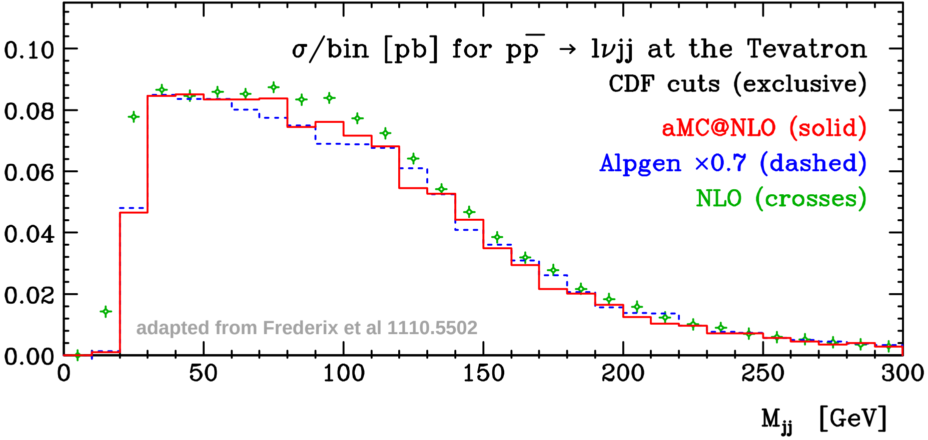
NLO has substantial shape differences: should we worry?



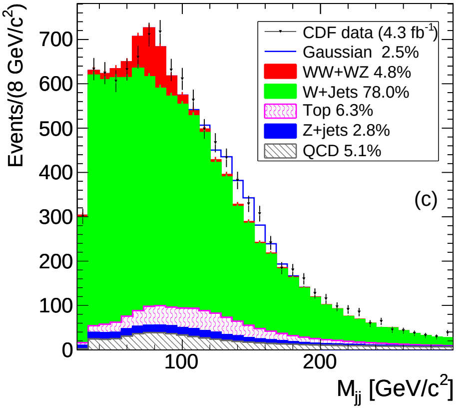
CDF & DØ use Alpgen (scaled): tree level QCD + parton shower

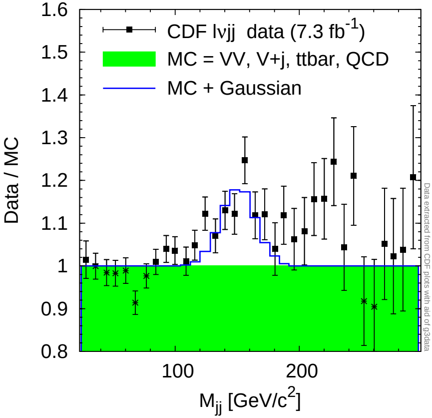
NLO has substantial shape differences: should we worry?

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



Instead of data − MC ⇒ **data/MC**





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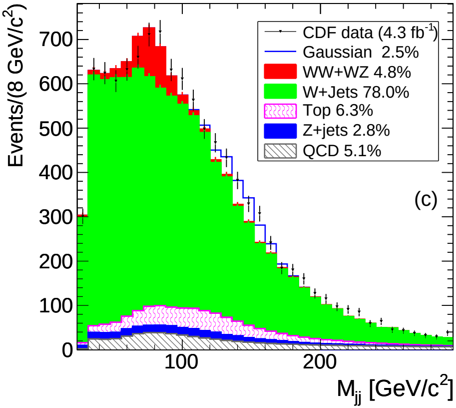

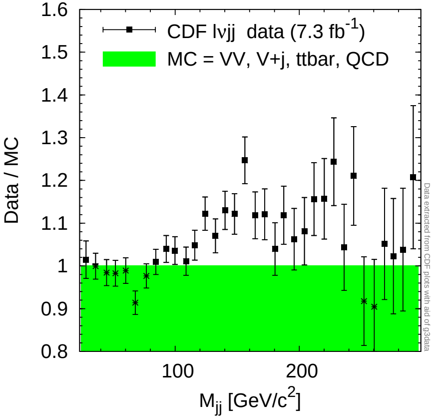

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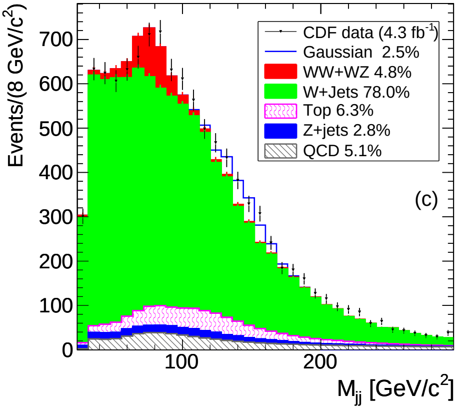
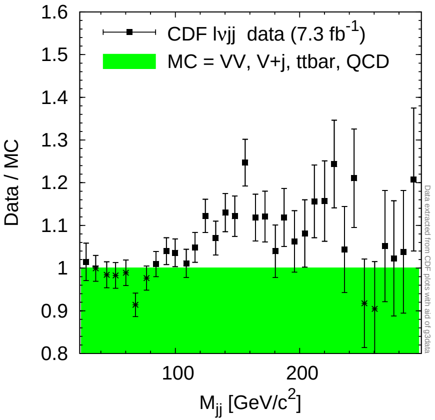
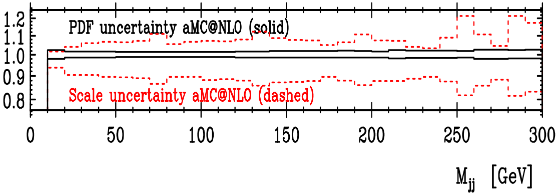




aMC@NLO uncertainties: ⟶



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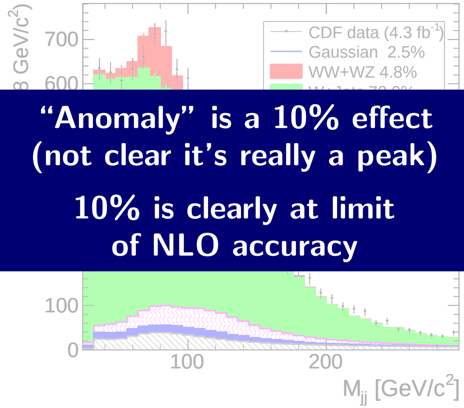
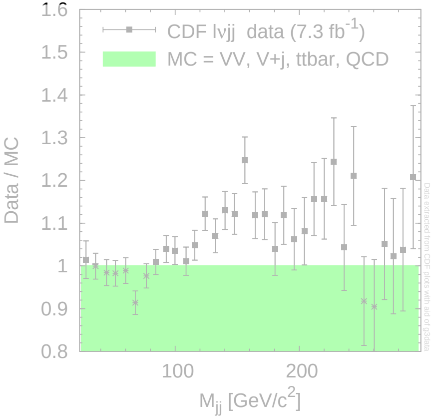


"Anomaly" is a 10% effect (not clear it's really a peak)

10% is clearly at limit of NLO accuracy



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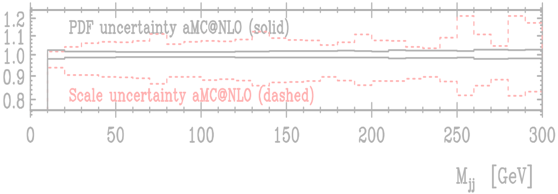


Going beyond limitations of NLO

[two of the options]

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

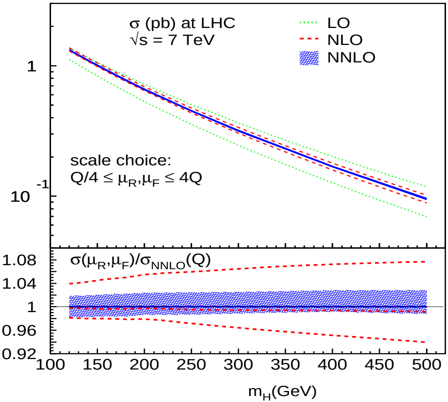
✓ W, Z, Higgs, $\gamma\gamma$, VBF, VH, $(t\bar{t})$

✗ $V\,V$, $(t\bar{t})$, inclusive jets, etc.

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

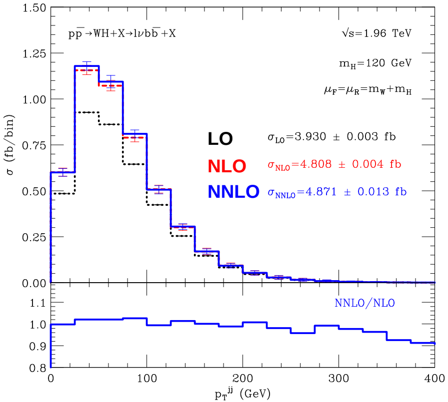
Generally by finding ways to distinguish signals from the background more efficiently, i.e. increasing S/B.

New in 2010: **NNLO VBF→H**



Bolzoni, Maltoni, Moch & Zaro

New in 2011: **NNLO WH (differential)**



Ferrera, Grazzini & Tramontano

Most groundbreaking new NNLO calculation of past years:

$$q\bar{q} \to t\bar{t}$$

Baernreuther, Czakon and Mitov 2012

First NNLO calculation with coloured particles in the initial **and** final state. Its new techniques may help open the way to many other important NNLO calculations.

Until now analyzed in approximate NNLO

Beneke, Czakon, Falgari, Mitov, Schwinn `09

... as an extension of the NLO

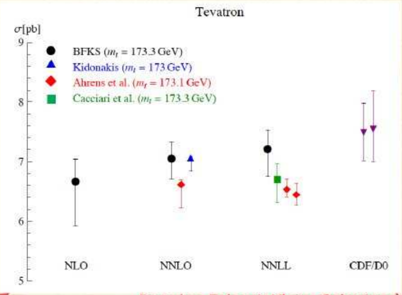
Nason, Dawson, Ellis '88
Beenakker et al '89

... resumed NLL

Sterman, Kidonakis '97
Bonciani, Catani, Mangano, Nason '98

and now NNLL resummation

Beneke, Falgari, Schwinn '10
Czakon, Mitov, Sterman '10
Ahrens et al '10-'11



Beneke, Falgari, Klein, Schwinn `11

Comparison between various groups shows:

✓ Significant differences between various predictions

✓ Suggests the true approximate NNLO uncertainty

✓ The realistic improvements over NLO+NLL are small (to be expected)

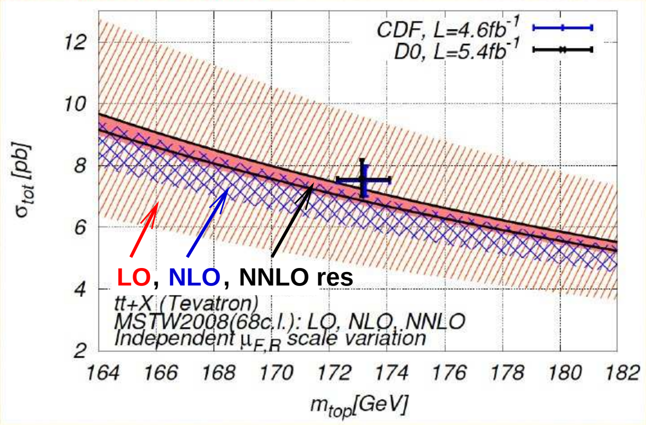
Cacciari, Czakon, Mangano, Mitov, Nason `11

Baernreuther, Czakon & Mitov NNLO $q\bar{q} \to t\bar{t}$ cross-section

Good perturbative convergence:

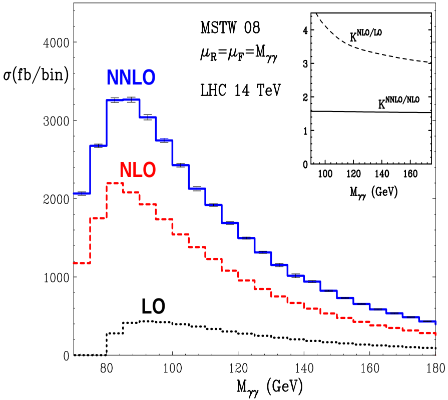
P. Baernreuther et al arXiv:1204.5201

- ✓ Independent F/R scales
- ✓ mt=173.3



- ✓ Good overlap of various orders (LO, NLO, NNLO).
- ✓ Suggests our (restricted) independent scale variation is good

New in 2011: **NNLO $\gamma\gamma$**



Catani, Cieri, de Florian, Ferrera & Grazzini

Some key processes see large or giant NLO/NNLO corrections.

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

One series that's ugly: gluon fusion Higgs cross section

For 8 TeV pp collisions, $m_H = 125$ GeV:

$$\begin{aligned}\sigma_{gg\to H} &= 6.8 \text{ pb} \left(1 + 9.9\alpha_s + 36\alpha_s^2 + \cdots\right) \\ &= 6.8 \text{ pb} \left(1 + 1.23 + 0.56 + \cdots\right) = 19.0 \text{ pb}\end{aligned}$$

for $\mu_R = \mu_F = \frac{1}{2} m_H$, $\alpha_s(\mu_R) = 0.124$

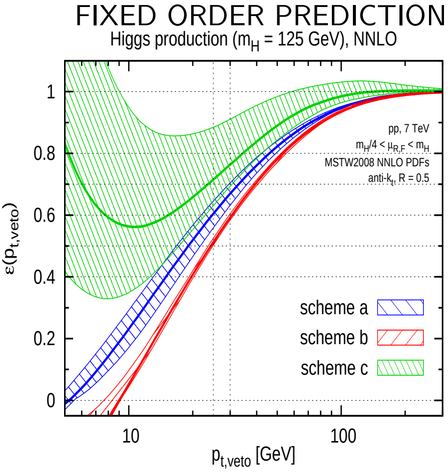
$$\begin{aligned}\sigma_{gg\to H} &= 5.6 \text{ pb} \left(1 + 11.4\alpha_s + 63\alpha_s^2 + \cdots\right) \\ &= 5.6 \text{ pb} \left(1 + 1.27 + 0.79 + \cdots\right) = 17.2 \text{ pb}\end{aligned}$$

for $\mu_R = \mu_F = m_H$, $\alpha_s(\mu_R) = 0.112$

There are explanations: threshold logarithms, π^2 terms from analytic continuation. A problem is perhaps that there are too many explanations...

Baglio & Djouadi have raised the convergence issue before

Everything else you try about (gluon-fusion) Higgs production suffers as a result of the original bad series: e.g. **jet veto efficiency**



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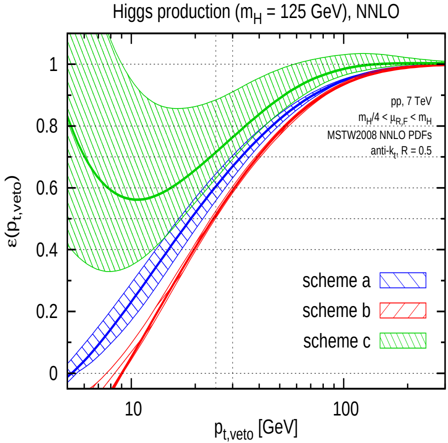
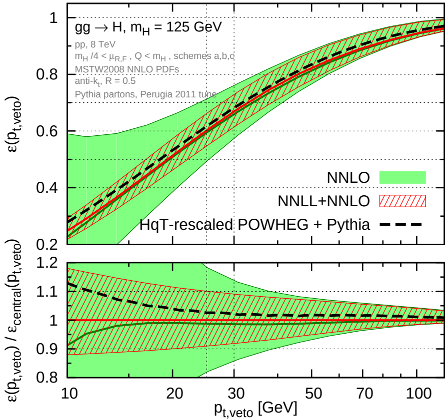
FIXED ORDER PREDICTION



RESUMMED PREDICTION

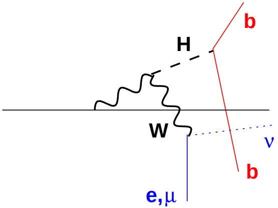


Banfi, Monni, GPS & Zanderighi '12
see also Becher & Neubert '12

Looking at data differently

$H \to b\bar{b}$ (57% of decays) v. hard to see

Best hope is $pp \to W^{\pm}H$ (and ZH), $W^{\pm} \to \ell^{\pm}\nu$, $H \to b\bar{b}$.



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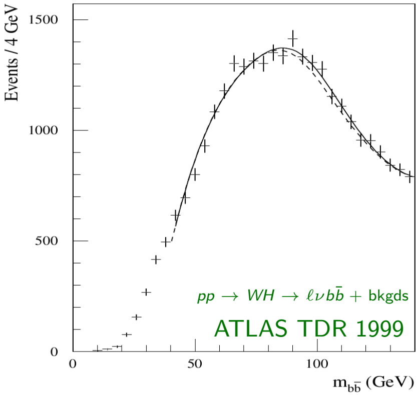
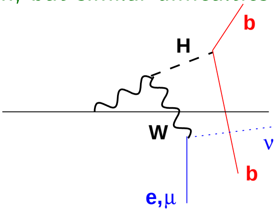


Conclusion (ATLAS TDR):

"The extraction of a signal from $H \to b\bar{b}$ decays in the WH channel will be very difficult at the LHC, even under the most optimistic assumptions [...]"

Low efficiency, huge backgrounds, e.g. $t\bar{t}$

NB: Evidence of this channel seen recently at Tevatron, but similar difficulties



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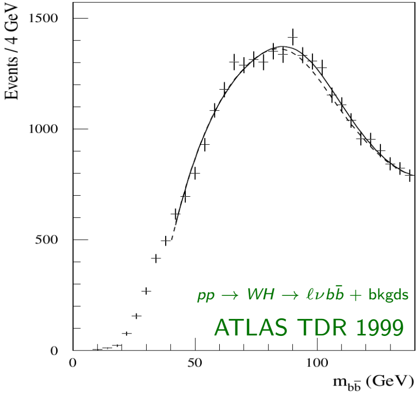

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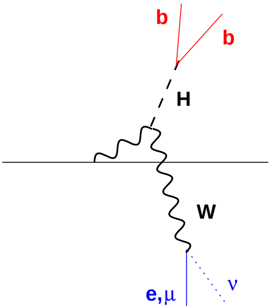
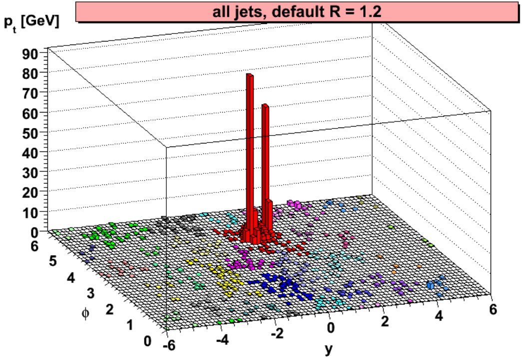


Analysis of signal/bkgd suggests:

- Go to high p_t ($p_{tH}, p_{tW} > 200$ GeV)
- Lose 95% of signal, but more efficient?
- Maybe kill $t\bar{t}$ & gain clarity?

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



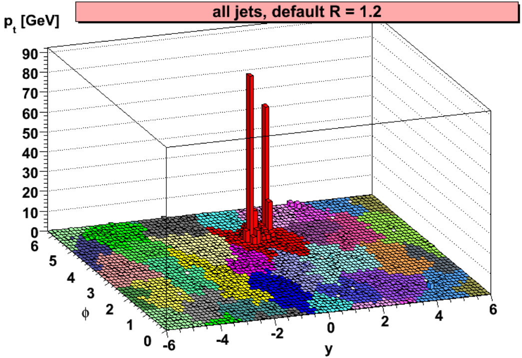
Cluster event, C/A, R=1.2

Butterworth, Davison, Rubin & GPS '08

also earlier work by Seymour; Butterworth et al

$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



Fill it in, $\rightarrow$ show jets more clearly

Butterworth, Davison, Rubin & GPS '08

also earlier work by Seymour; Butterworth et al

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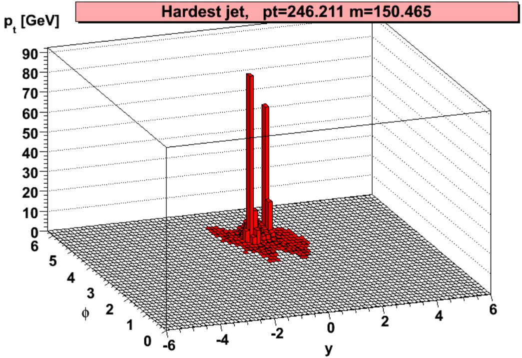

Consider hardest jet, $m = 150$ GeV

Butterworth, Davison, Rubin & GPS '08

also earlier work by Seymour; Butterworth et al

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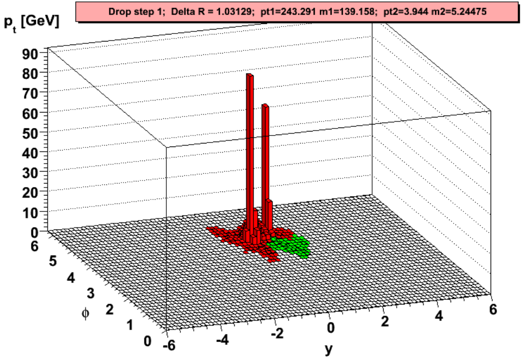

split: $m = 150$ GeV, $\frac{\max(m_1, m2)}{m} = 0.92 \to$ repeat

Butterworth, Davison, Rubin & GPS '08

also earlier work by Seymour; Butterworth et al

$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

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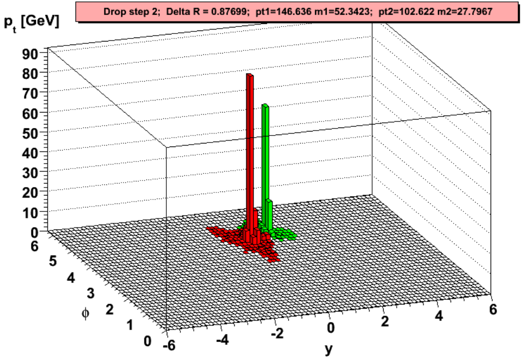
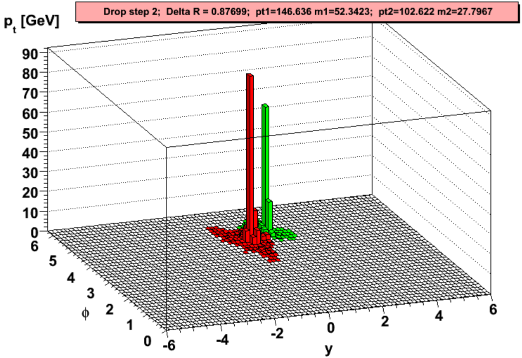


split: $m = 139$ GeV, $\frac{\max(m_1, m2)}{m} = 0.37 \to$ mass drop

Butterworth, Davison, Rubin & GPS '08

also earlier work by Seymour; Butterworth et al

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3

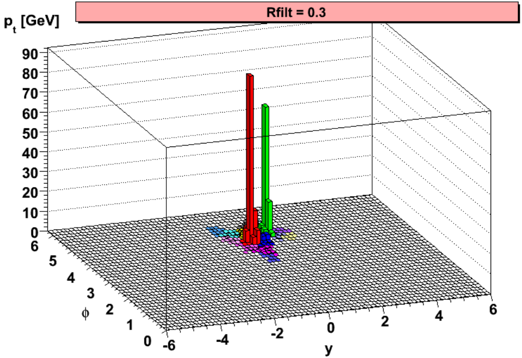


check: $y_{12} \simeq \frac{p_{t2}}{p_{t1}} \simeq 0.7 \to$ OK + 2 b-tags (anti-QCD)

Butterworth, Davison, Rubin & GPS '08

also earlier work by Seymour; Butterworth et al

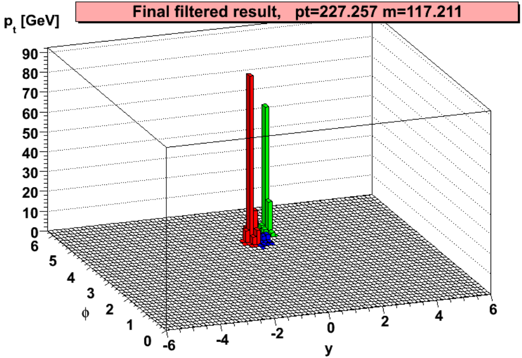
Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



$R_{filt} = 0.3$

Butterworth, Davison, Rubin & GPS '08
also earlier work by Seymour; Butterworth et al

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3

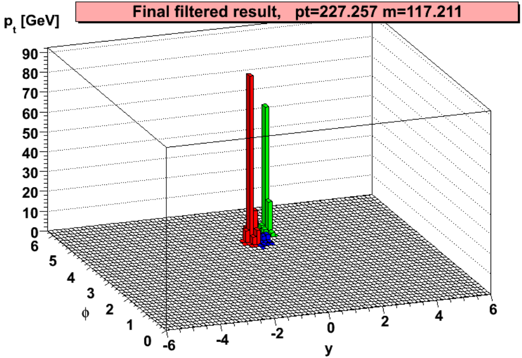


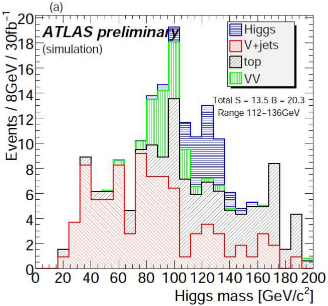
$R_{filt} = 0.3$: take 3 hardest, **m = 117 GeV**

Butterworth, Davison, Rubin & GPS '08

also earlier work by Seymour; Butterworth et al

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3





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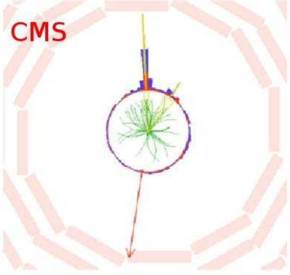
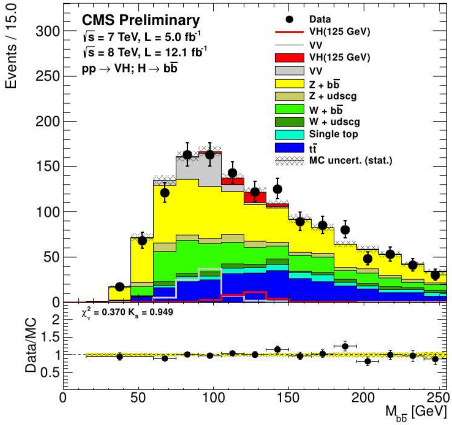
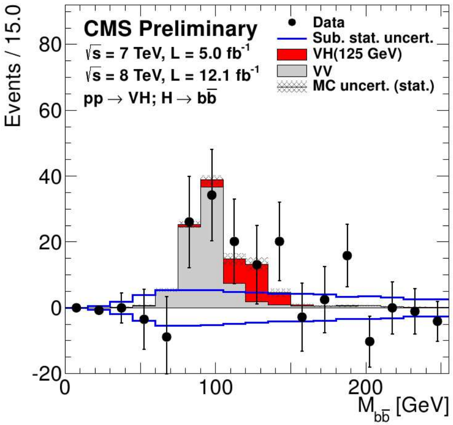
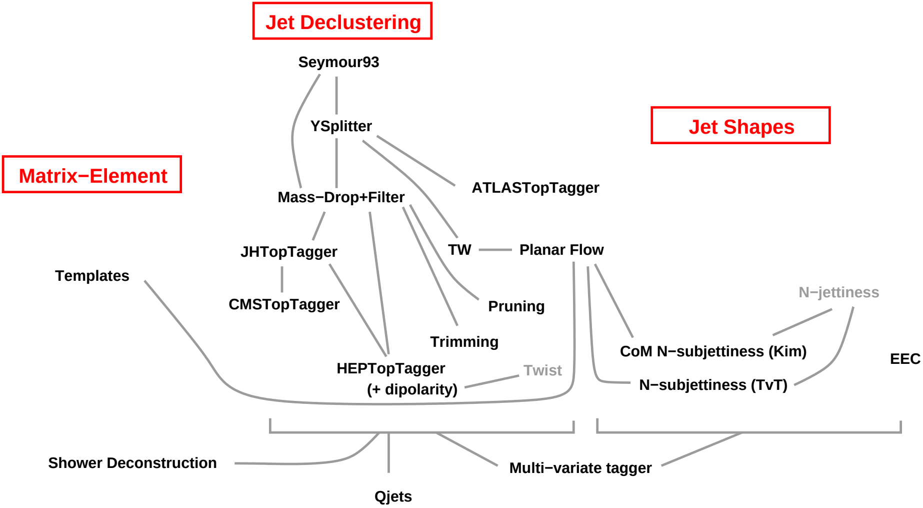


ATLAS and CMS $H \to b\bar{b}$ are high-p_t, but 2-jet based



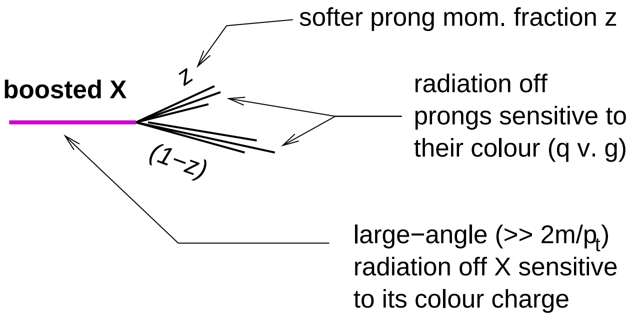


Some taggers and jet-substructure observables



apologies for omitted taggers, arguable links, etc.

[NB: many of the tools available in FastJet & SpartyJet]

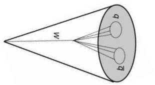


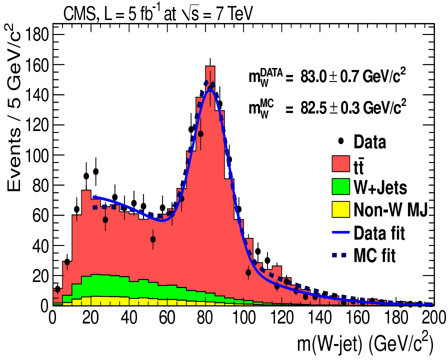
	$g_{\to gg(g)}$	$q_{\to qg(g)}$	$g_{\to b\bar{b}}$	$H_{\to b\bar{b}}$	$t_{\to qq\bar{q}}$
softer prong z	soft	soft	hard	hard	hard
prong colour factors	$2\times C_A$	$C_F + C_A$	$2\times C_F$	$2\times C_F$	$3\times C_F$
system colour factor	C_A	C_F	C_A	0	C_F

Background-like — Signal-like

Boosted Ws and tops in single jets: data!

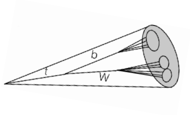
W's in a single jet

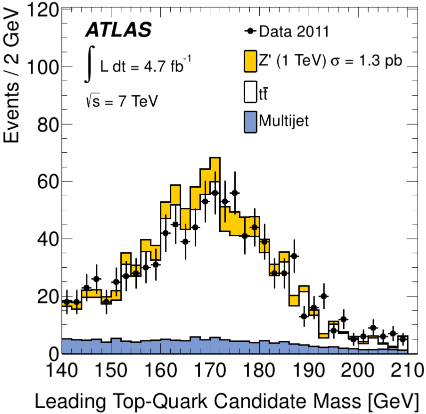




with Pruning + Mass Drop requirement
NB: combined in IR unsafe way...

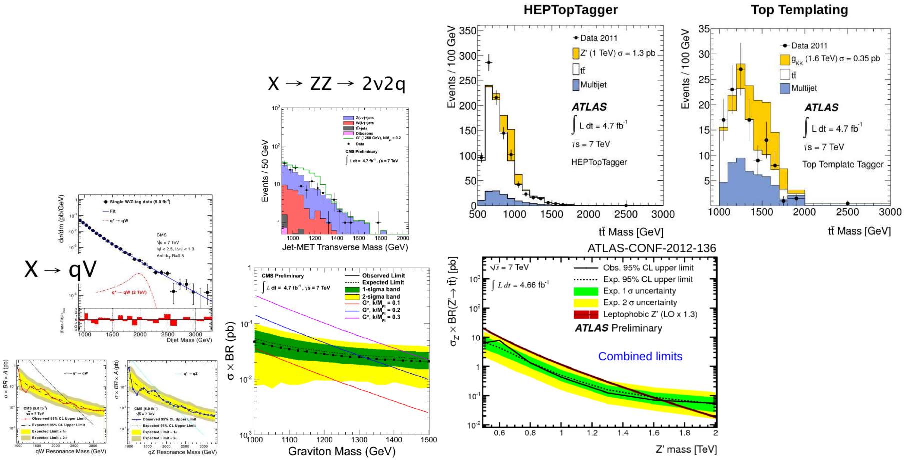
tops in a single jet





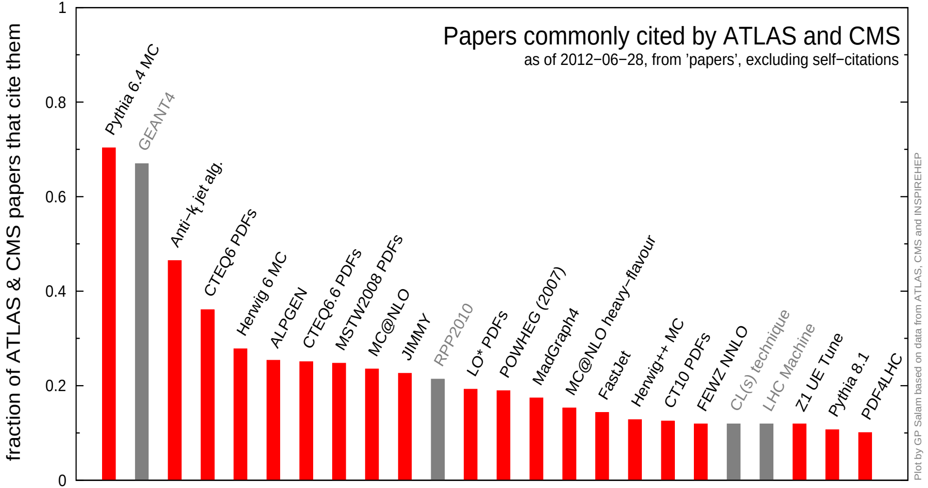
with HEPTopTagger

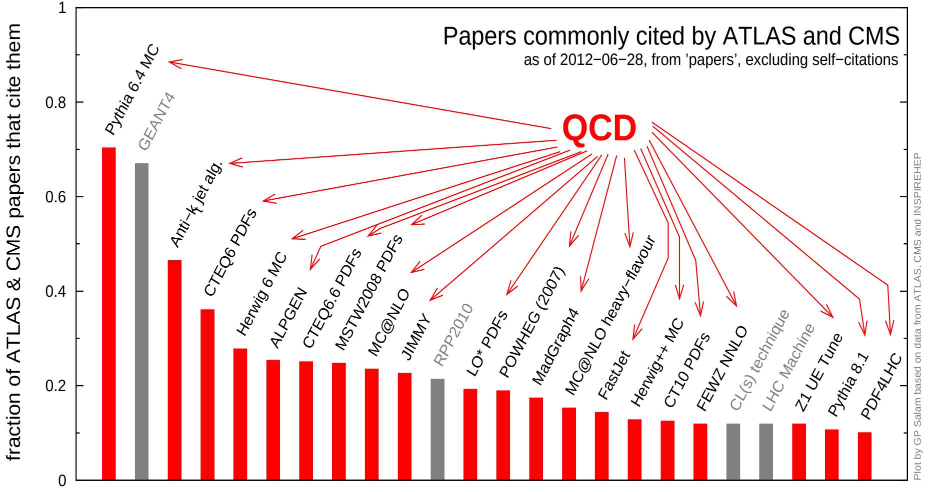
Some BSM searches with jet-substructure techniques



A range of techniques being used for varied BSM scenarios

Closing


Papers commonly cited by ATLAS and CMS
as of 2012−06−28, from 'papers', excluding self−citations
fraction of ATLAS & CMS papers that cite them
1
0.8
0.6
0.4
0.2
0
Pythia 6.4 MC
GEANT4
Anti−k_t jet alg.
CTEQ6 PDFs
Herwig 6 MC
ALPGEN
CTEQ6.6 PDFs
MSTW2008 PDFs
MC@NLO
JIMMY
RPP2010
LO* PDFs
POWHEG (2007)
MadGraph4
MC@NLO heavy−flavour
FastJet
Herwig++ MC
CT10 PDFs
FEWZ NNLO
CL(s) technique
LHC Machine
Z1 UE Tune
Pythia 8.1
PDF4LHC
Plot by GP Salam based on data from ATLAS, CMS and INSPIREHEP



today's progress in QCD = tomorrow's workhorse

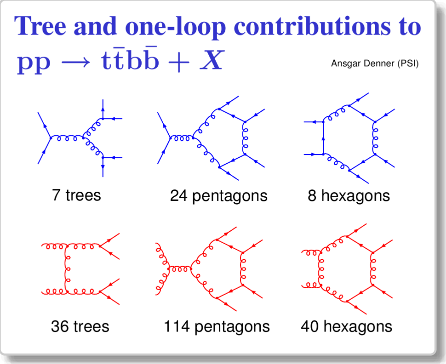
EXTRAS

NLO bottleneck: 1-loop part

Traditional

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

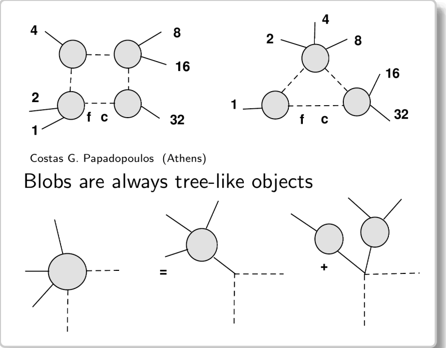
Work hard to reduce integrals to known forms (+ tricks).



Recursive/unitarity methods

Assemble loop-diagrams from individual tree-level diagrams.

Build trees by sticking together simpler tree-level diagrams



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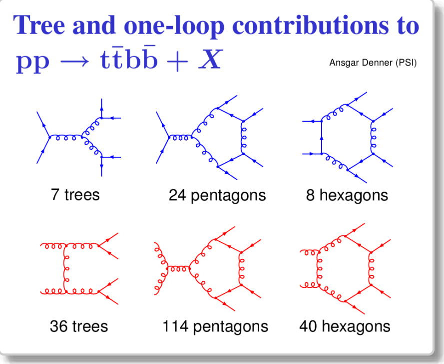

Recursive/unitarity methods

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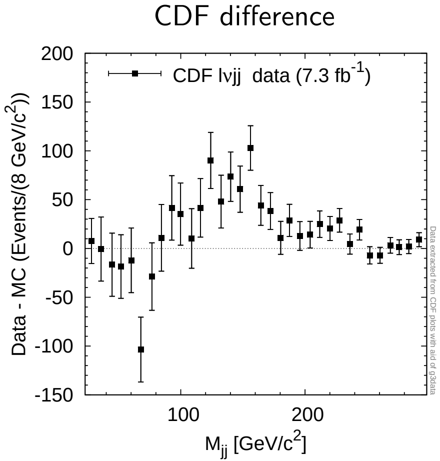
Build trees by sticking together simpler tree-level diagrams

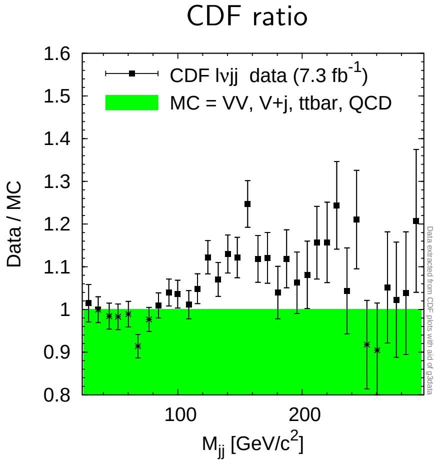
Some main ideas:

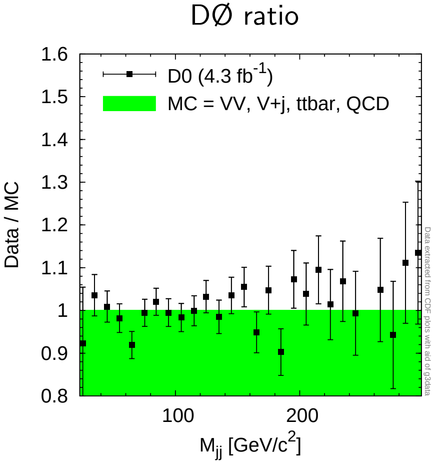
Bern, Dixon & Kosower '93
[sewing together trees]

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

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


CDF difference
CDF lνjj data (7.3 fb-1)
Data - MC (Events/(8 GeV/c2))
200
150
100
50
0
-50
-100
-150
100
200
Mjj [GeV/c2]
Data extracted from CDF plots with aid of g3data


CDF ratio
CDF lνjj data (7.3 fb-1)
MC = VV, V+j, ttbar, QCD
Data / MC
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
100
200
Mjj [GeV/c2]
Data extracted from CDF plots with aid of g3data


DØ ratio
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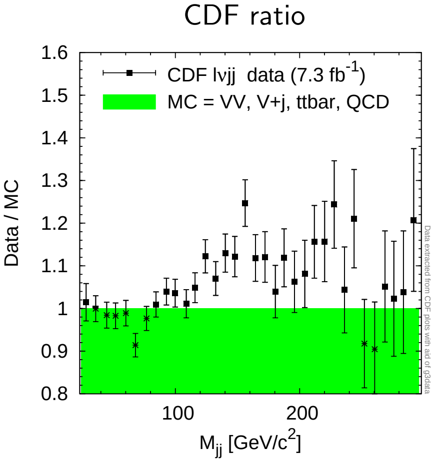
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
Data / MC
D0 (4.3 fb^{-1})
MC = VV, V+j, ttbar, QCD
100
200
M_{jj} [GeV/c^2]
Data extracted from CDF plots with aid of g3data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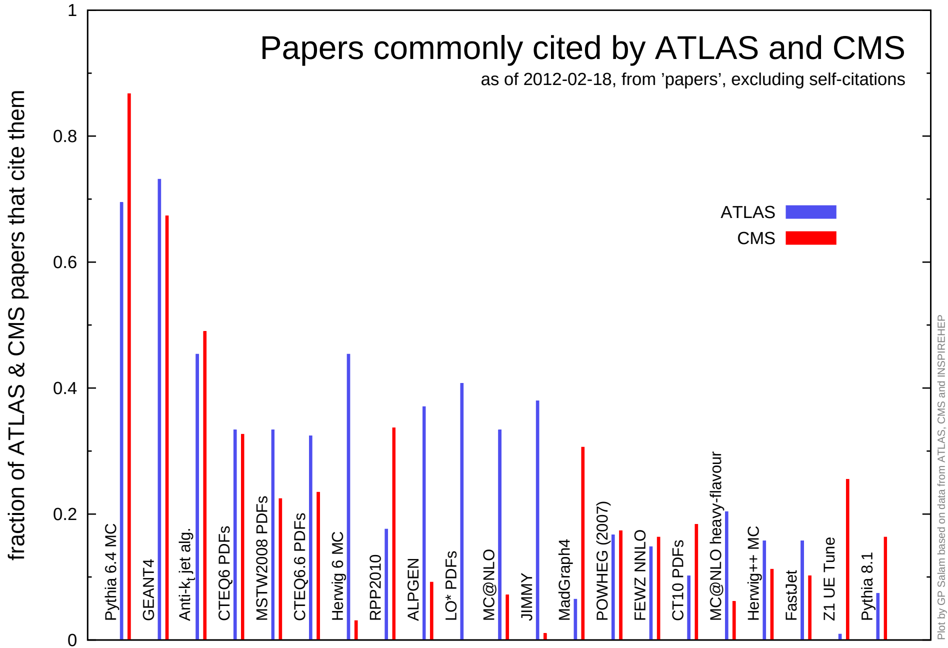
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CTEQ6.6 PDFs
Herwig 6 MC
RPP2010
ALPGEN
LO* PDFs
MC@NLO
JIMMY
MadGraph4
POWHEG (2007)
FEWZ NNLO
CT10 PDFs
MC@NLO heavy-flavour
Herwig++ MC
FastJet
Z1 UE Tune
Pythia 8.1
Plot by GP Salam based on data from ATLAS, CMS and INSPIREHEP