QCD in hadron collisions

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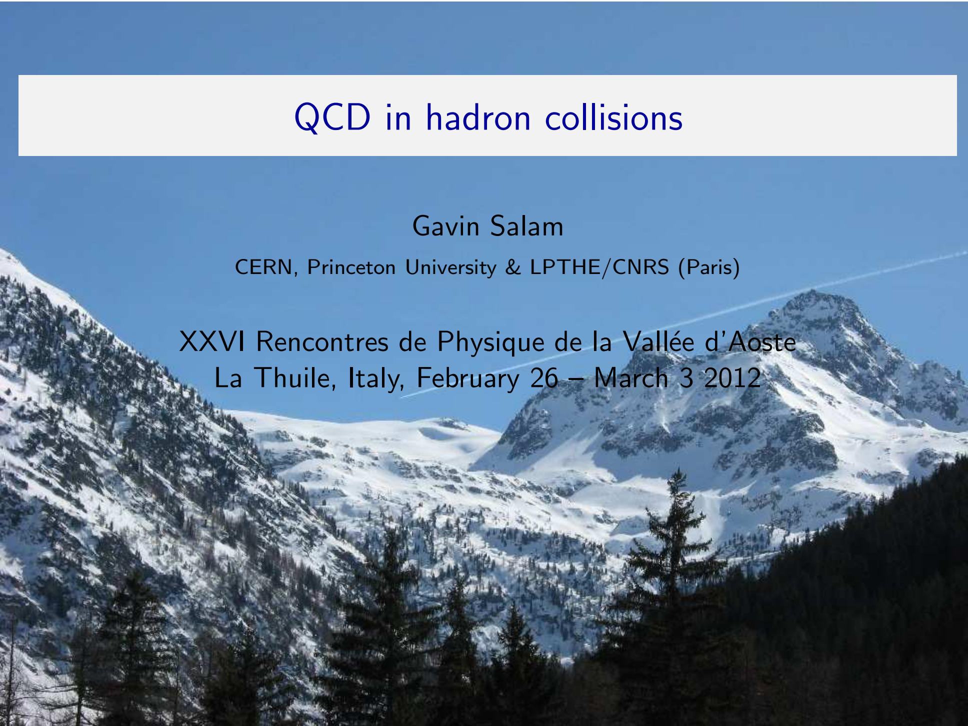


An exciting past 18 months

$t\bar{t}$ asymmetry

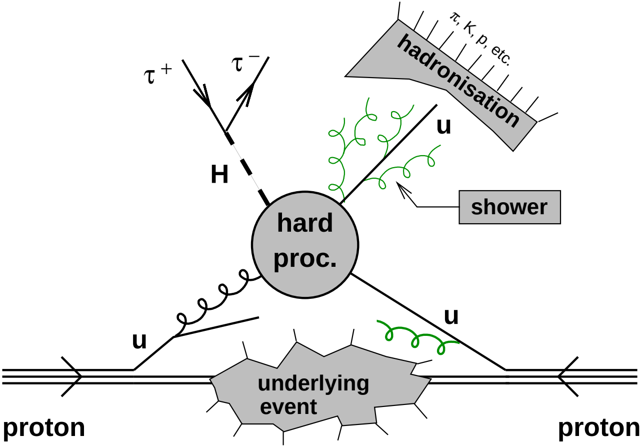
W + dijet CDF anomaly

Exclusion of swathes of SUSY, etc.

Higgs Hints

...

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


π, K, p, etc.
hadronisation
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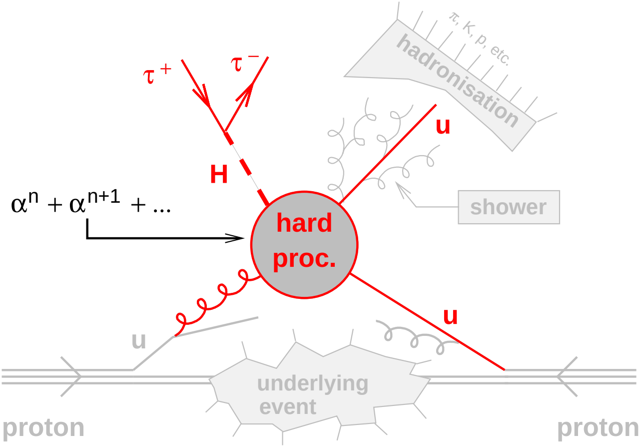
proton


π, K, p, etc.
hadronisation
τ +
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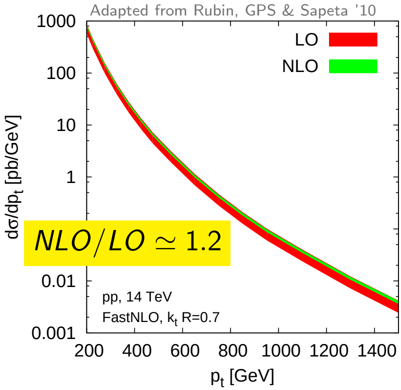
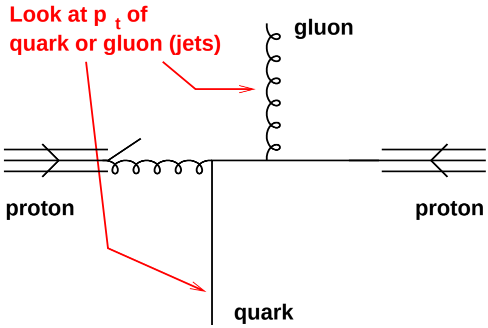
Consider LO, NLO and their ratio $K = \frac{\text{NLO}}{\text{LO}}$

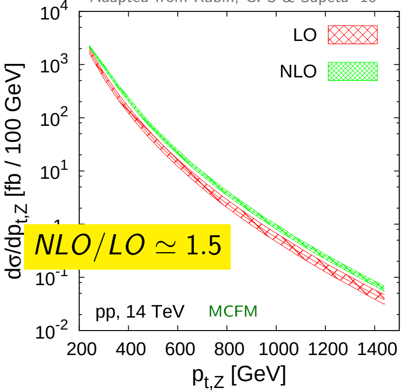


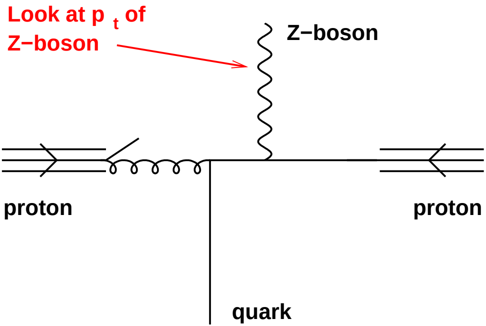


K of 1.2 is compatible with being $1 + \mathcal{O}(\alpha_s)$

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

Adapted from Rubin, GPS & Sapeta '10



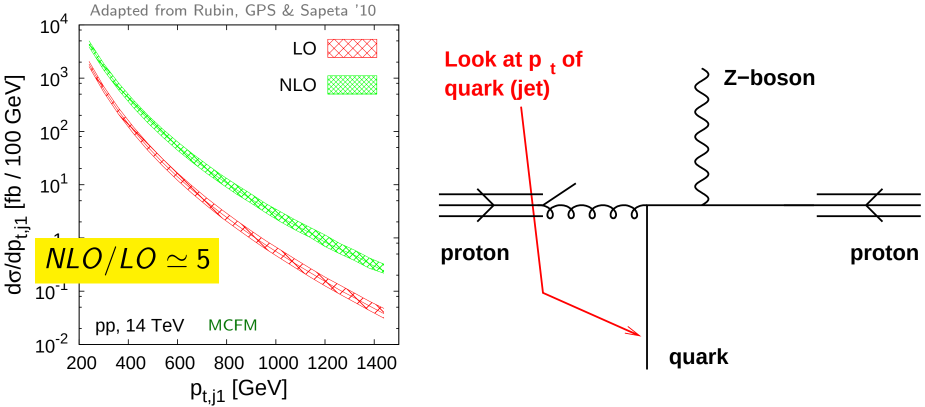


K of 1.5 is compatible with being $1 + C \times \alpha_s$, with quite large C

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 $K = \frac{\text{NLO}}{\text{LO}}$

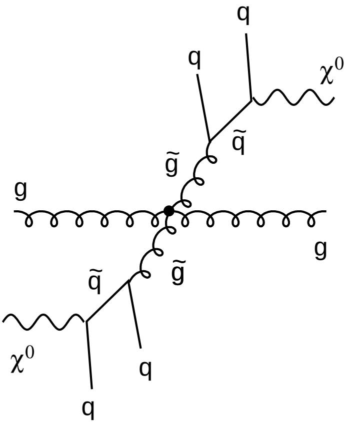


$1 + C\alpha_s \longrightarrow K = 5$?!! Often driven by new topologies

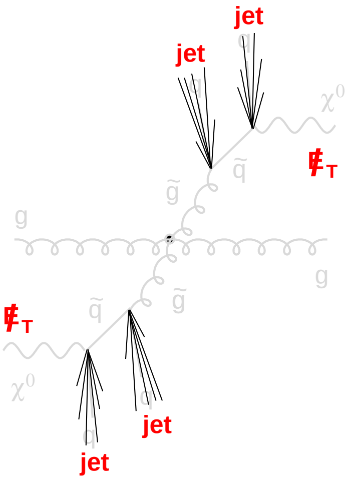
The NLO revolution

and one way it's being used

Signal

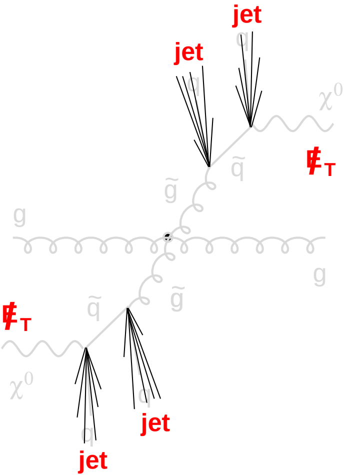


Signal

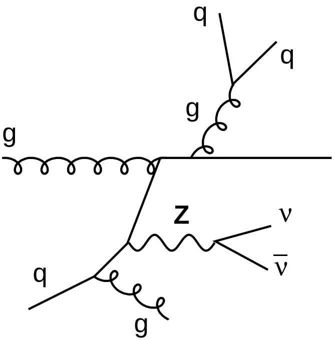

jet
jet
q
q
χ^0
$\not{E}_T$
$\tilde{q}$
$\tilde{g}$
g
g
$\tilde{g}$
$\tilde{q}$
$\not{E}_T$
χ^0
q
q
jet
jet

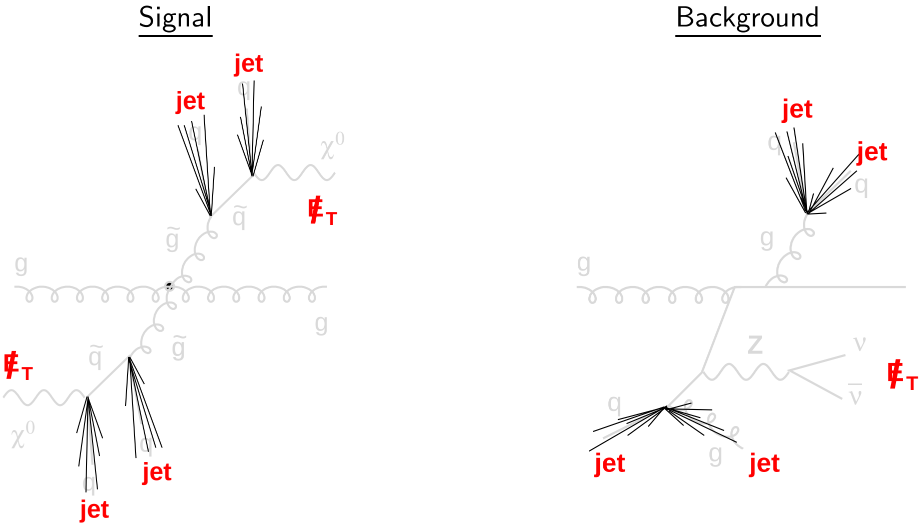
SUSY example: gluino pair production

Signal



Background




Signal
jet
jet
q
q
χ0
q̃
g̃
E̸T
g
g
g̃
q̃
E̸T
χ0
q
q
jet
jet
Background
jet
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Z
ν
ν̄
E̸T
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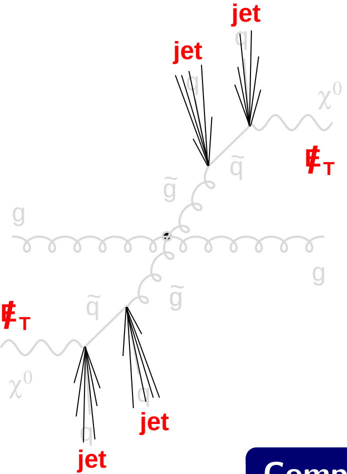
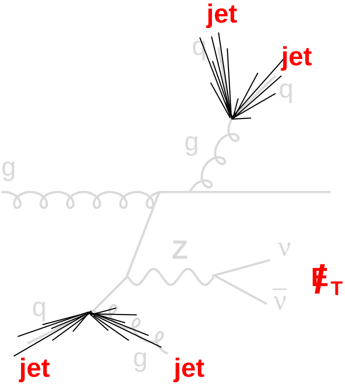
jet

SUSY example: gluino pair production

Signal



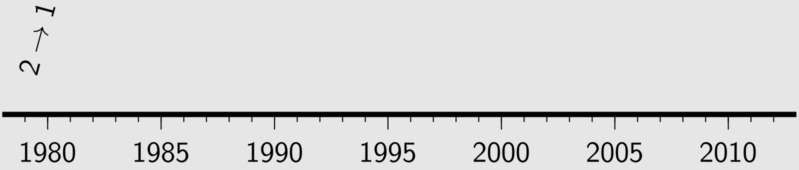
Background



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

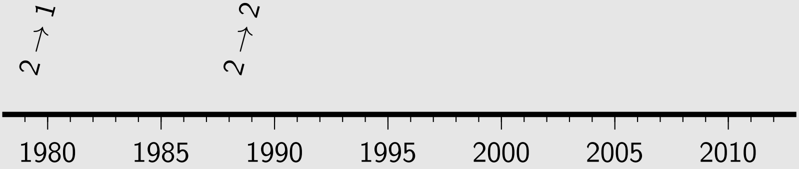
NLO timeline

NLO timeline



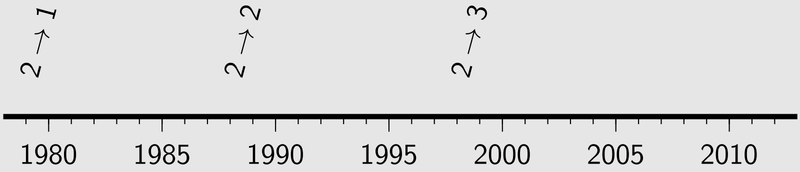
1979: NLO Drell-Yan [Altarelli, Ellis & Martinelli]

NLO timeline



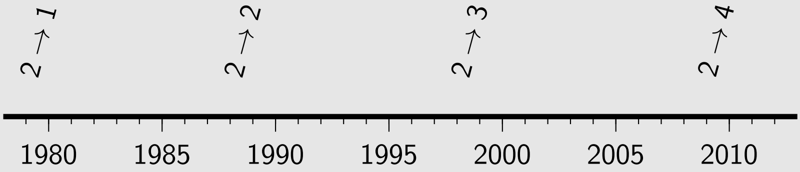
1987: NLO high-p_t photoproduction [Aurenche et al]
1988: NLO $b\bar{b}$, $t\bar{t}$ [Nason et al]
1993: dijets, Vj [JETRAD, Giele, Glover & Kosower]

NLO timeline

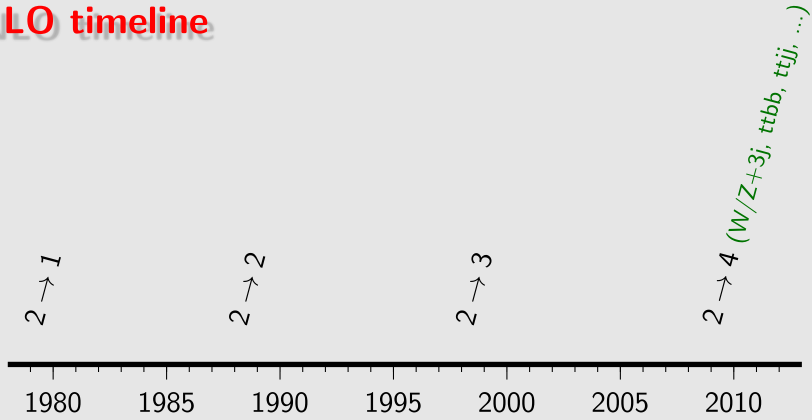


1998: NLO $Wb\bar{b}$ [MCFM: Ellis & Veseli]
2000: NLO $Zb\bar{b}$ [MCFM: Campbell & Ellis]
2001: NLO $3j$ [NLOJet++: Nagy]
...
2007: NLO $t\bar{t}j$ [Dittmaier, Uwer & Weinzierl '07]
...

NLO timeline

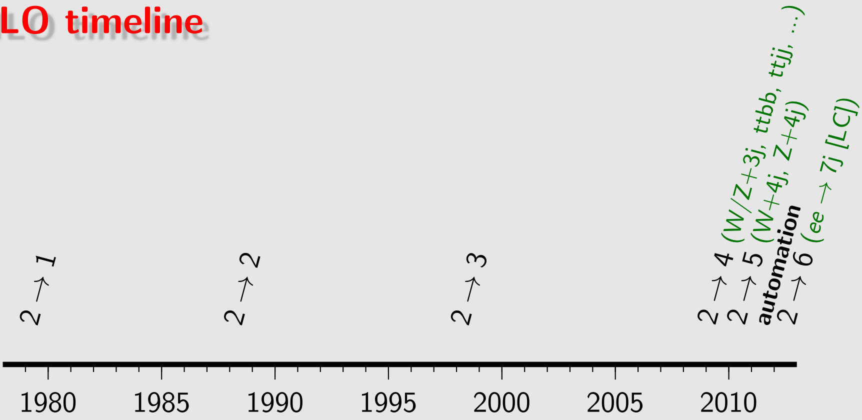


NLO timeline



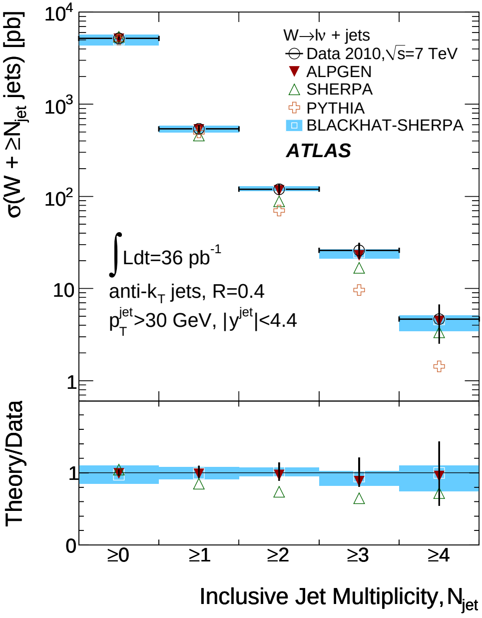
2009: NLO W+3j [Rocket: Ellis, Melnikov & Zanderighi] [unitarity]
2009: NLO W+3j [BlackHat+Sherpa: Berger et al] [unitarity]
2009: NLO $t\bar{t}b\bar{b}$ [Bredenstein et al] [traditional]
2009: NLO $t\bar{t}b\bar{b}$ [HELAC-NLO: Bevilacqua et al] [unitarity]
2009: NLO $q\bar{q} \to b\bar{b}b\bar{b}$ [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: 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: $e^+e^- \to 7j$ [Becker et al, leading colour] [numerical loops]

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

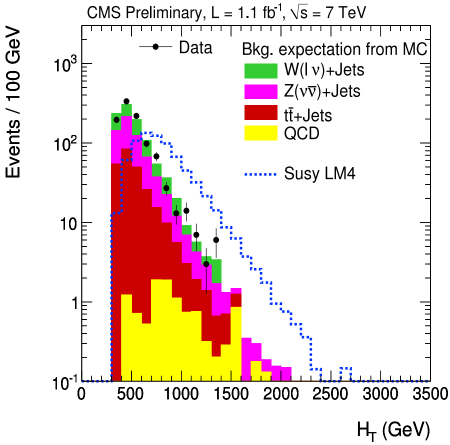


Technical revolution has gone hand-in-hand with LHC measurements of these complex processes.

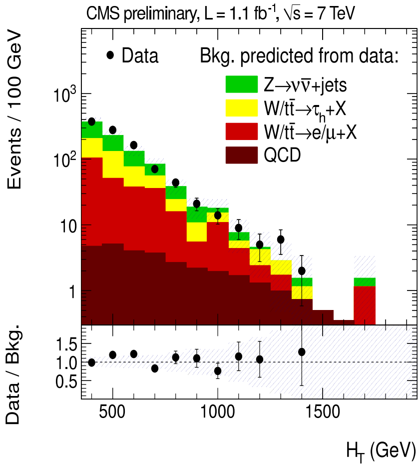
Powerful validation of NLO approach.

So do SUSY searches now just compare data to NLO?

Data v. Monte Carlo backgrounds



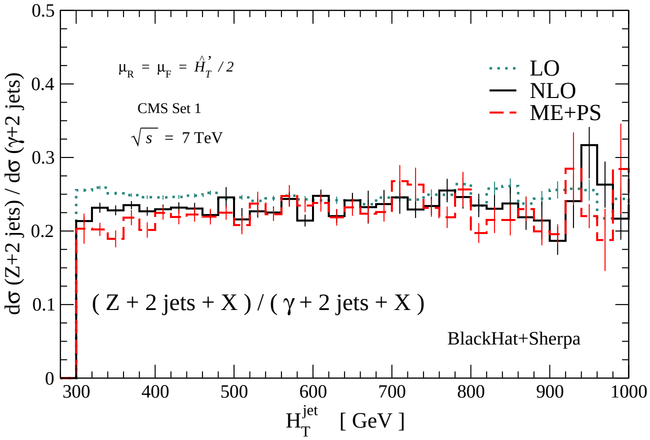
Data v. "data-driven" backgrounds



So where are the NLO predictions being used?

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

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



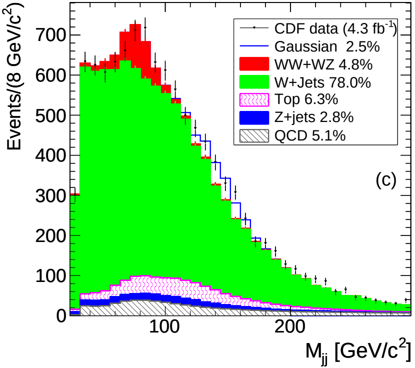
Example of widely used **data-driven** bkgd estimates

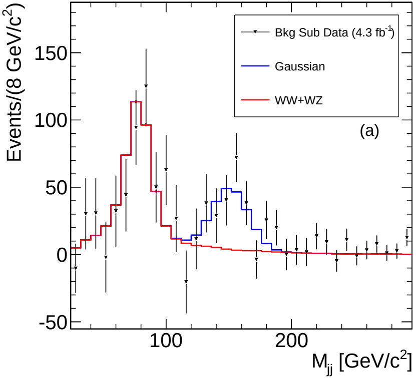
Combine best of theory knowledge with best of experimental knowledge.

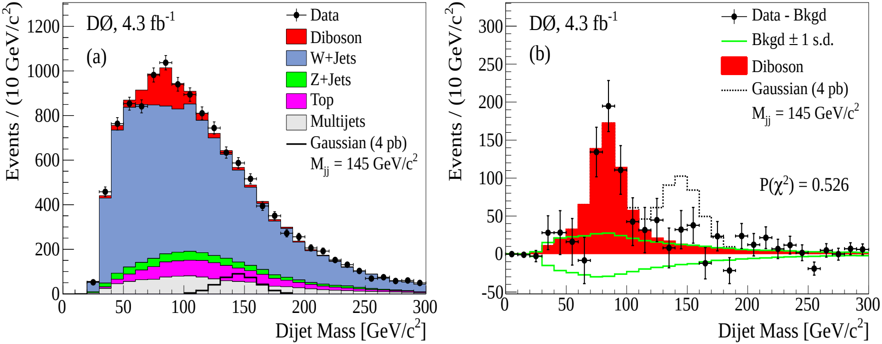
Merging NLO and showers

and the CDF W + dijet anomaly

Remember the CDF W+dijet excess?







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

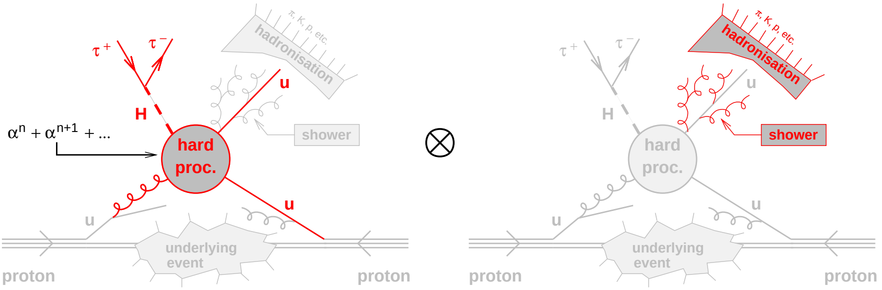
They are "detector-level" data and can only be compared to hadron-level calculations + detector simulation.

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

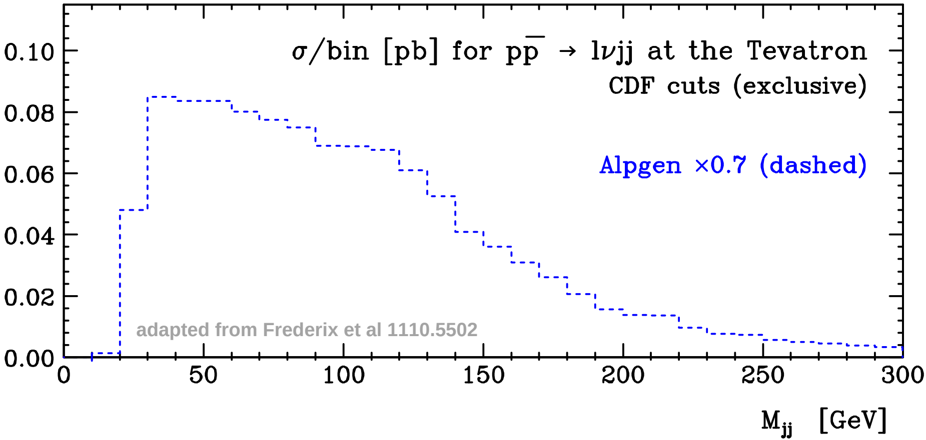
Recently: move towards automation:

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

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

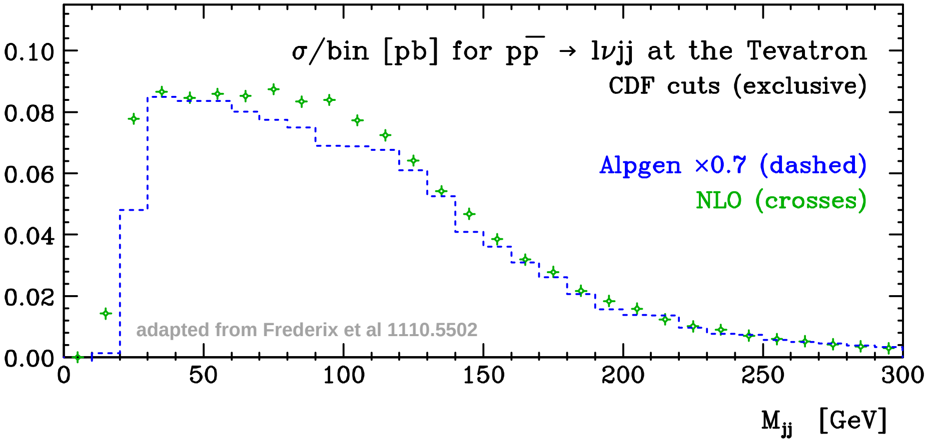
A key application of this progress has been to the W+dijet anomaly

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



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

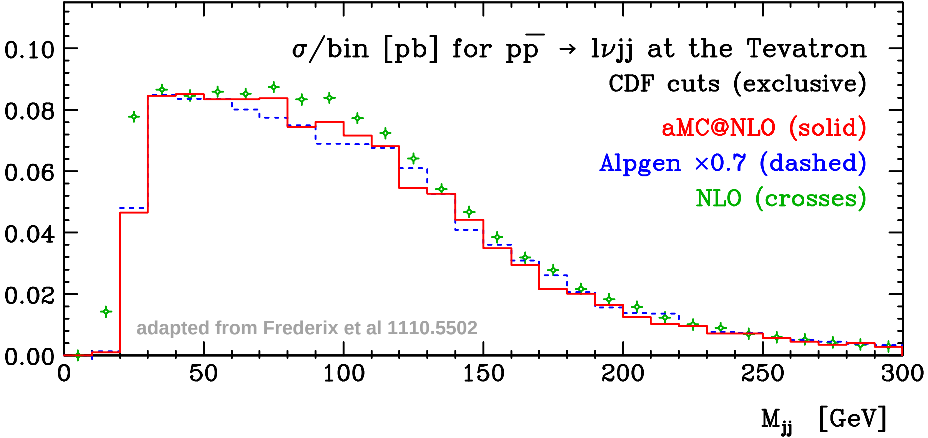
NLO has substantial shape differences: should we worry?



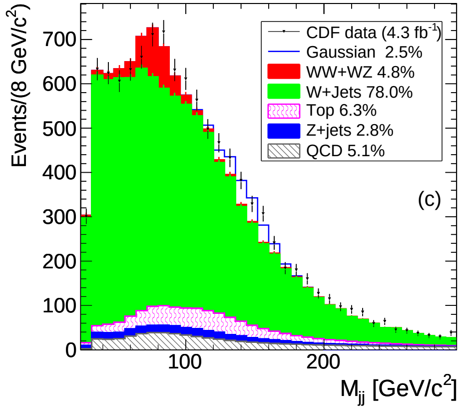
CDF & DØ use Alpgen (scaled): tree level QCD + parton shower

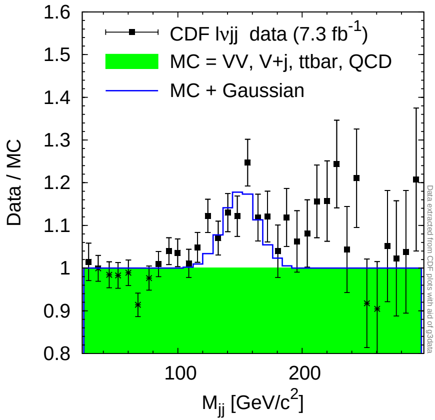
NLO has substantial shape differences: should we worry?

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



Instead of data − MC ⇒ **data/MC**





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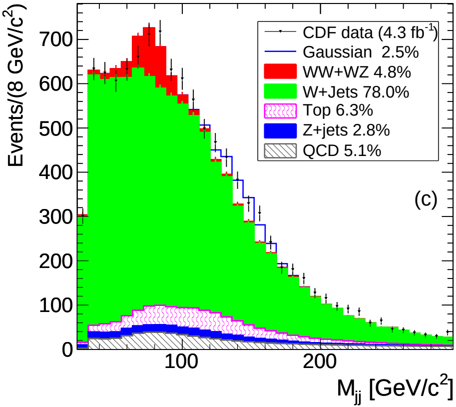

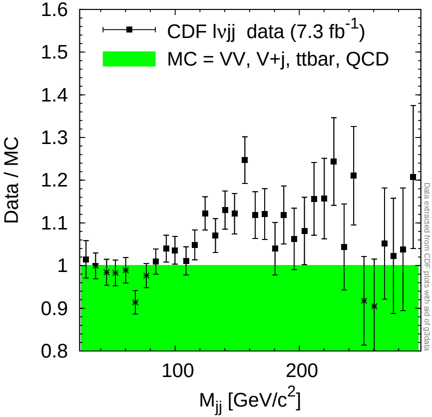

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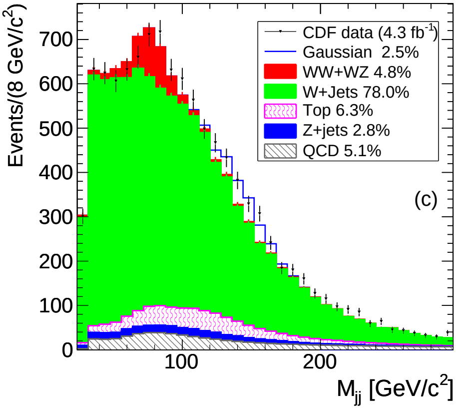
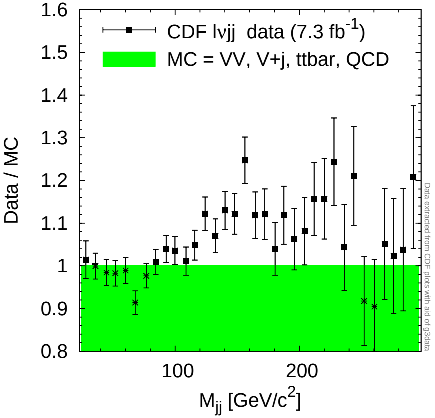
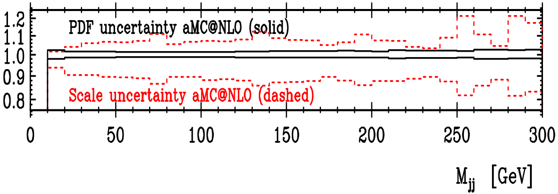
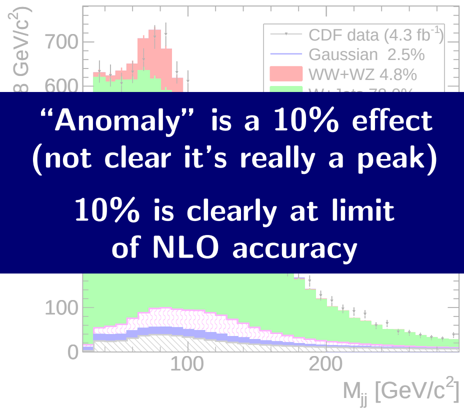




aMC@NLO uncertainties: ⟶

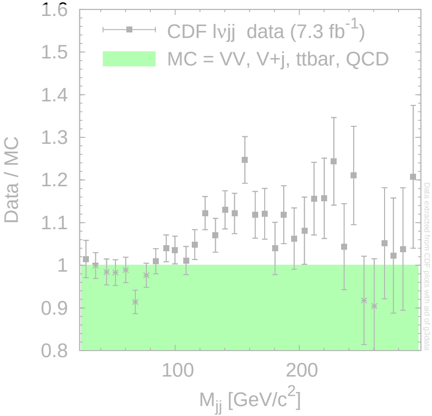


Instead of data – MC ⇒ **data/MC**

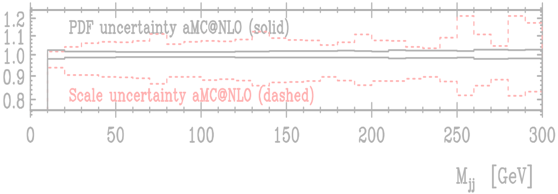


"Anomaly" is a 10% effect (not clear it's really a peak)

10% is clearly at limit of NLO accuracy



aMC@NLO uncertainties: ⟶



Going beyond limitations of NLO

[two of the options]

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

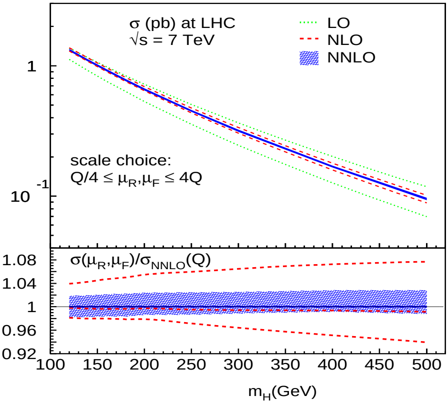
✓ W, Z, Higgs, $\gamma\gamma$, VBF, VH

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

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

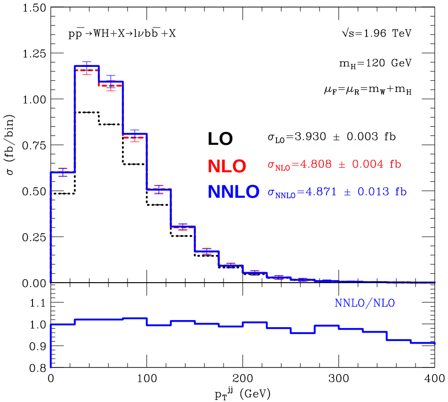
Generally by finding ways to distinguish signals from the background more efficiently, i.e. increasing S/B.

New in 2010: **NNLO VBF→H**



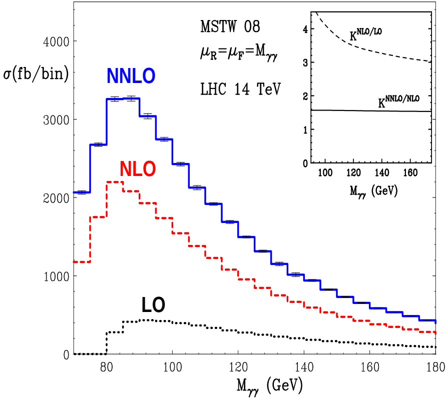
Bolzoni, Maltoni, Moch & Zaro

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



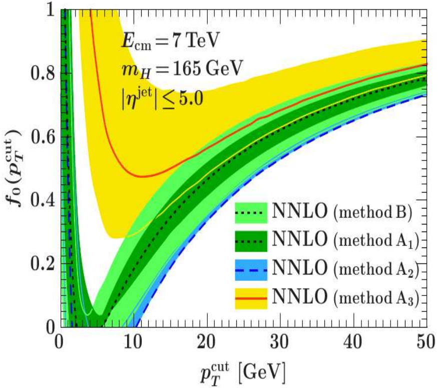
Ferrera, Grazzini & Tramontano

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



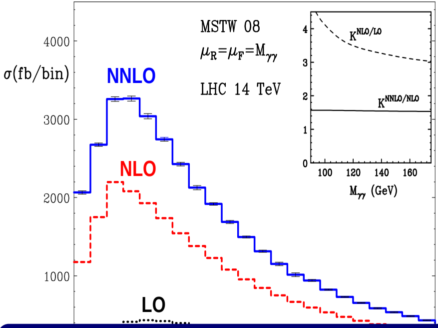
Catani et al

Higgs jet veto efficiency

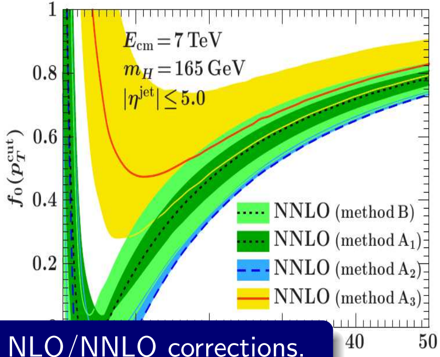


analyses by Stewart & Tackmann '12
+ Banfi, GPS & Zanderighi
using FeHiP/HNNLO

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



Higgs jet veto efficiency



mann '12

Zanderighi

/HNNLO

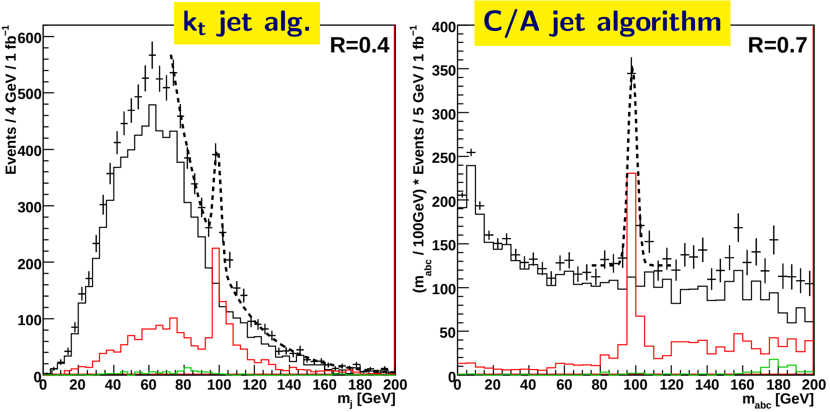
Some key processes see large or giant NLO/NNLO corrections.

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 $gg \to H$ case.

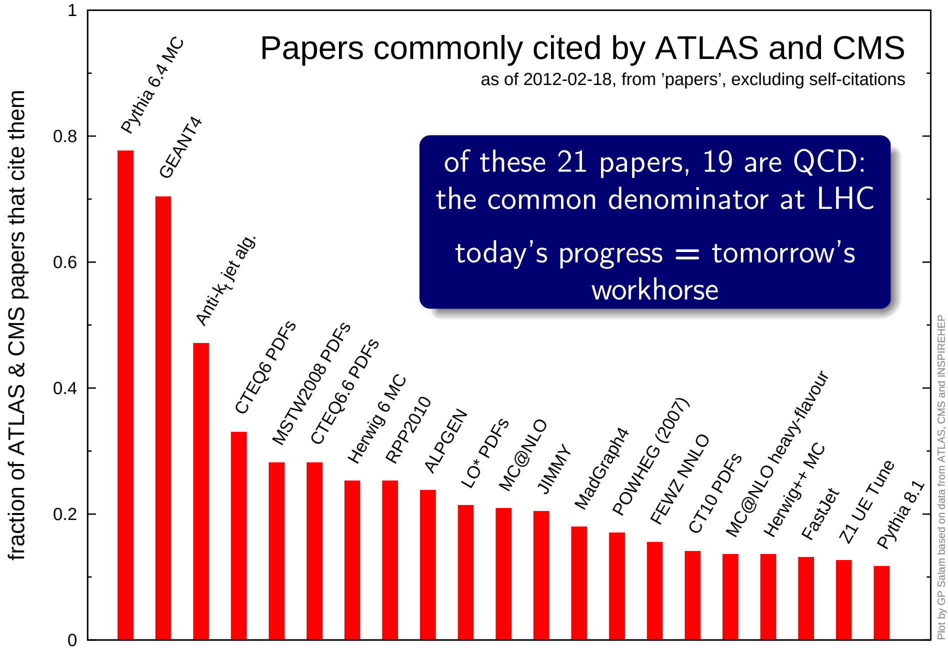
A new sub-field has emerged, “Boost”, for finding boosted tops/Z/H/etc.

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 $\chi^0 \to qqq$; Butterworth, Ellis, Raklev & GPS ’09]

Closing

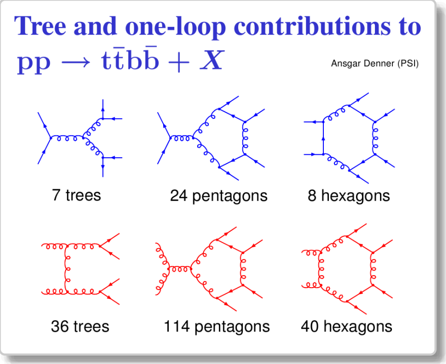

Papers commonly cited by ATLAS and CMS
as of 2012-02-18, from 'papers', excluding self-citations
of these 21 papers, 19 are QCD:
the common denominator at LHC
today's progress = tomorrow's
workhorse
fraction of ATLAS & CMS papers that cite them
Pythia 6.4 MC
GEANT4
Anti-k_t jet alg.
CTEQ6 PDFs
MSTW2008 PDFs
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
1
0.8
0.6
0.4
0.2
0
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.

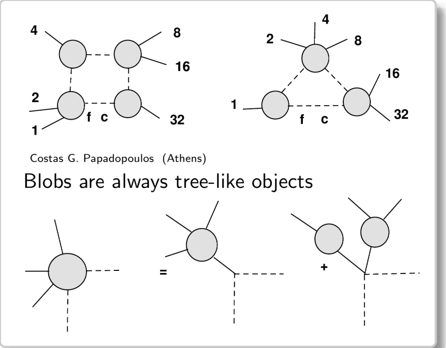
Work hard to reduce integrals to known forms (+ tricks).



Recursive/unitarity methods

Assemble loop-diagrams from individual tree-level diagrams.

Build trees by sticking together simpler tree-level diagrams



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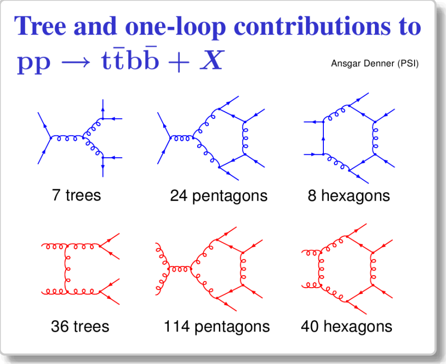

Recursive/unitarity methods

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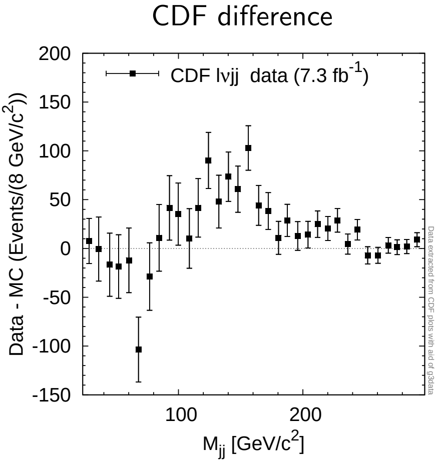
Some main ideas:

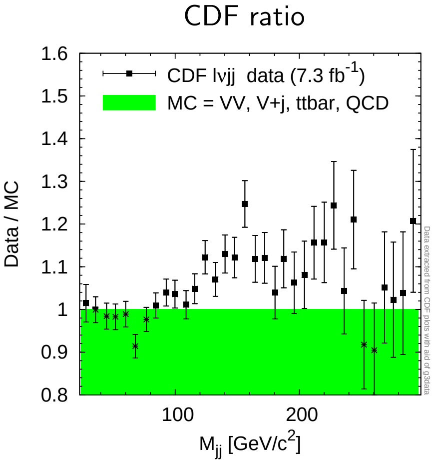
Bern, Dixon & Kosower '93
[sewing together trees]

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

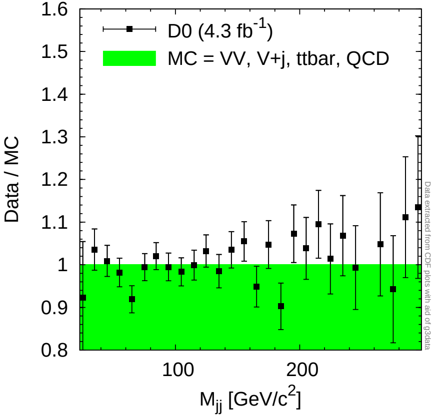
Ossola, Pittau & Papadopoulos '06
[handful of loop momentum choices give full amplitude]

CDF Wjj: difference wrt MC v. ratio to MC

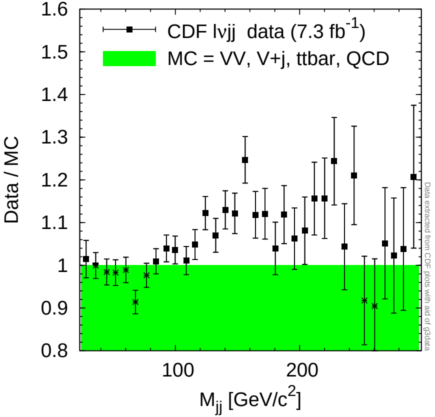


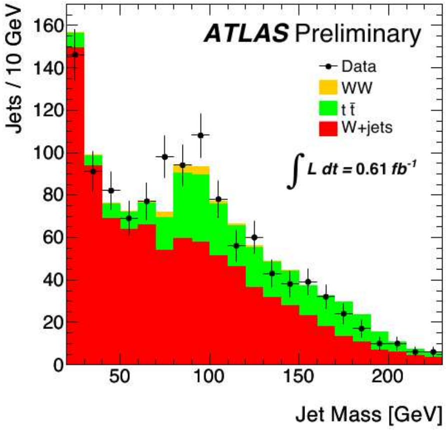


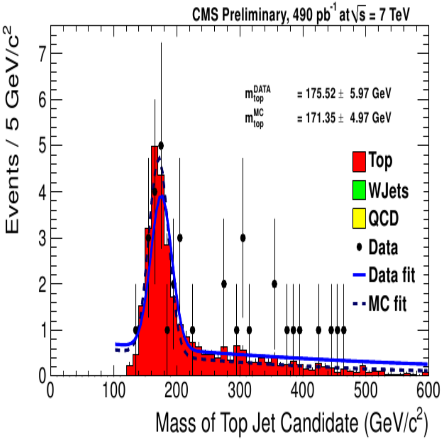
DØ ratio

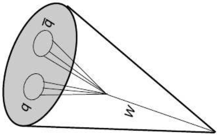


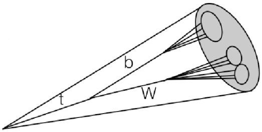
CDF ratio

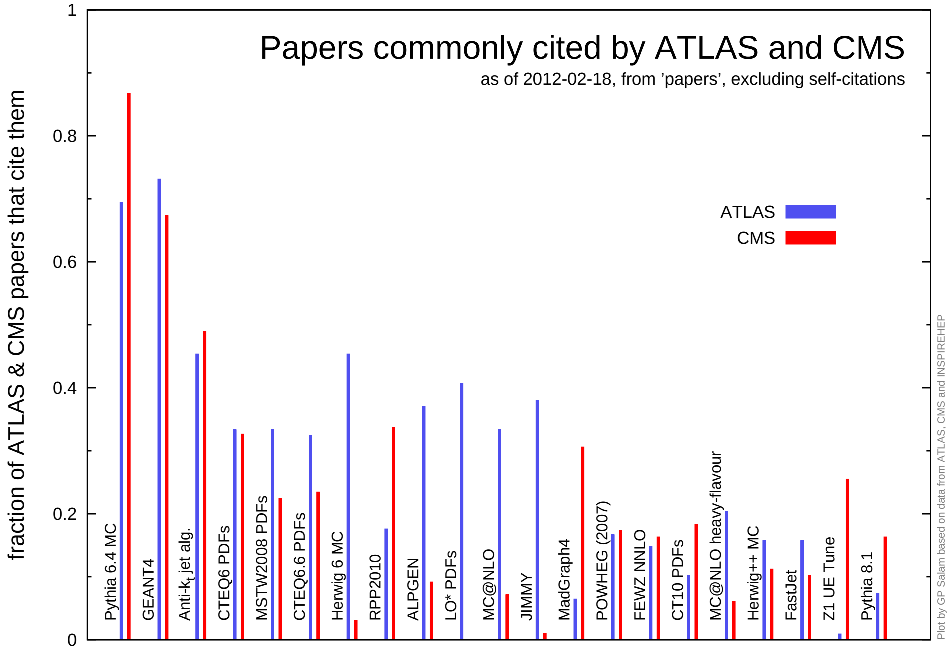



ATLAS Preliminary
Data
WW
t t̄
W+jets
$\int L\,dt = 0.61\ fb^{-1}$
Jets / 10 GeV
Jet Mass [GeV]
0
20
40
60
80
100
120
140
160
50
100
150
200


CMS Preliminary, 490 pb^{-1} at $\sqrt{s}$ = 7 TeV
m_{top}^{DATA} = 175.52 ± 5.97 GeV
m_{top}^{MC} = 171.35 ± 4.97 GeV
Top
WJets
QCD
Data
Data fit
MC fit
Events / 5 GeV/c^2
Mass of Top Jet Candidate (GeV/c^2)
0
1
2
3
4
5
6
7
100
200
300
400
500
600


q̄
q
W


b
t
W


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
1
0.8
0.6
0.4
0.2
0
ATLAS
CMS
Pythia 6.4 MC
GEANT4
Anti-kt jet alg.
CTEQ6 PDFs
MSTW2008 PDFs
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
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