QCD in hadron collisions

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An exciting past 18 months

$t\bar{t}$ asymmetry

W + dijet CDF anomaly

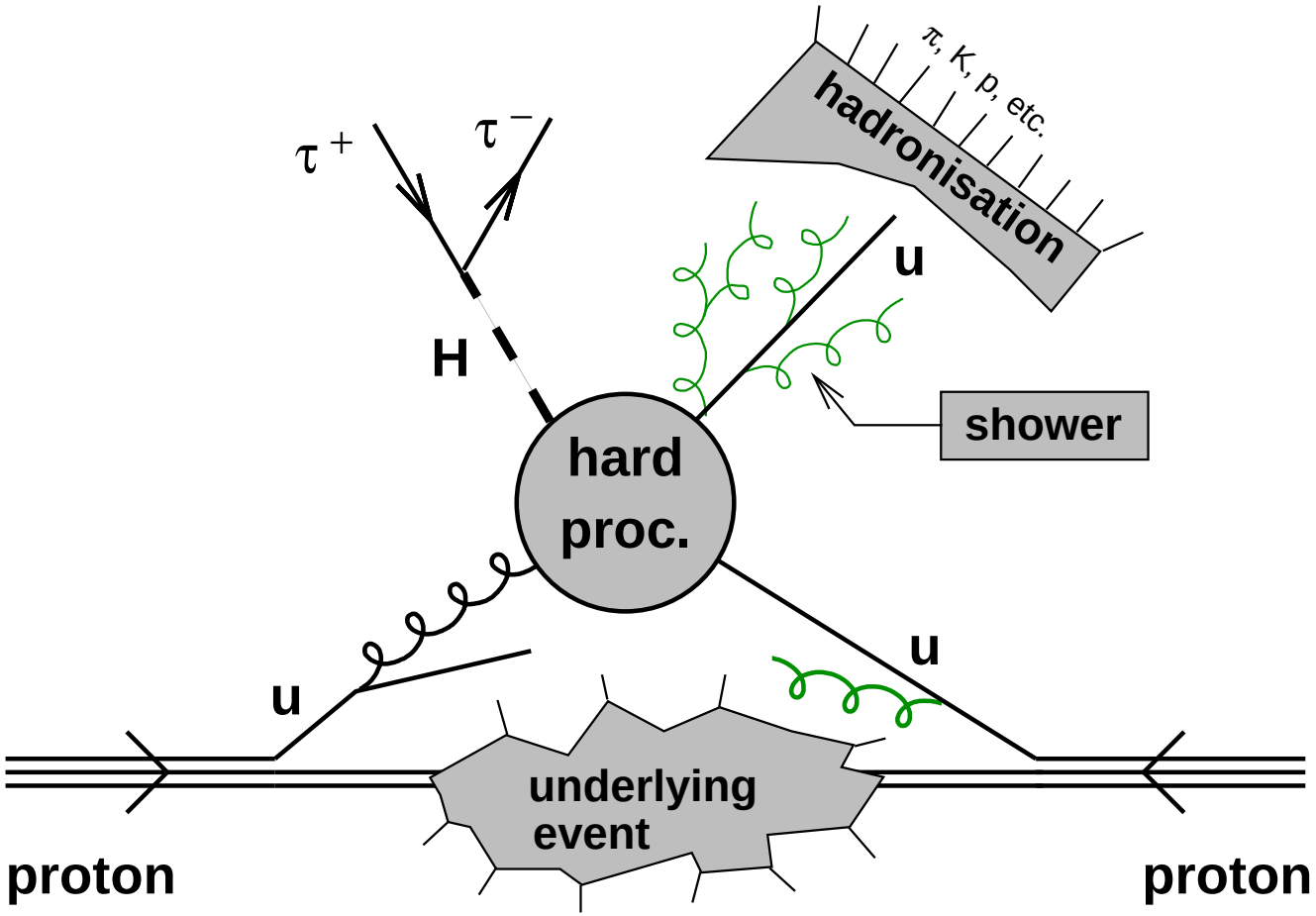
Exclusion of swathes of SUSY, etc.

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

Some of what goes into collider predictions



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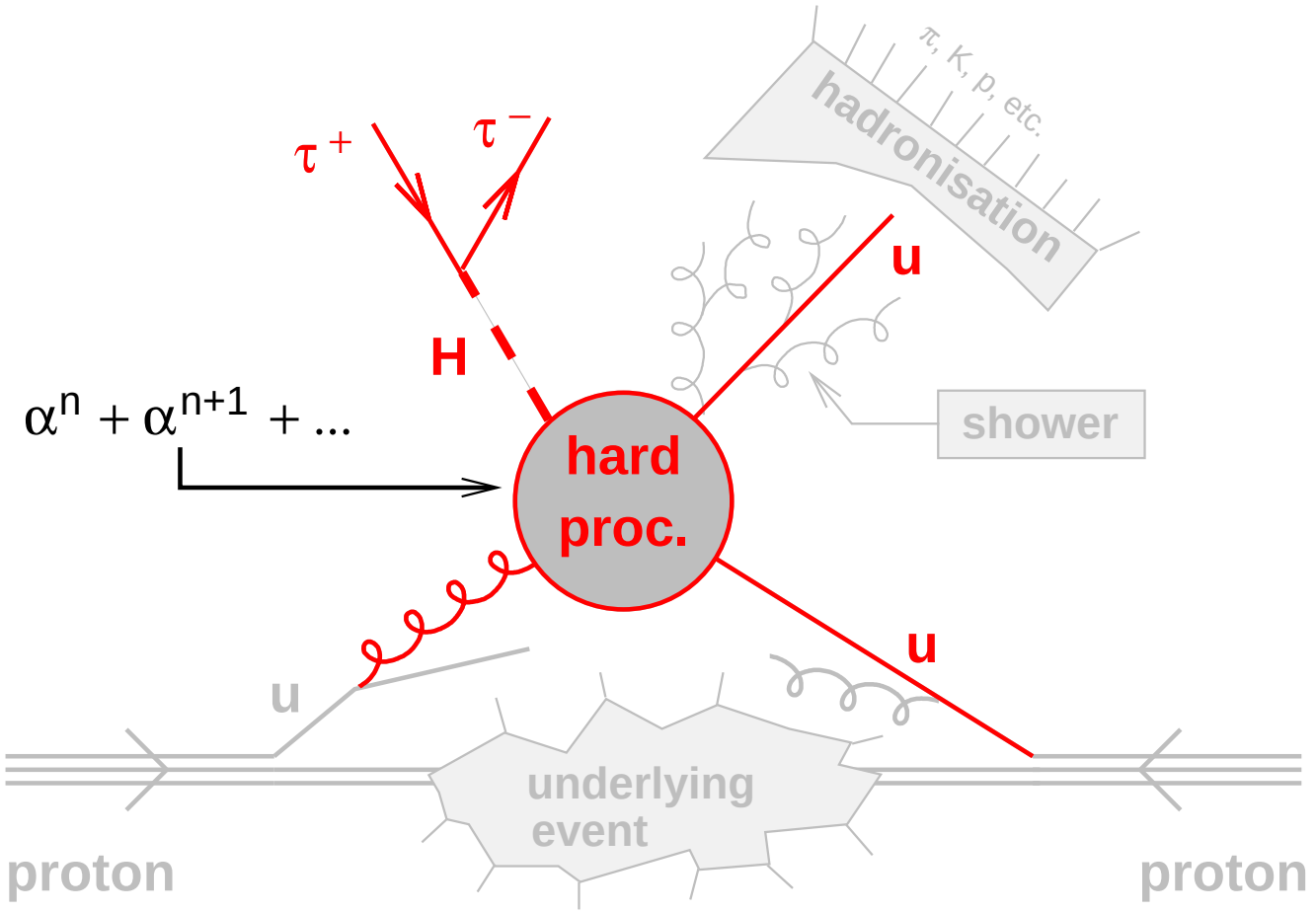
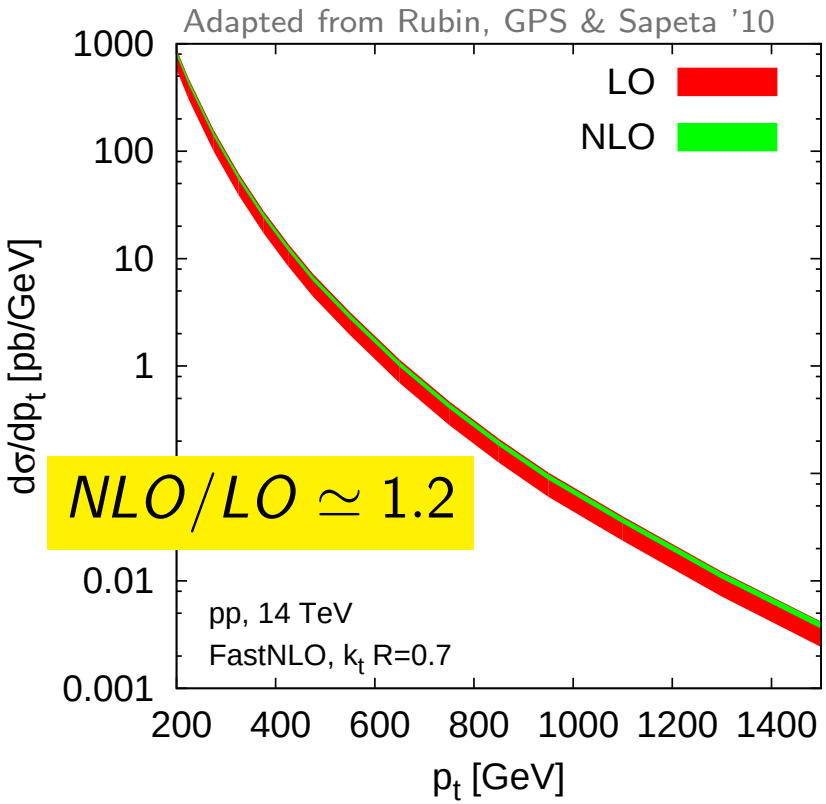
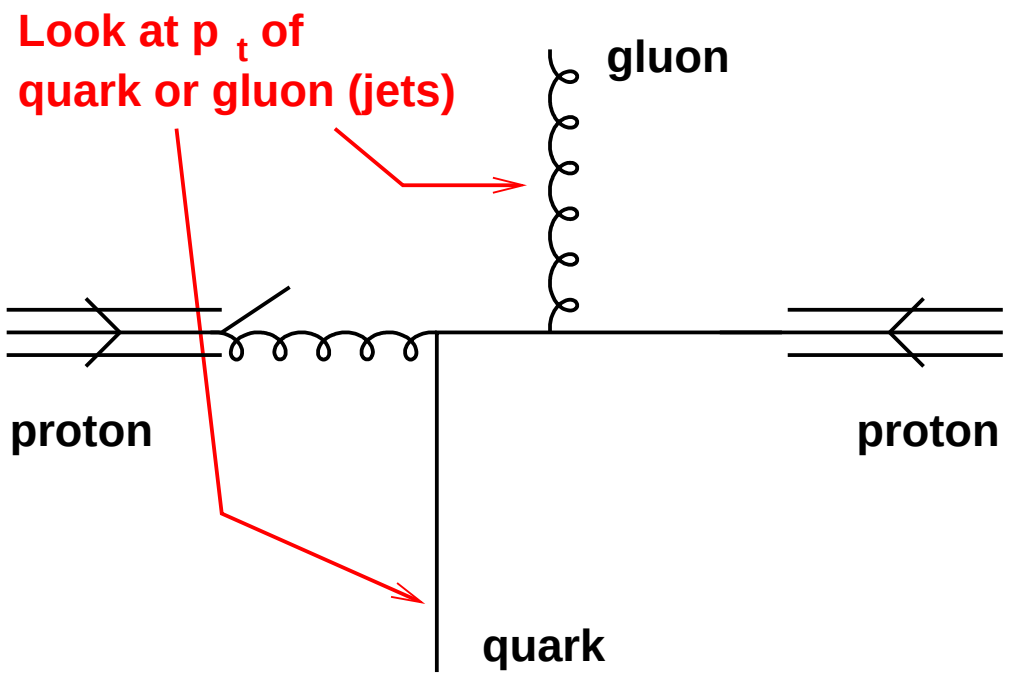


The hard process is where we use pQCD expansion in α_s

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





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

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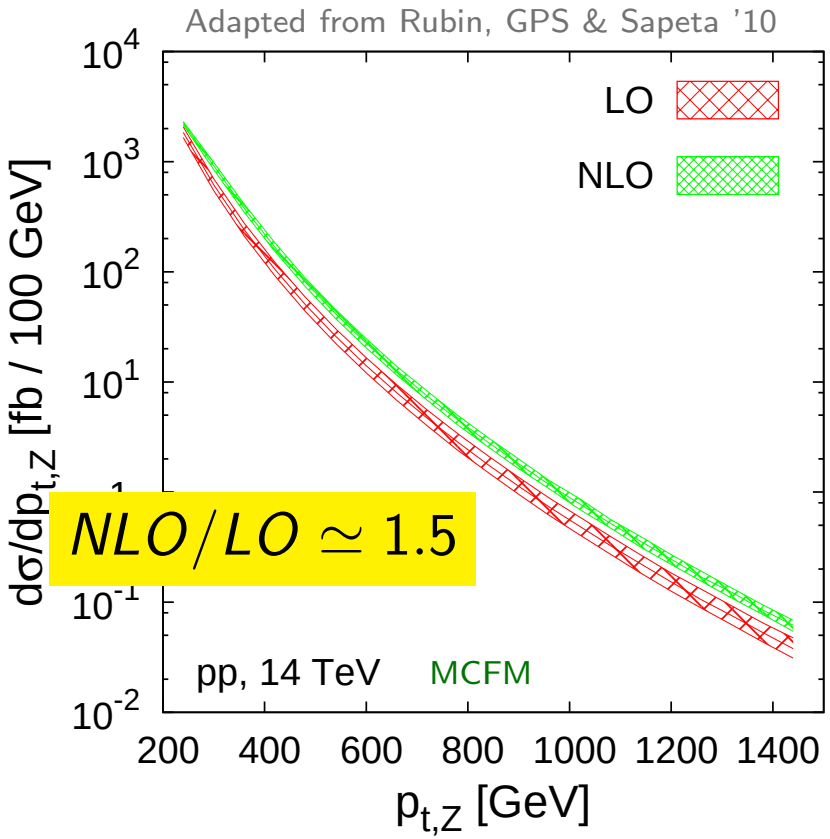
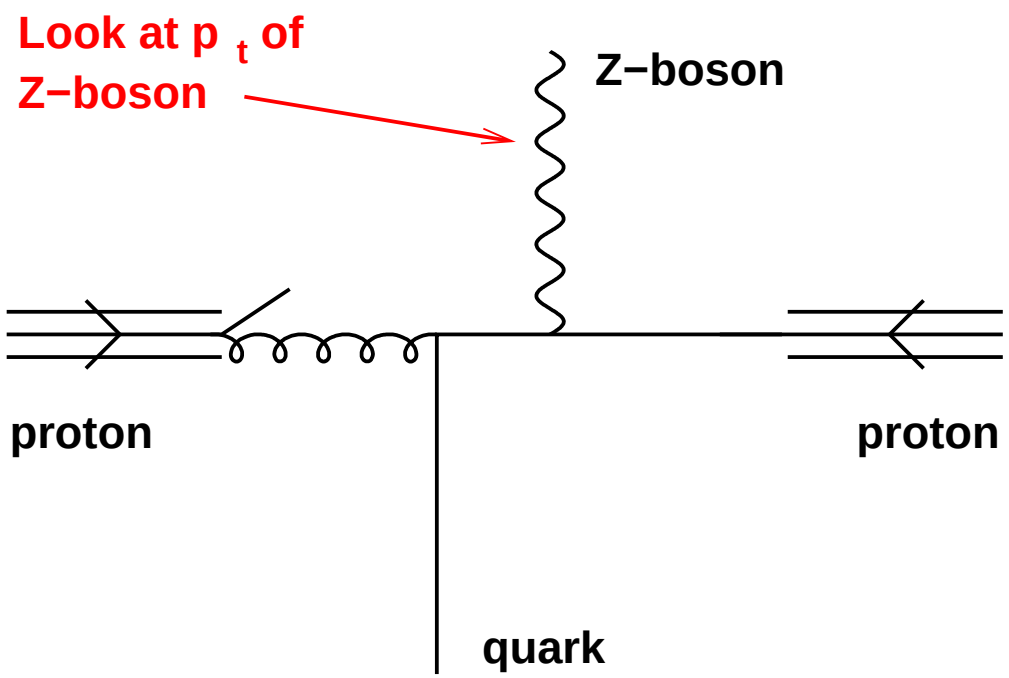


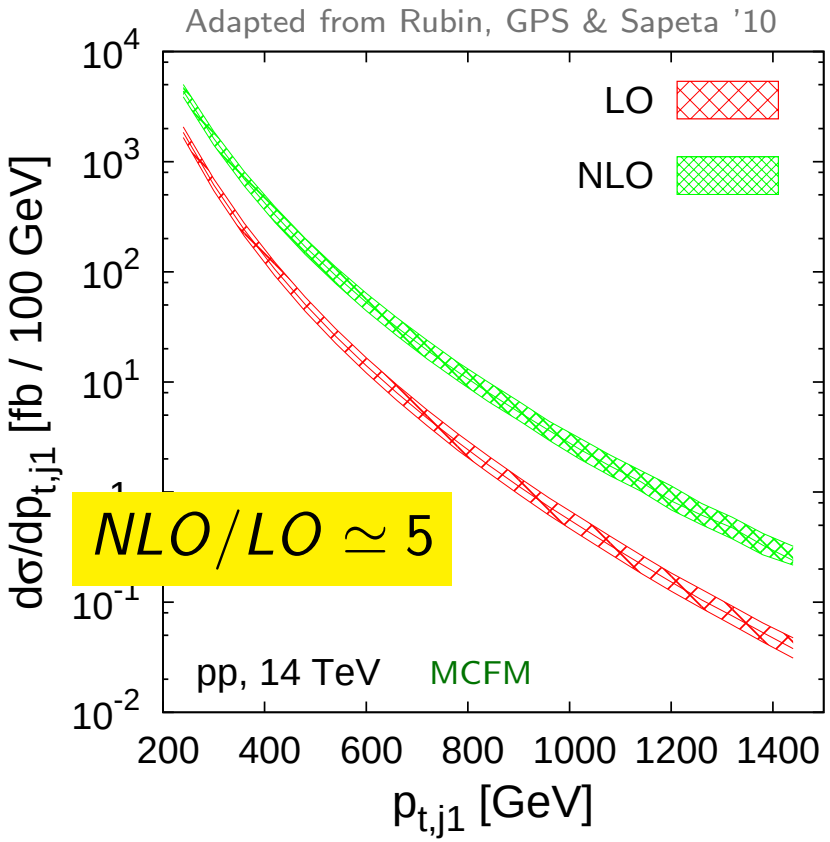


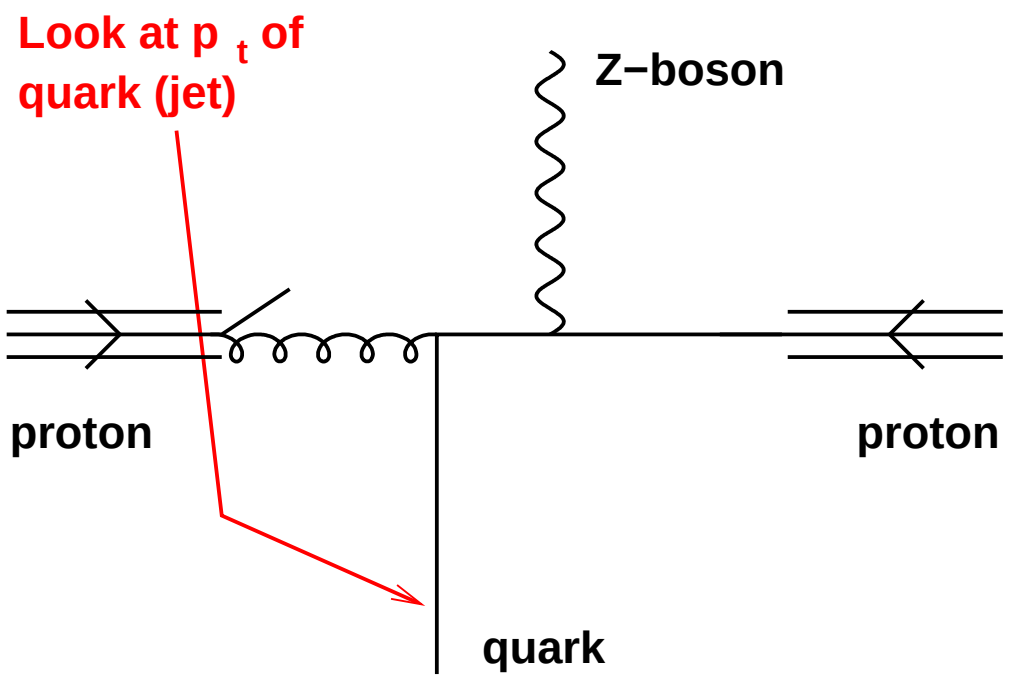
K of 1.5 is compatible with being $1 + C \times \alpha_s$, with quite large C

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





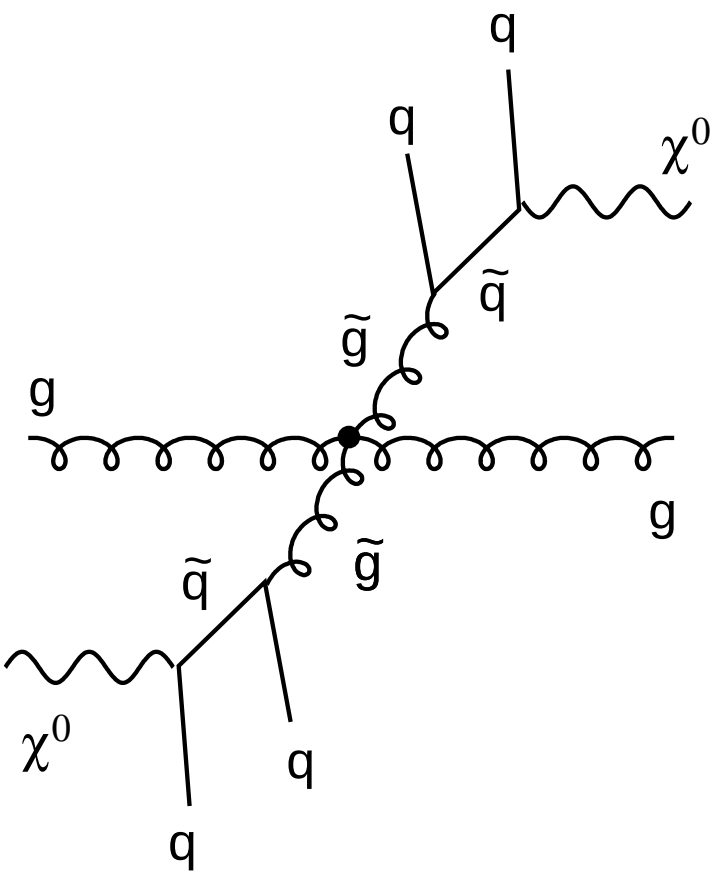
$1 + C\alpha_s \longrightarrow K = 5$?!! Often driven by new topologies

The NLO revolution

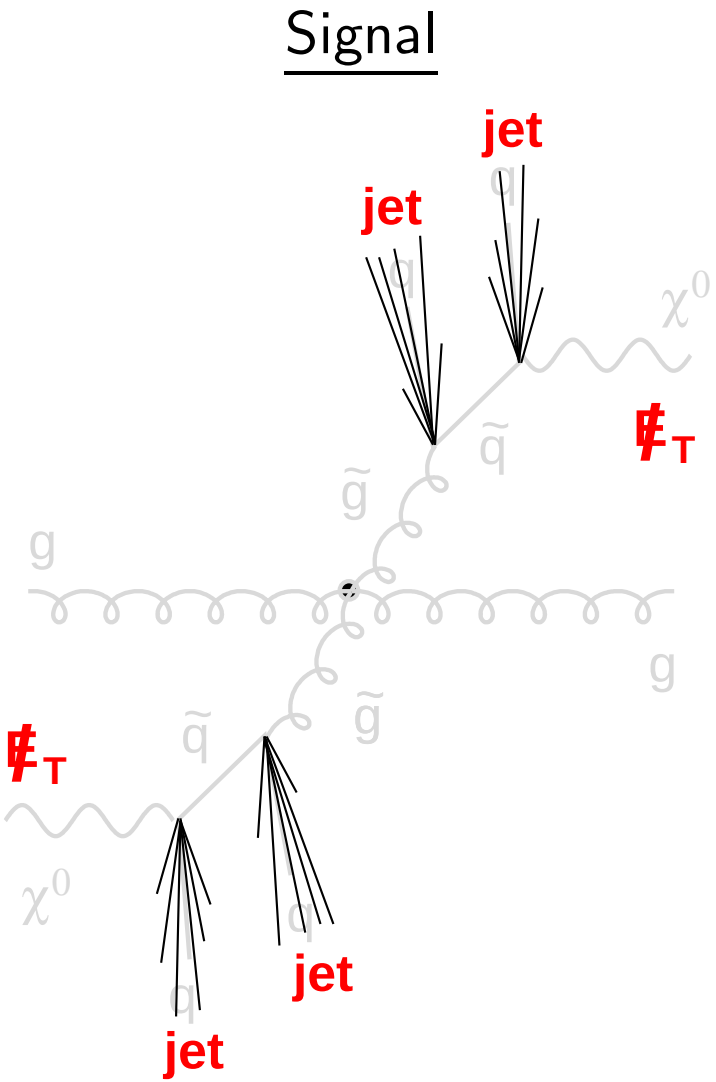
and one way it's being used

SUSY example: gluino pair production

Signal



SUSY example: gluino pair production



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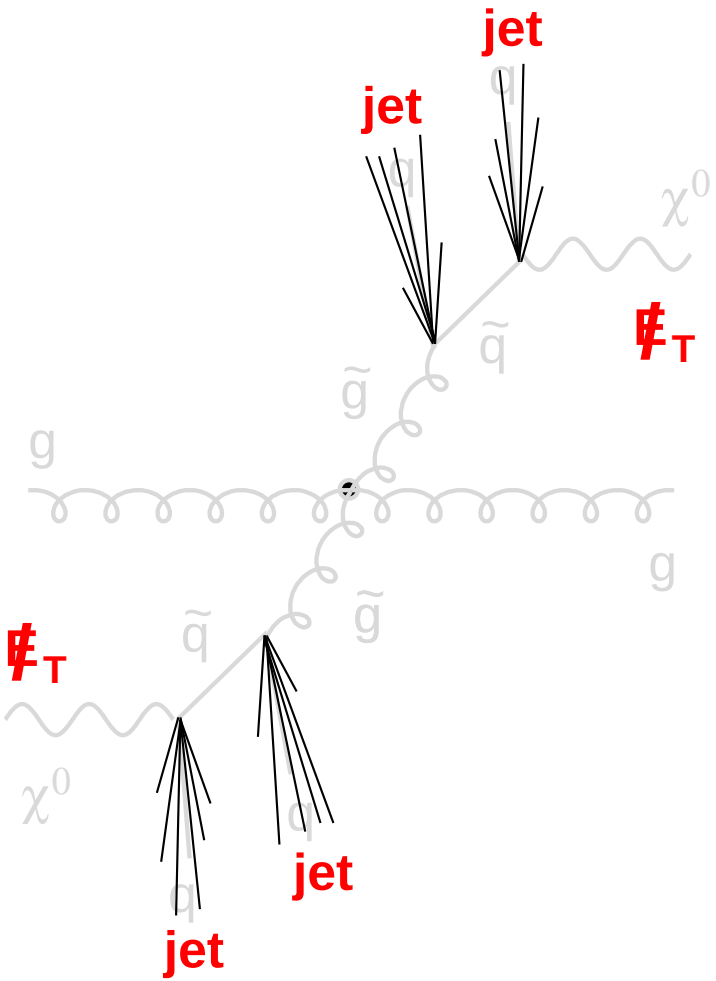
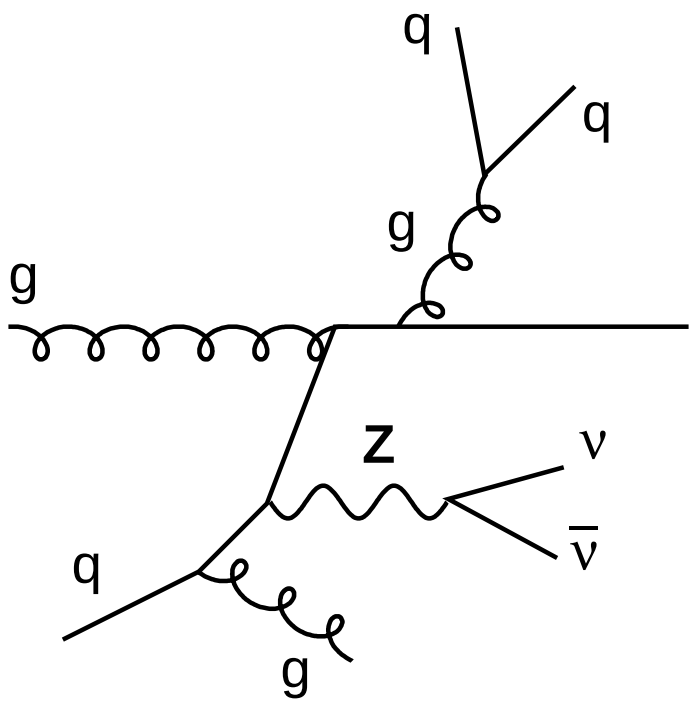


Background



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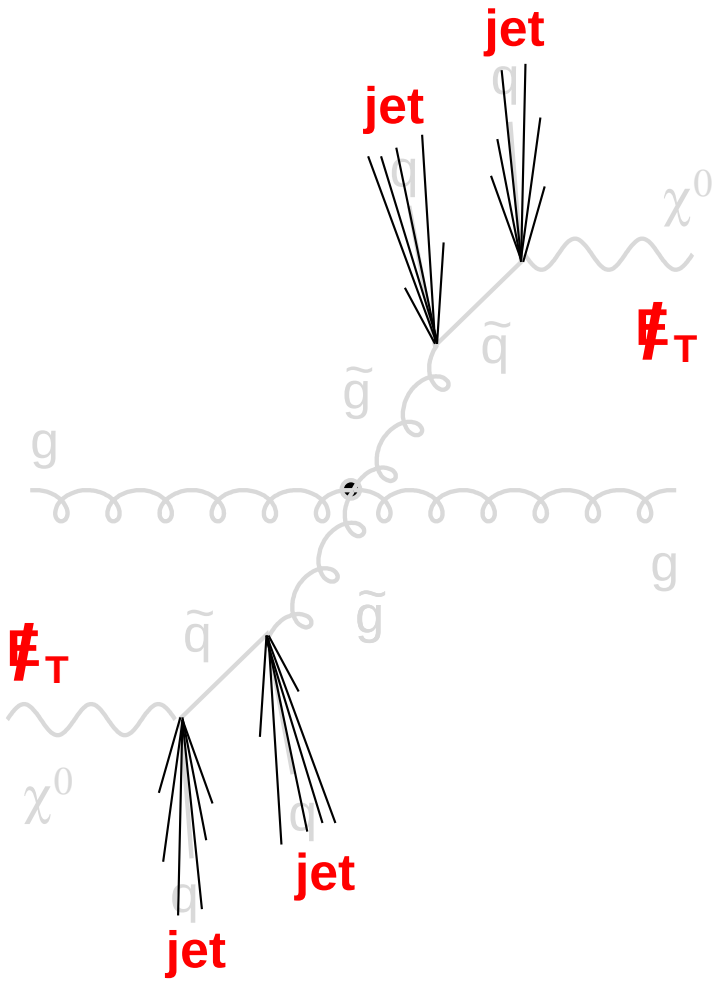

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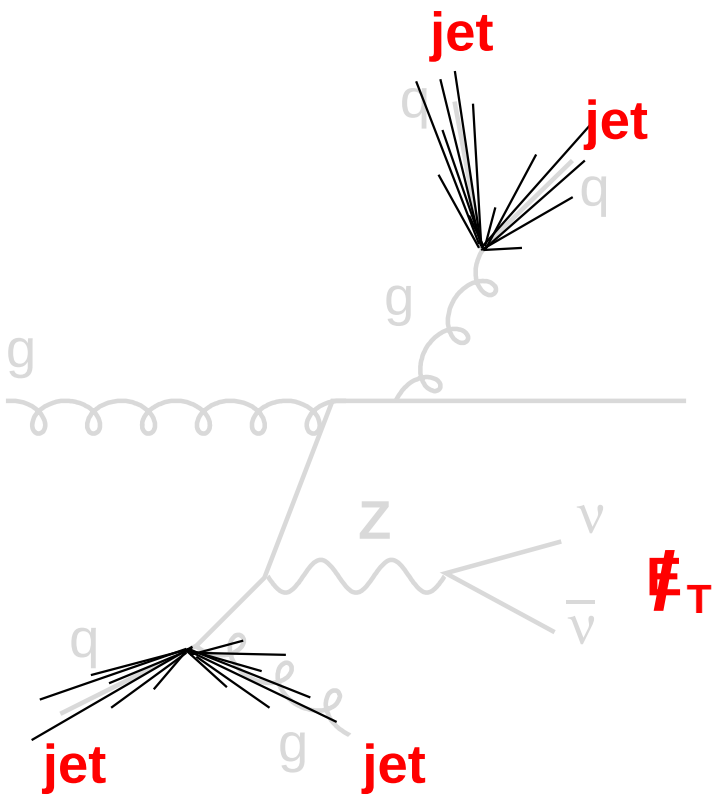

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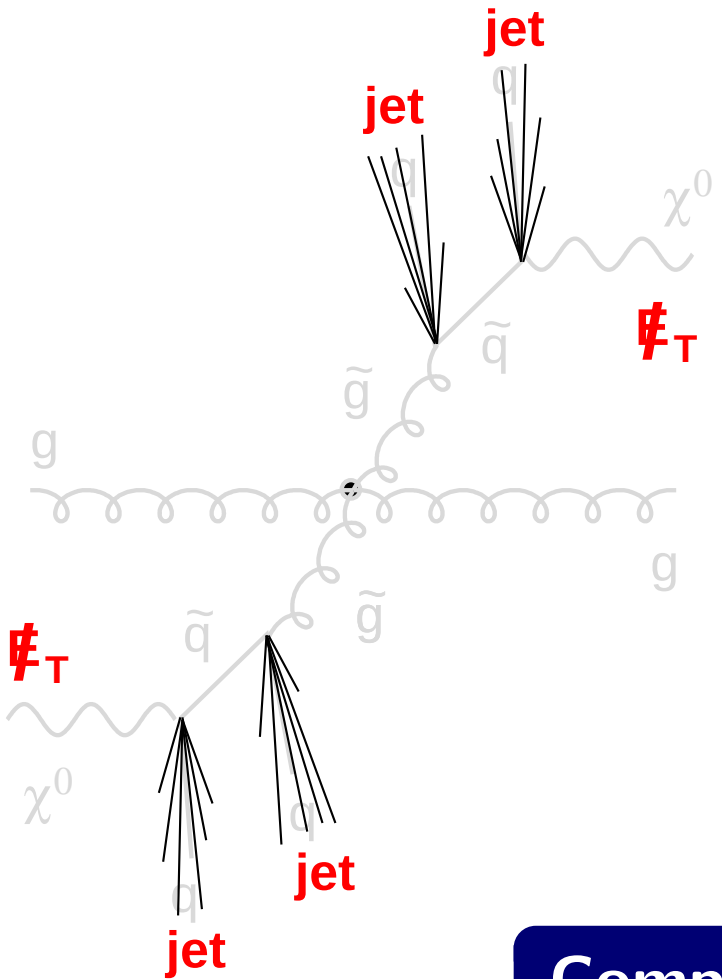
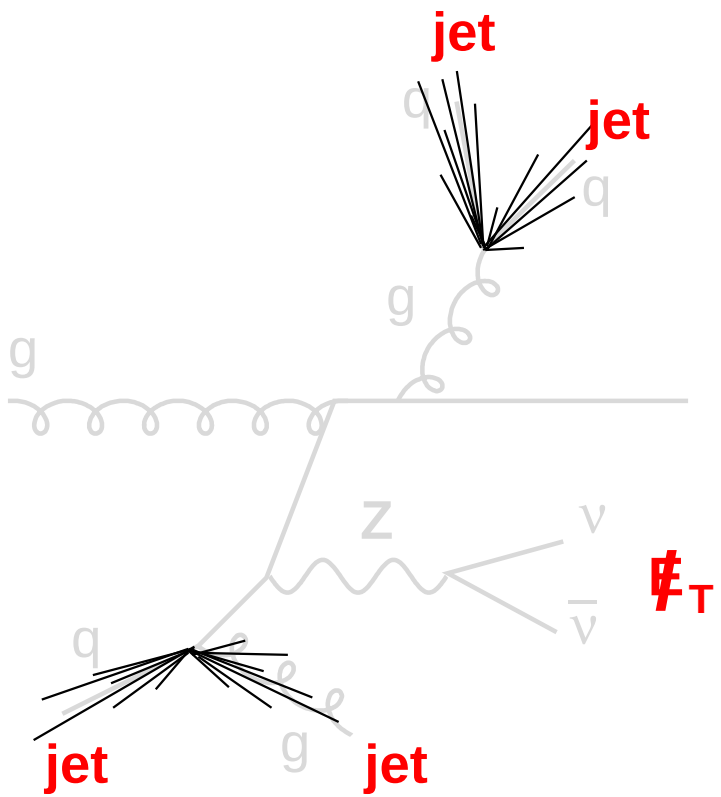
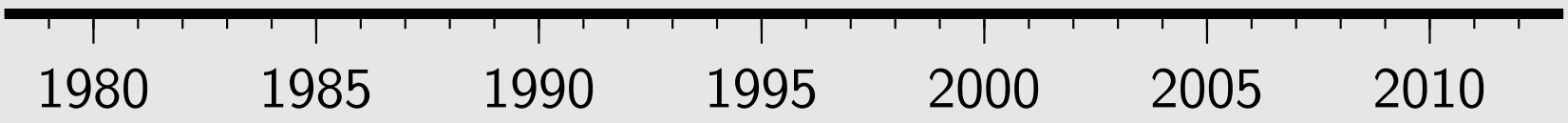


Background

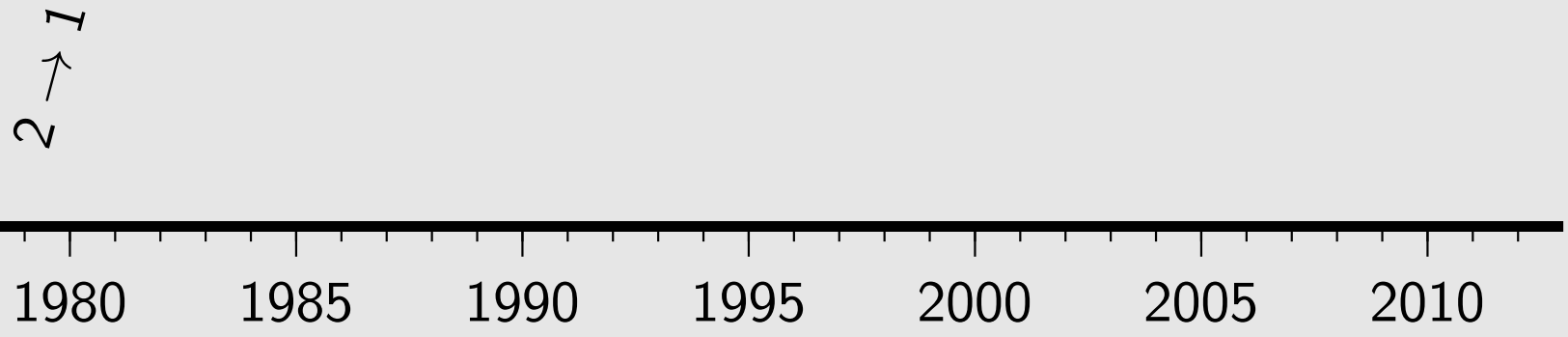


Complexity of NLO calculation determined by final-state multiplicity: a $2 \to 5$ process.

NLO timeline



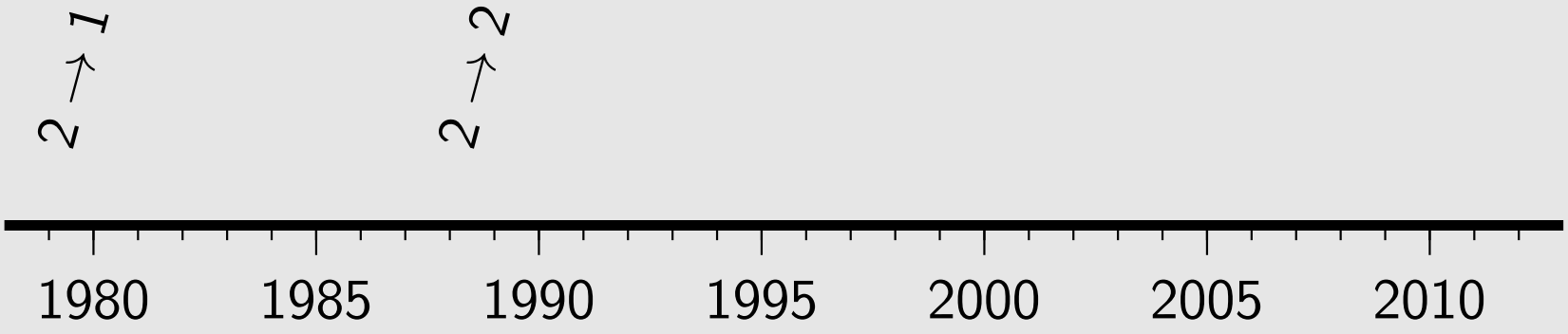
NLO timeline



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

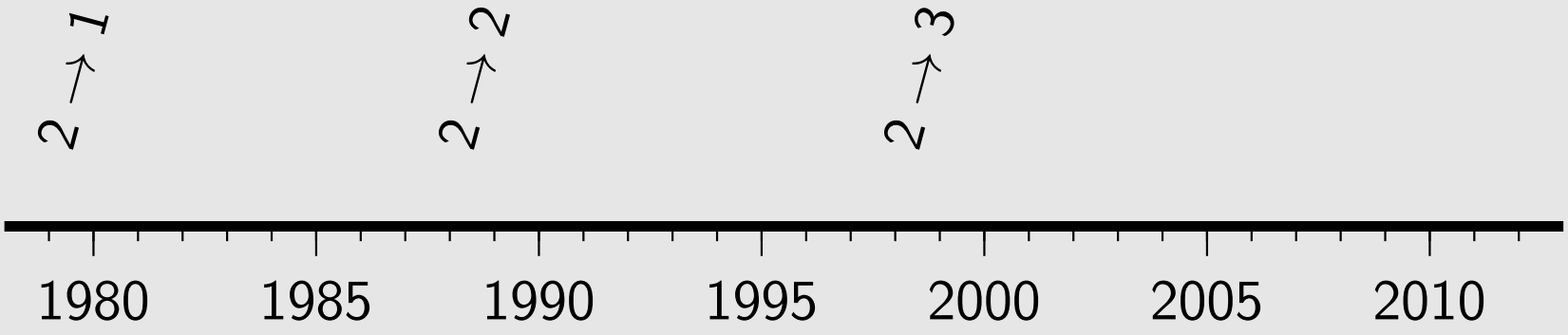
1991: NLO $gg \to$ Higgs [Dawson; Djouadi, Spira & Zerwas]

NLO timeline



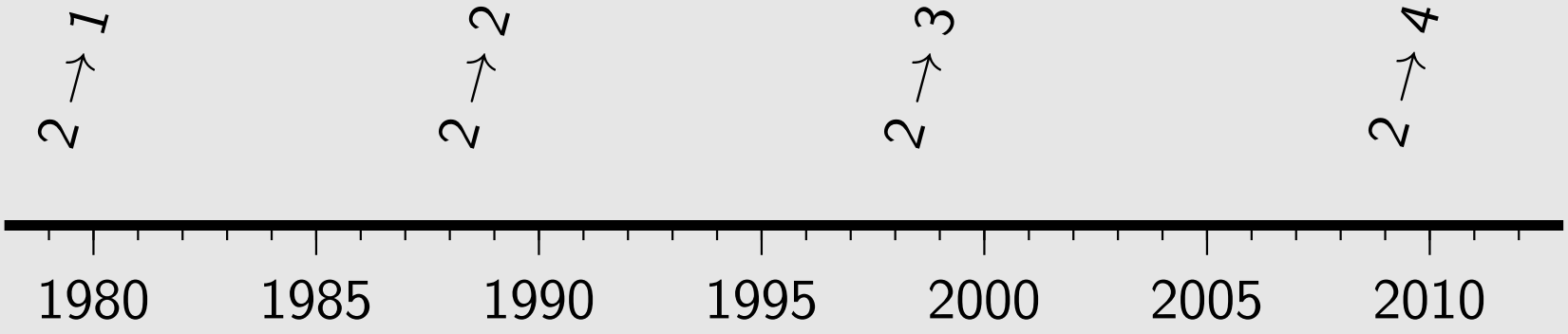
1987: NLO high-p_t photoproduction [Aurenche et al]
1988: NLO $b\bar{b}$, $t\bar{t}$ [Nason et al]
1988: NLO dijets [Aversa et al]
1993: Vj [JETRAD, Giele, Glover & Kosower]

NLO timeline

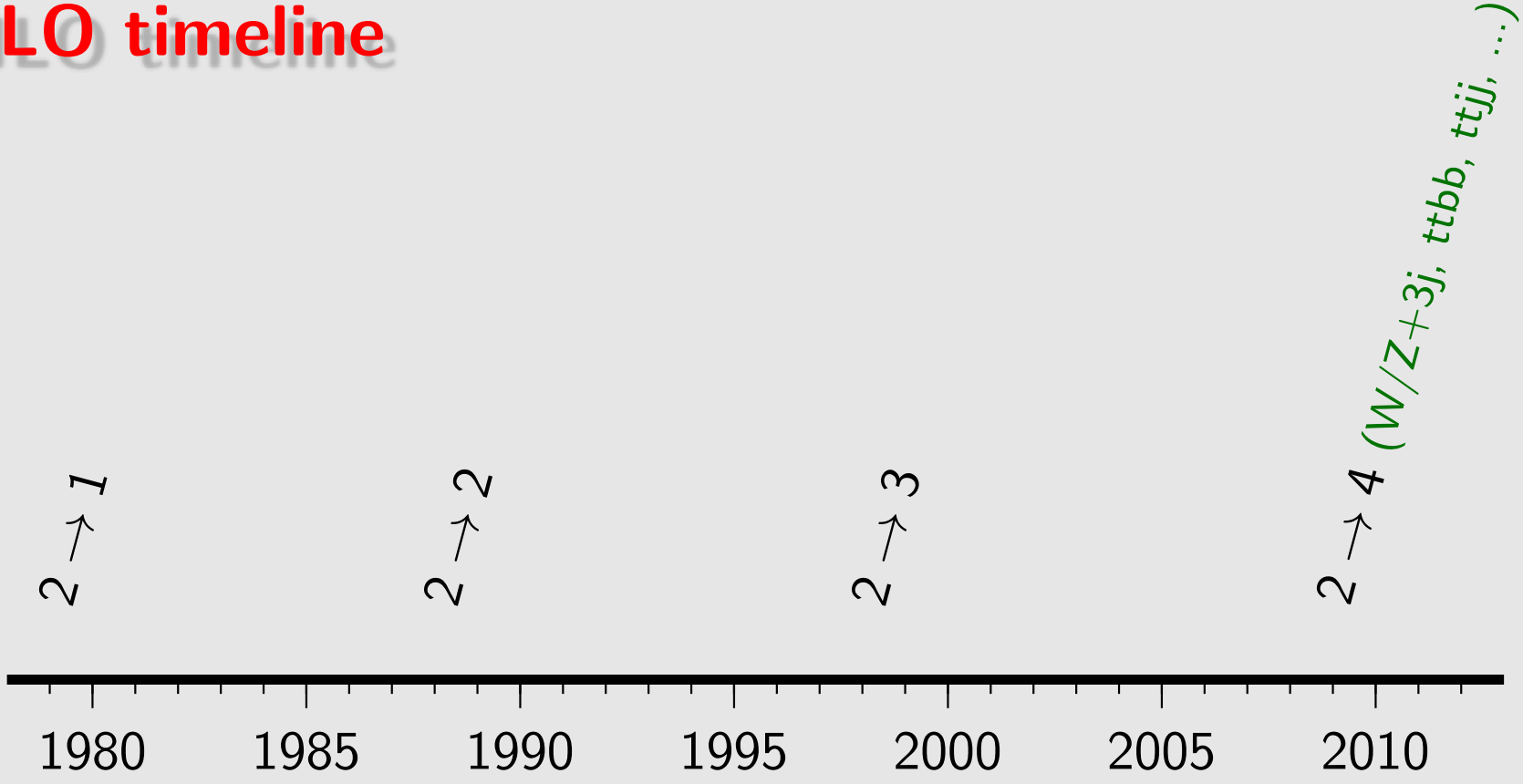


1998: NLO $Wb\bar{b}$ [MCFM: Ellis & Veseli]
2000: NLO $Zb\bar{b}$ [MCFM: Campbell & Ellis]
2001: NLO $3j$ [NLOJet++: Nagy]
...
2007: NLO $t\bar{t}j$ [Dittmaier, Uwer & Weinzierl '07]
...

NLO timeline

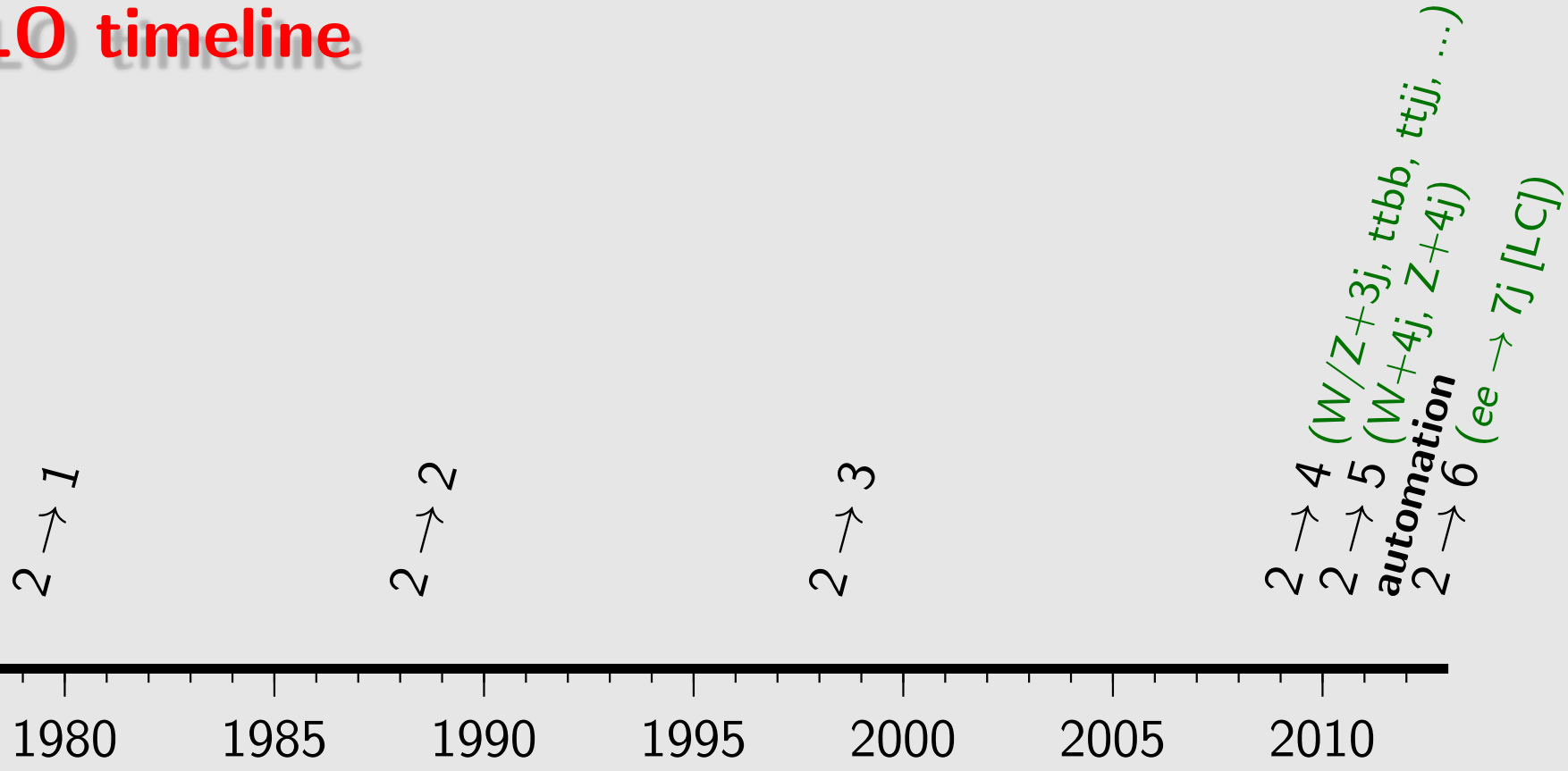


NLO timeline



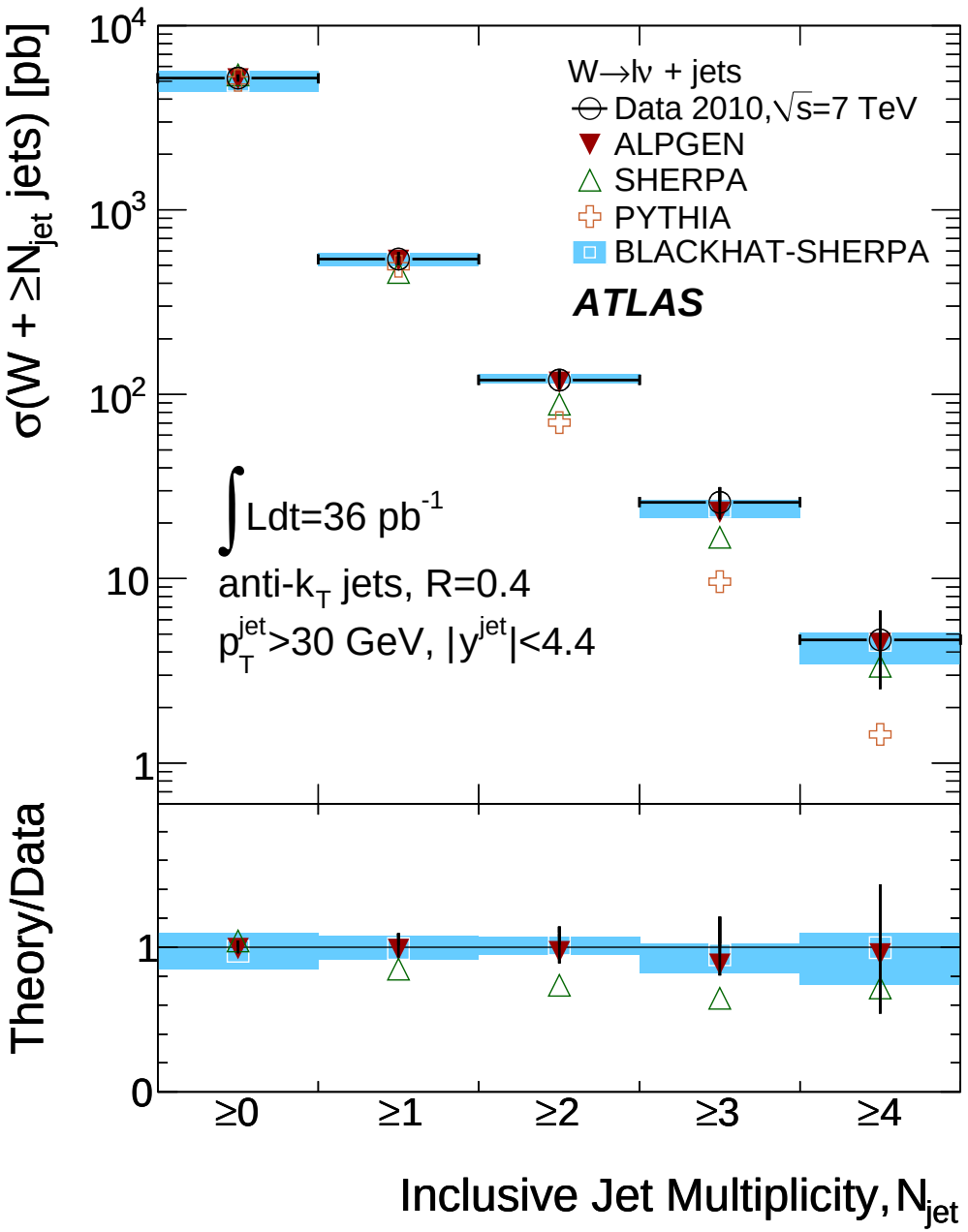
2009: NLO $W+3j$ [Rocket: Ellis, Melnikov & Zanderighi] [unitarity]
2009: NLO $W+3j$ [BlackHat+Sherpa: Berger et al] [unitarity]
2009: NLO $t\bar{t}b\bar{b}$ [Bredenstein et al] [traditional]
2009: NLO $t\bar{t}b\bar{b}$ [HELAC-NLO: Bevilacqua et al] [unitarity]
2009: NLO $q\bar{q} \to b\bar{b}b\bar{b}$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



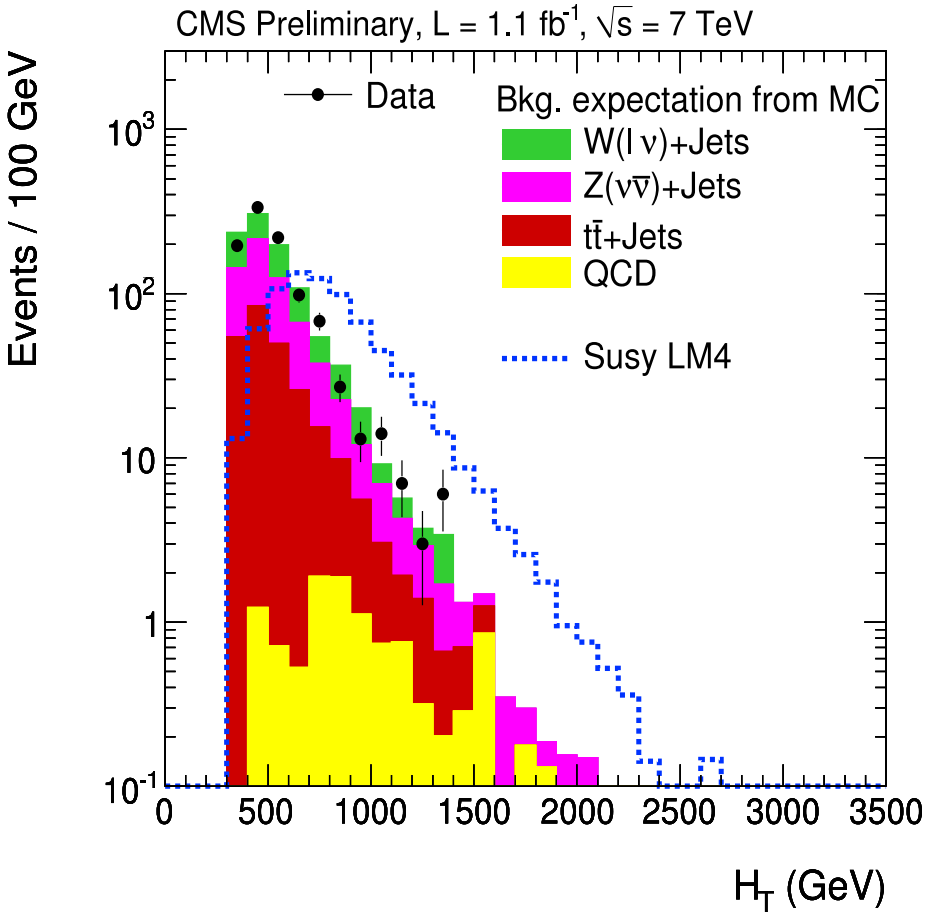
Technical revolution has gone hand-in-hand with LHC measurements of these complex processes.

Powerful validation of NLO approach.

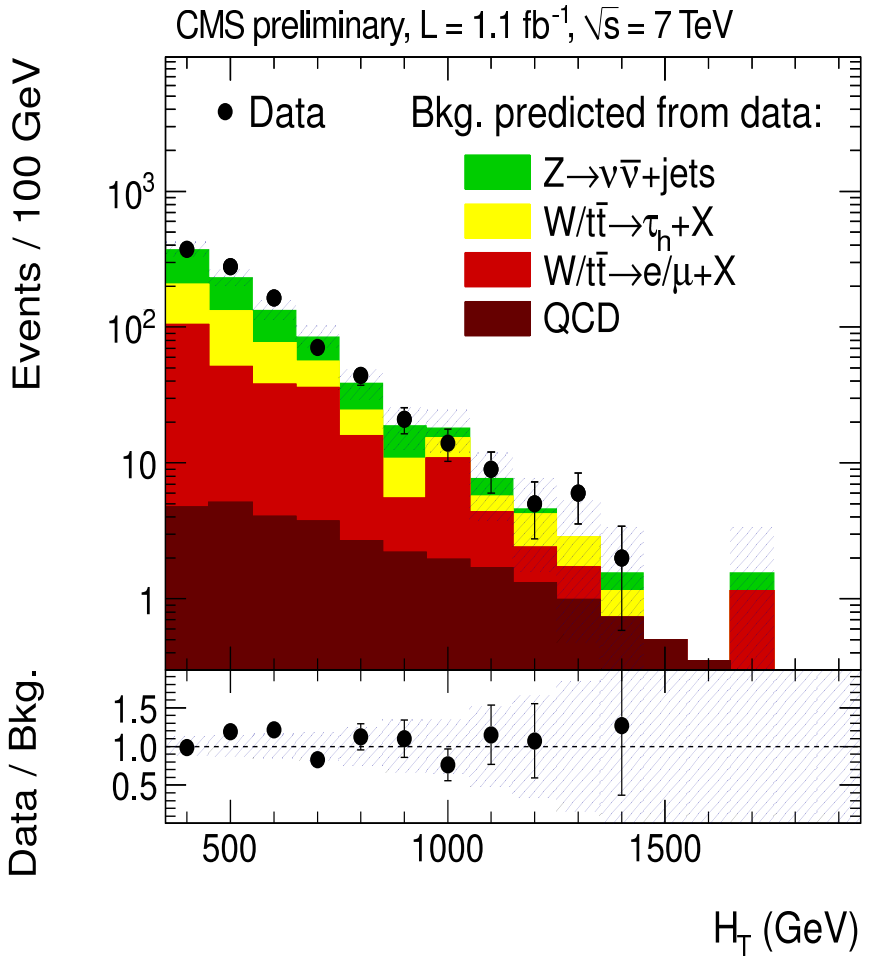
So do SUSY searches now just compare data to NLO?

Two plots from a CMS SUSY analysis

Data v. Monte Carlo backgrounds



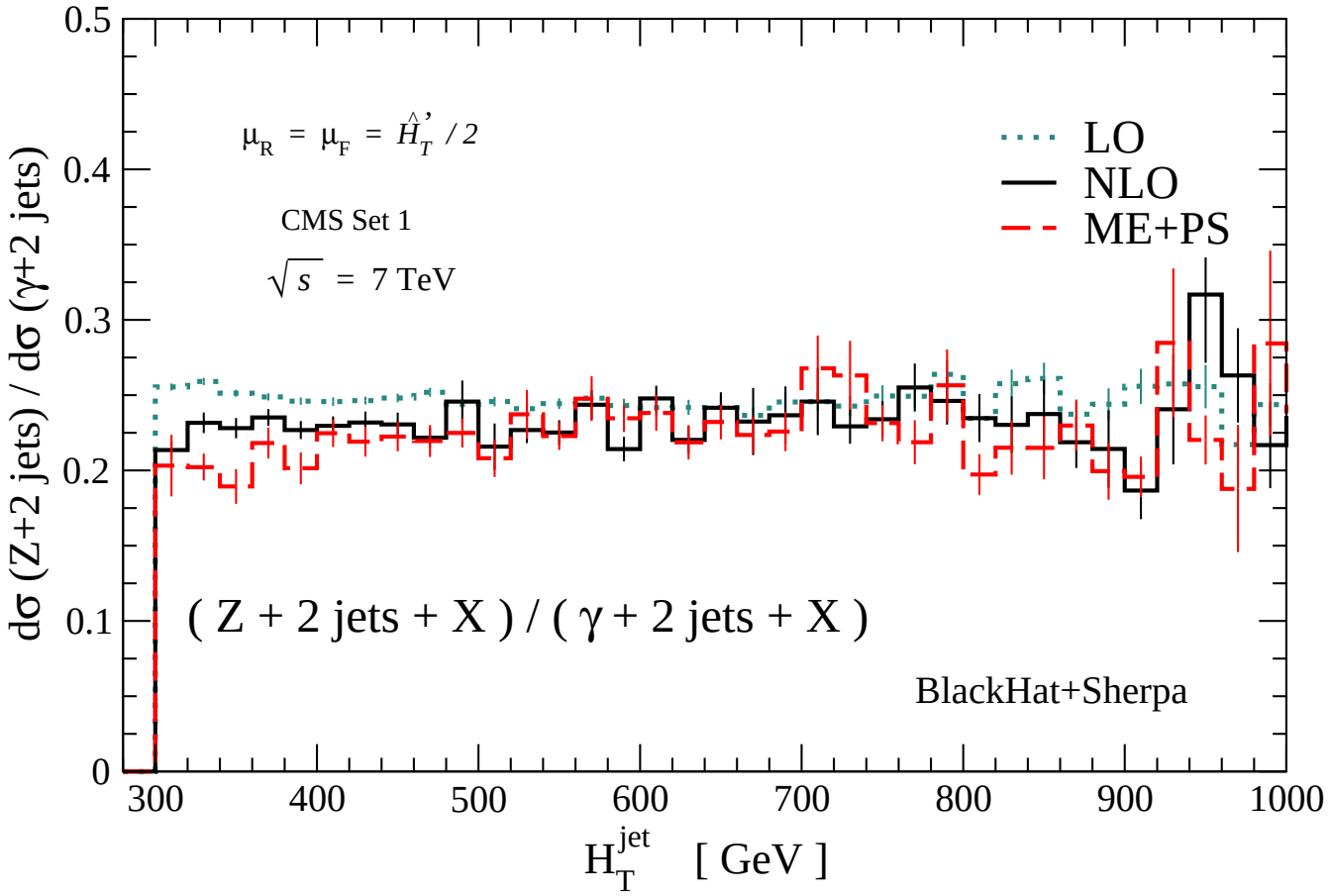
Data v. "data-driven" backgrounds



So where are the NLO predictions being used?

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

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



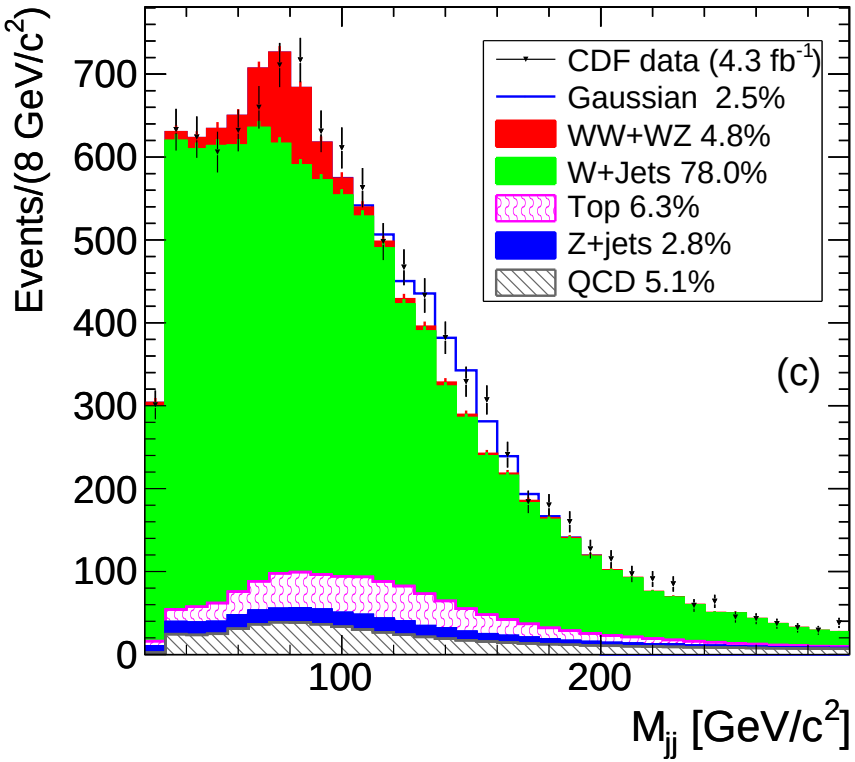
Example of widely used **data-driven** bkgd estimates

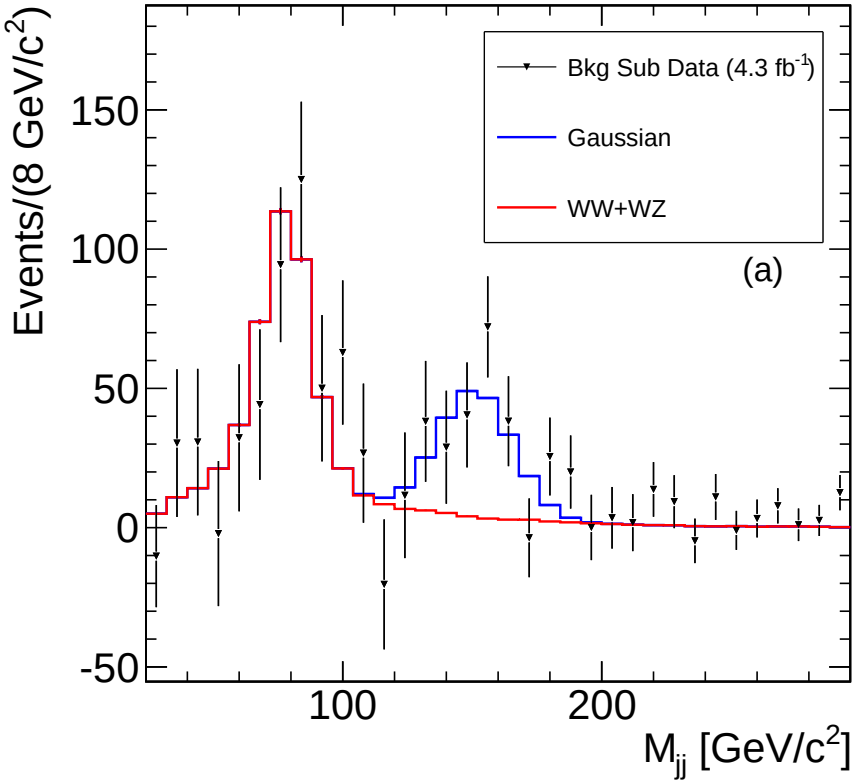
Combine best of theory knowledge with best of experimental knowledge.

Merging NLO and showers

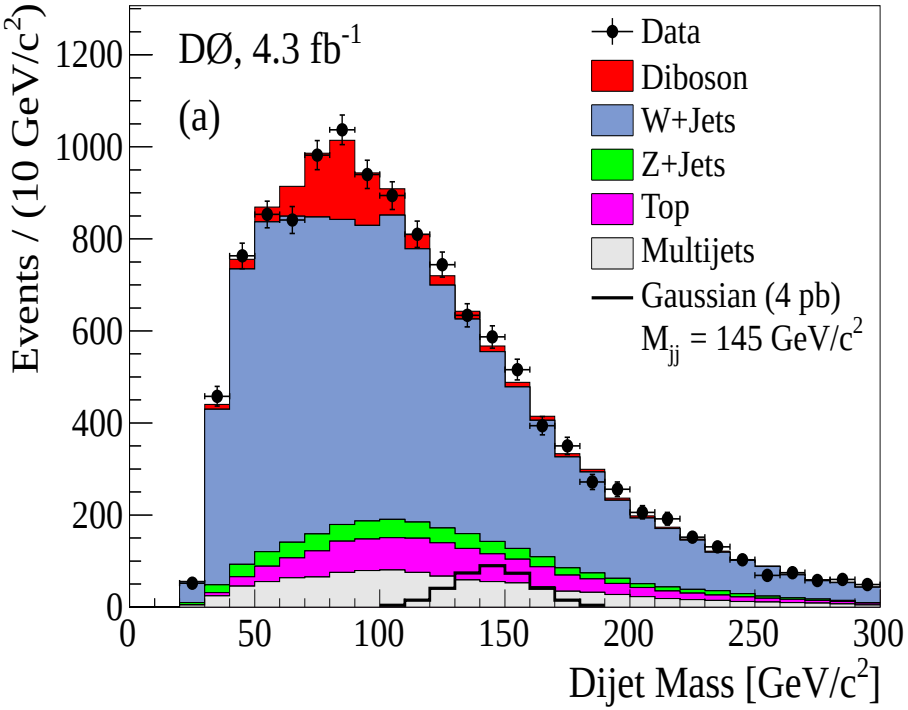
and the CDF W + dijet anomaly

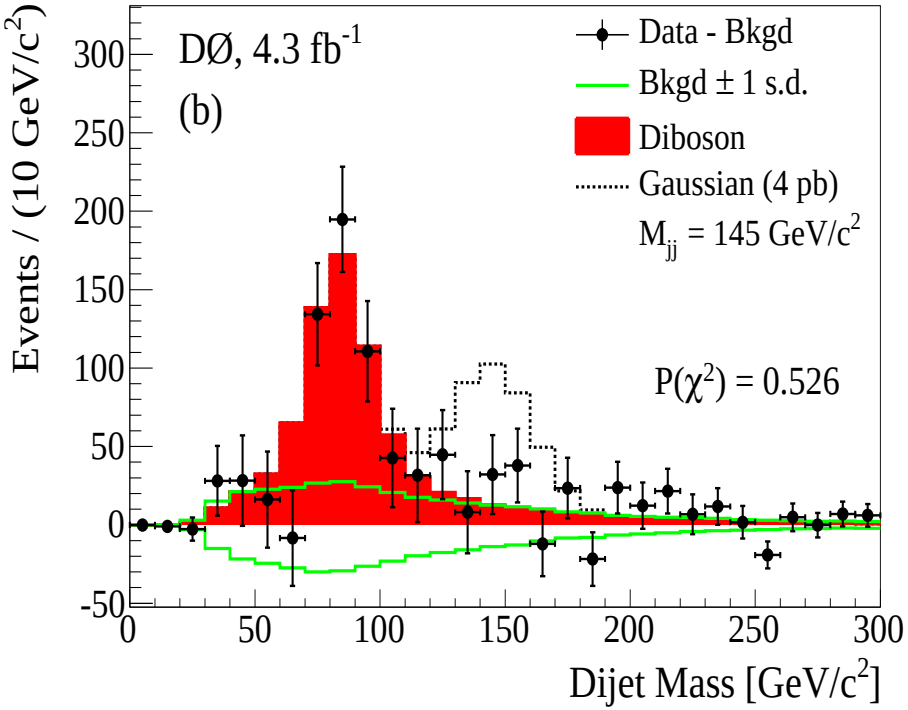
Remember the CDF W+dijet excess?





and the D0 W+dijet non-excess?





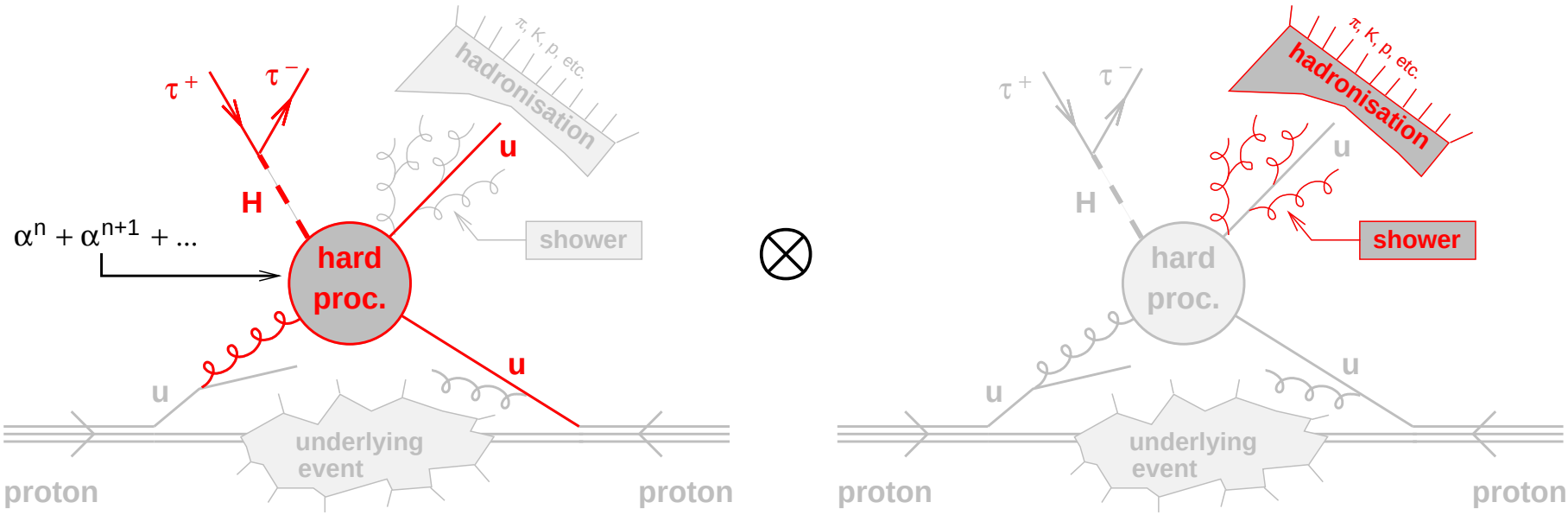
CDF and DØ data are **not** being compared to NLO (=W+partons):

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

In this case hadron-level = Alpgen $\otimes$ Pythia

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

Tree-level (LO) + PS
Different tree-level 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:

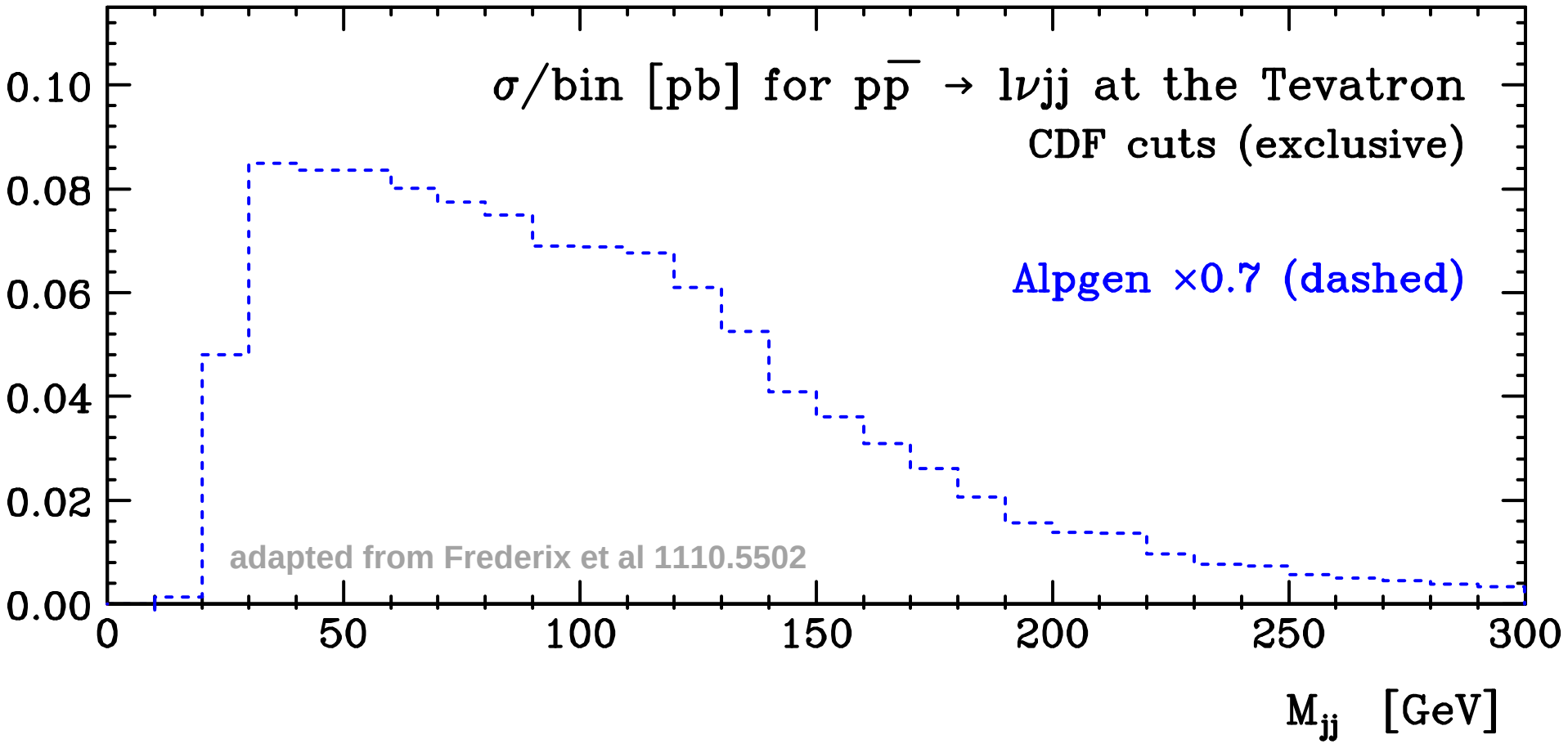
POWHEGBox: $t\bar{t}$+jet, W^+W^++2j, ...

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

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

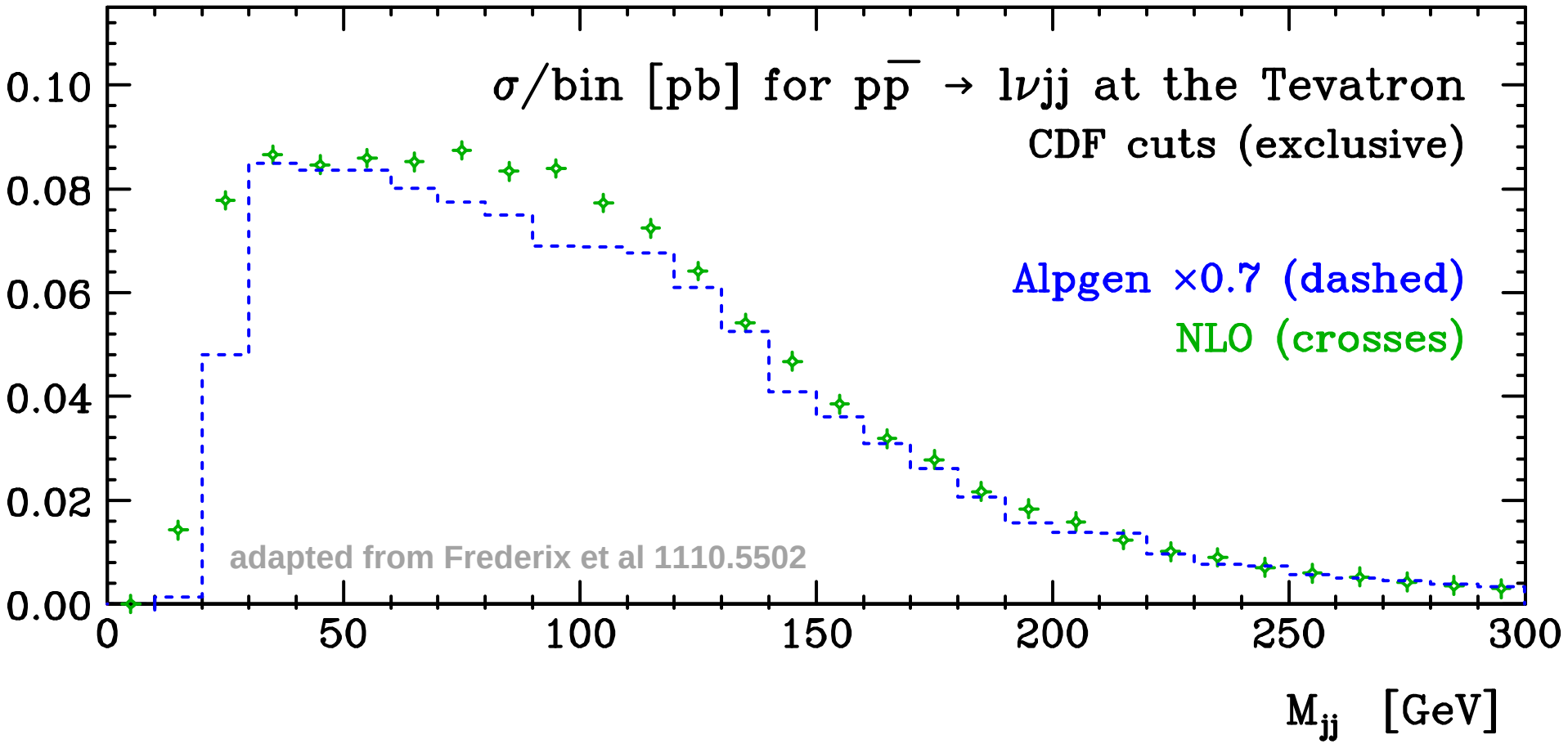
A key application of this progress has been to the W+dijet anomaly

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



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

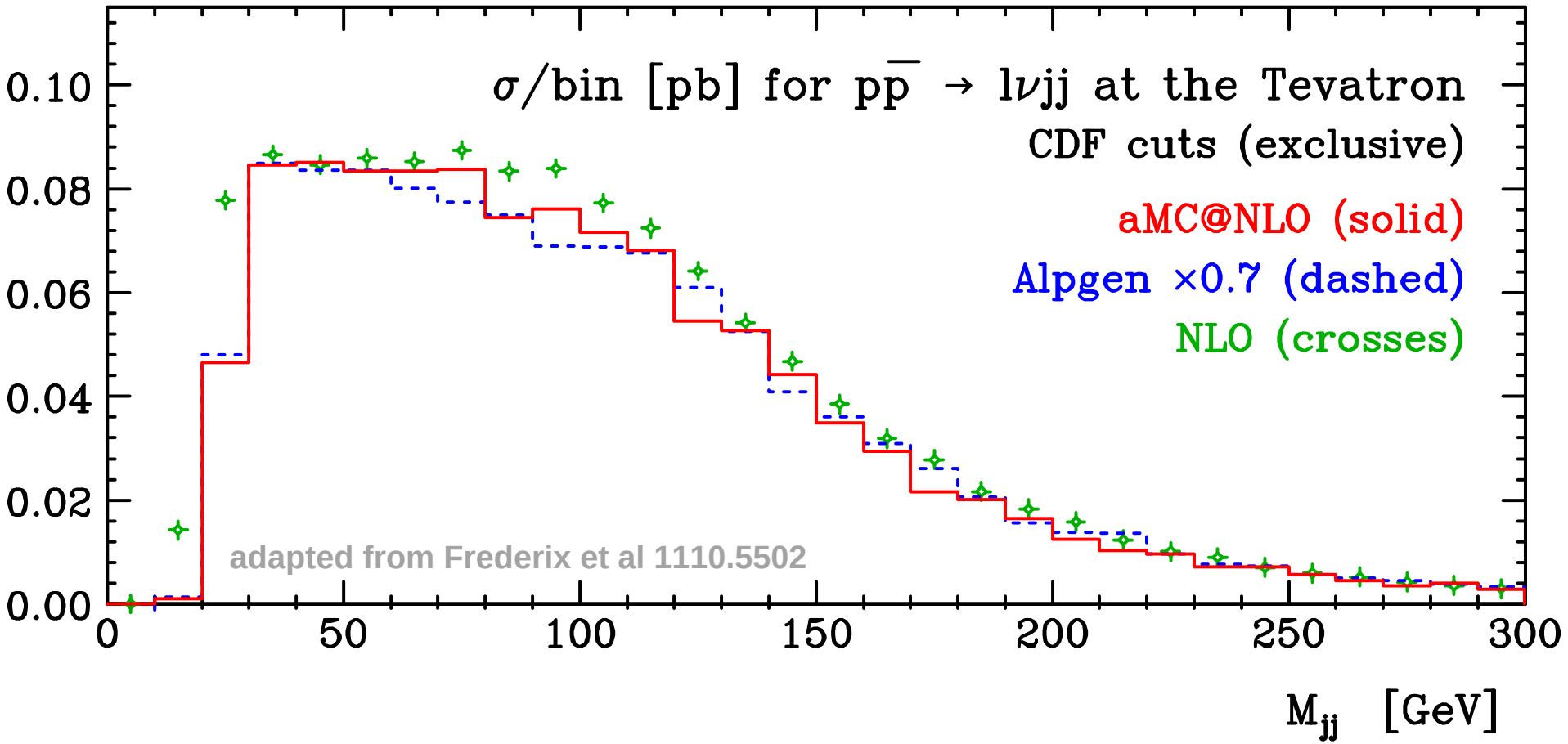
NLO has substantial shape differences: should we worry?



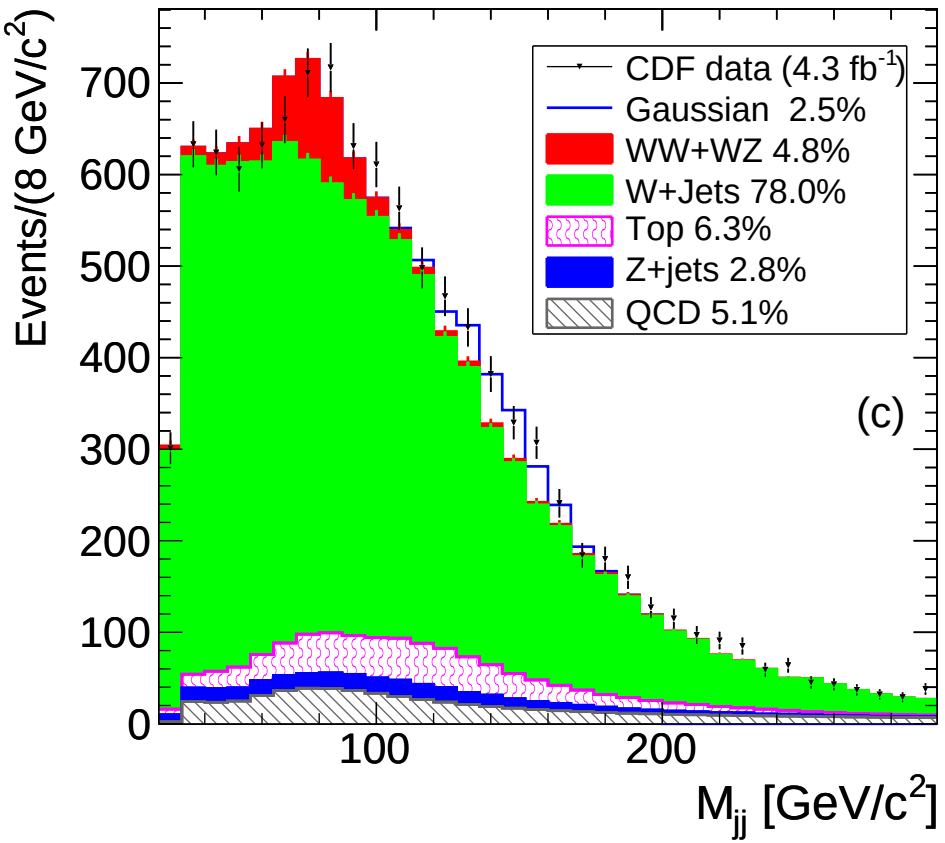
CDF & DØ use Alpgen (scaled): tree level QCD + parton shower

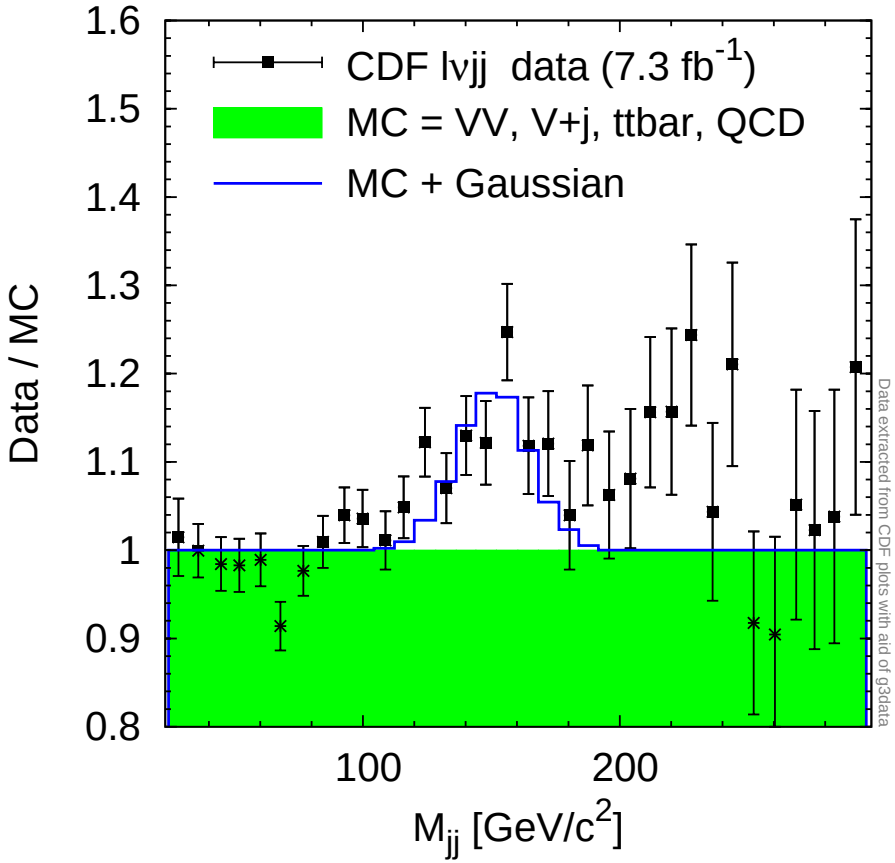
NLO has substantial shape differences: should we worry?

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



Instead of data − MC ⇒ **data/MC**





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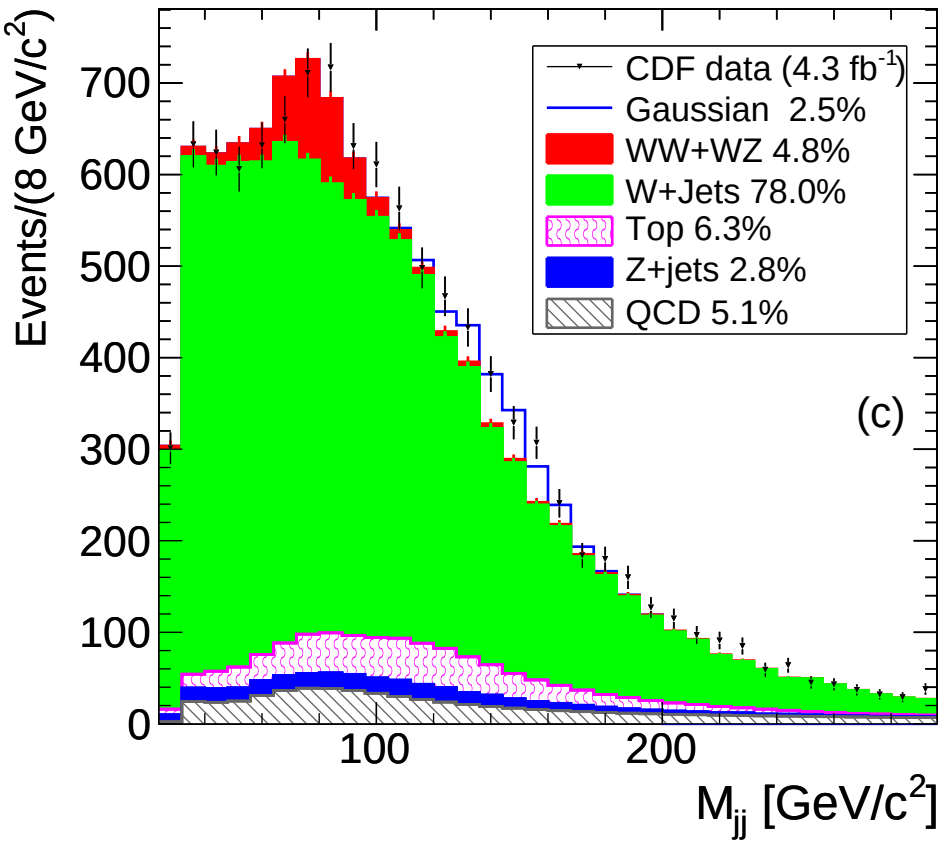

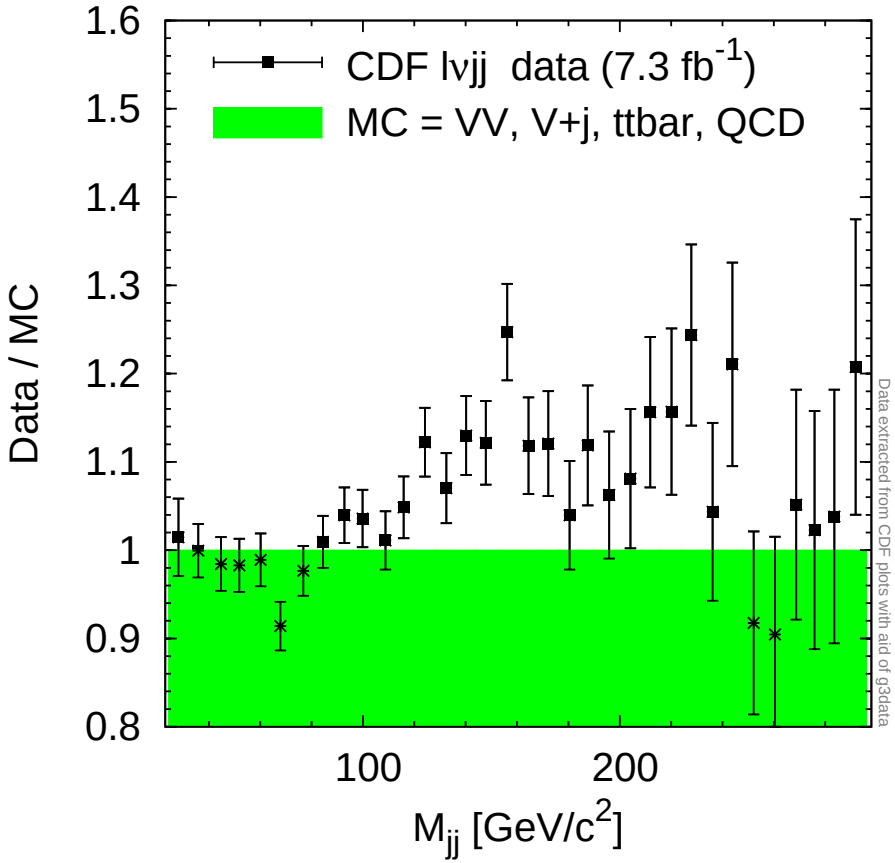

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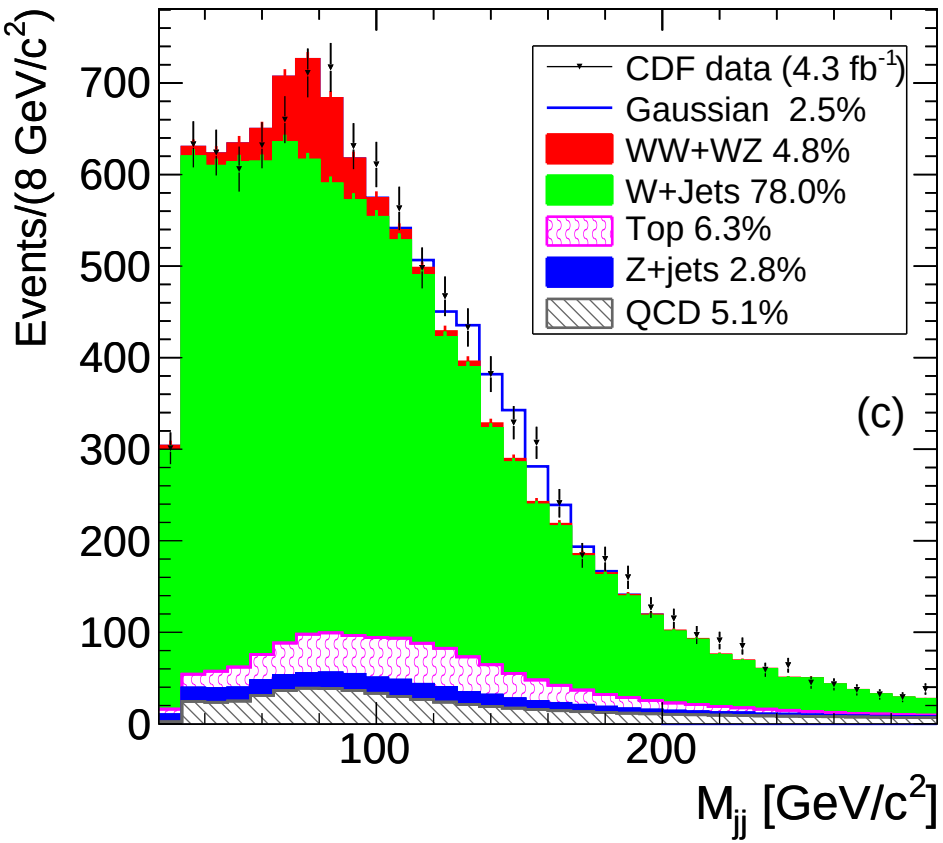
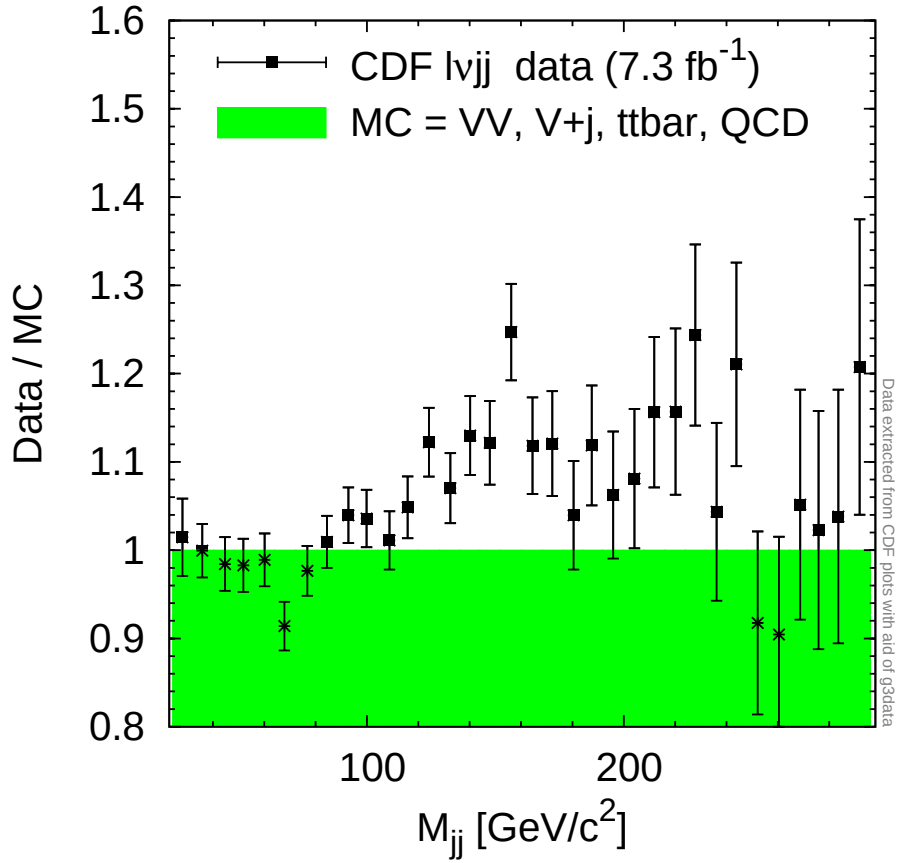
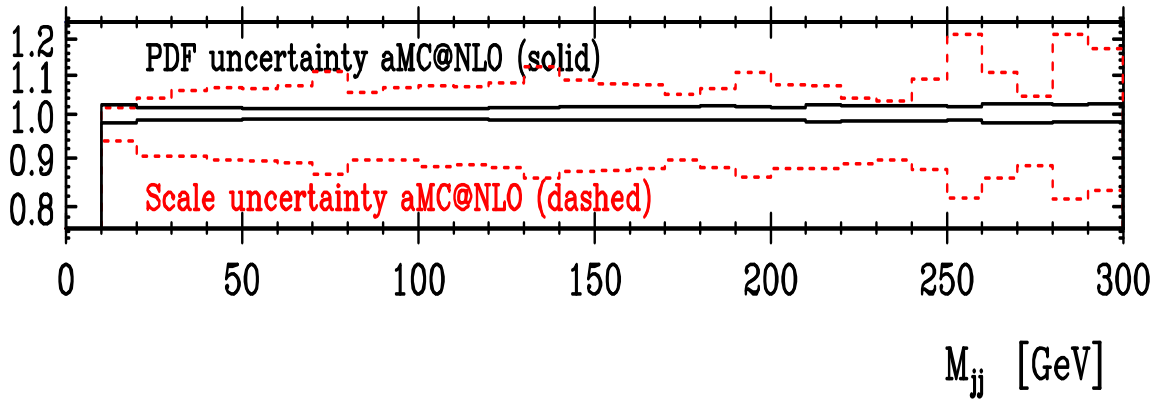
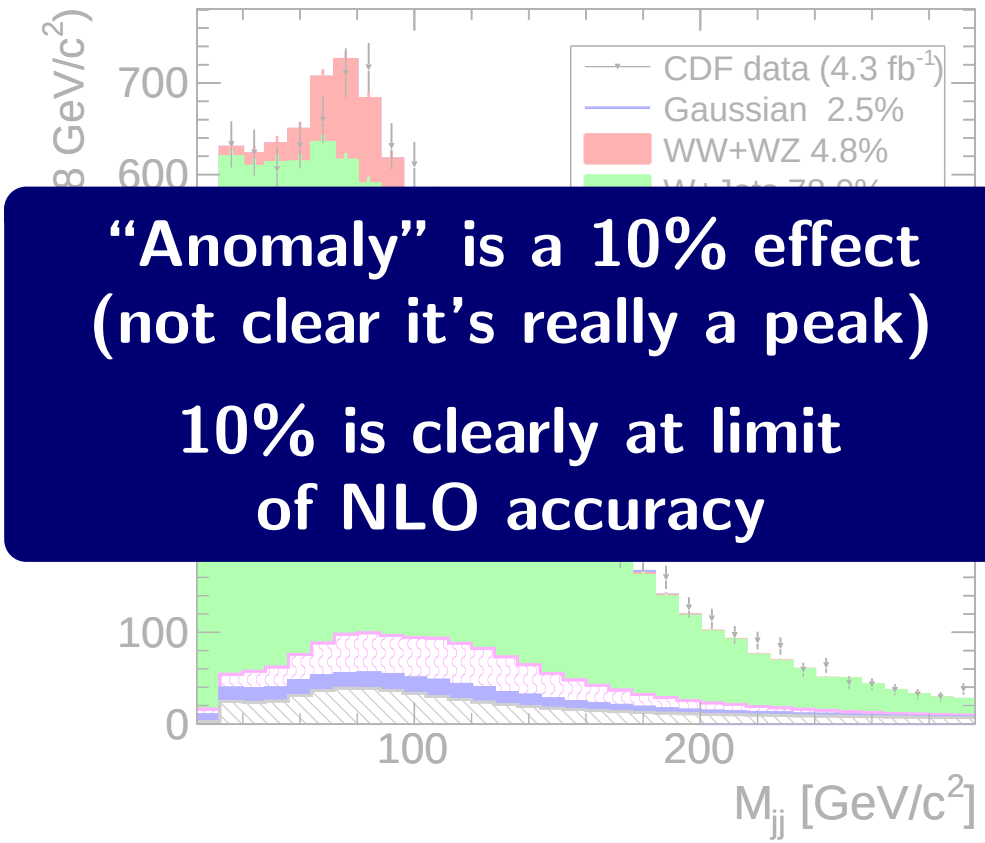




aMC@NLO uncertainties: ⟶

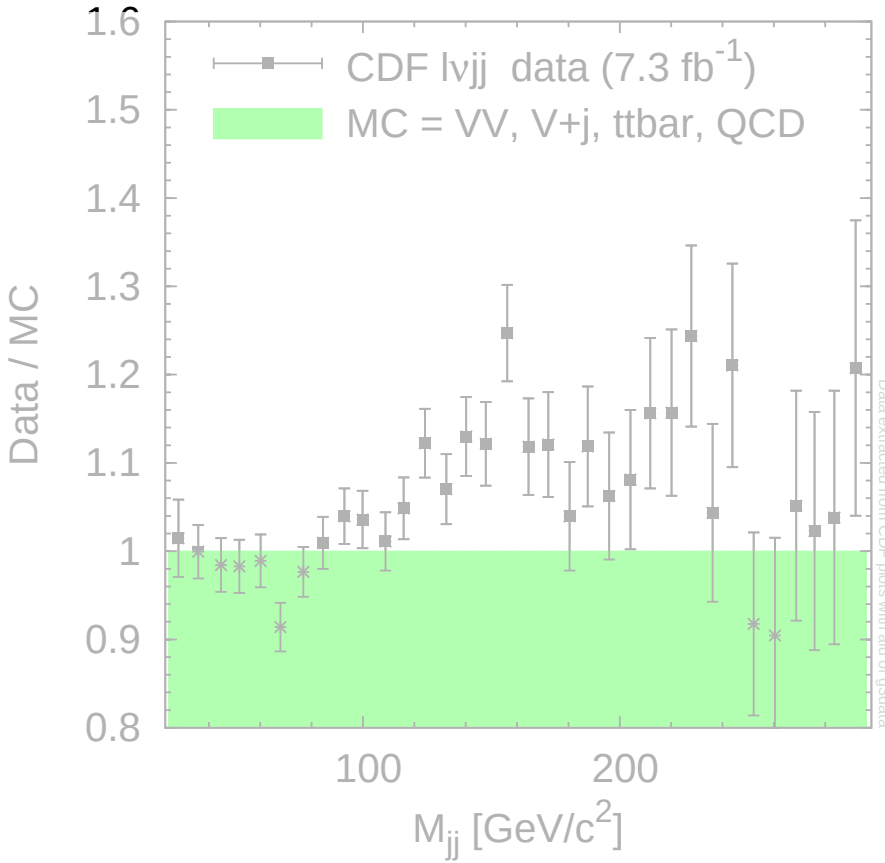


Instead of data – MC ⇒ **data/MC**

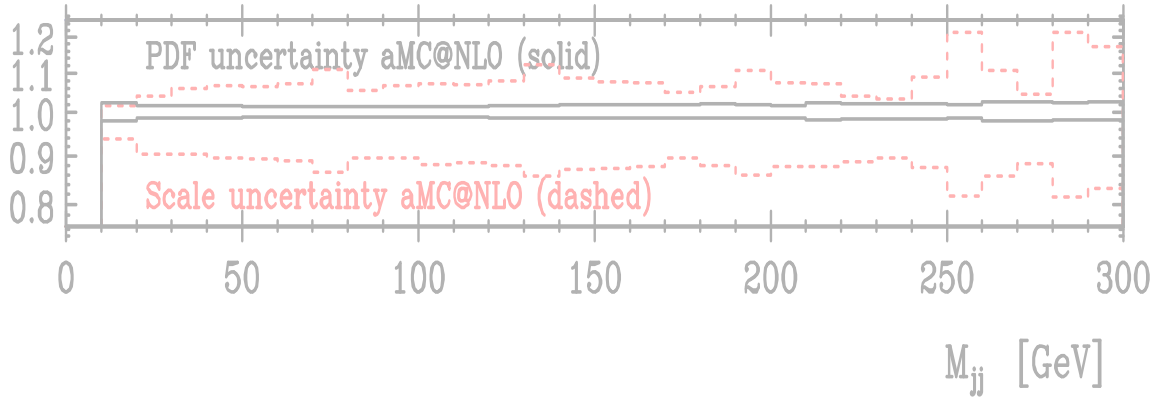


"Anomaly" is a 10% effect (not clear it's really a peak)

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

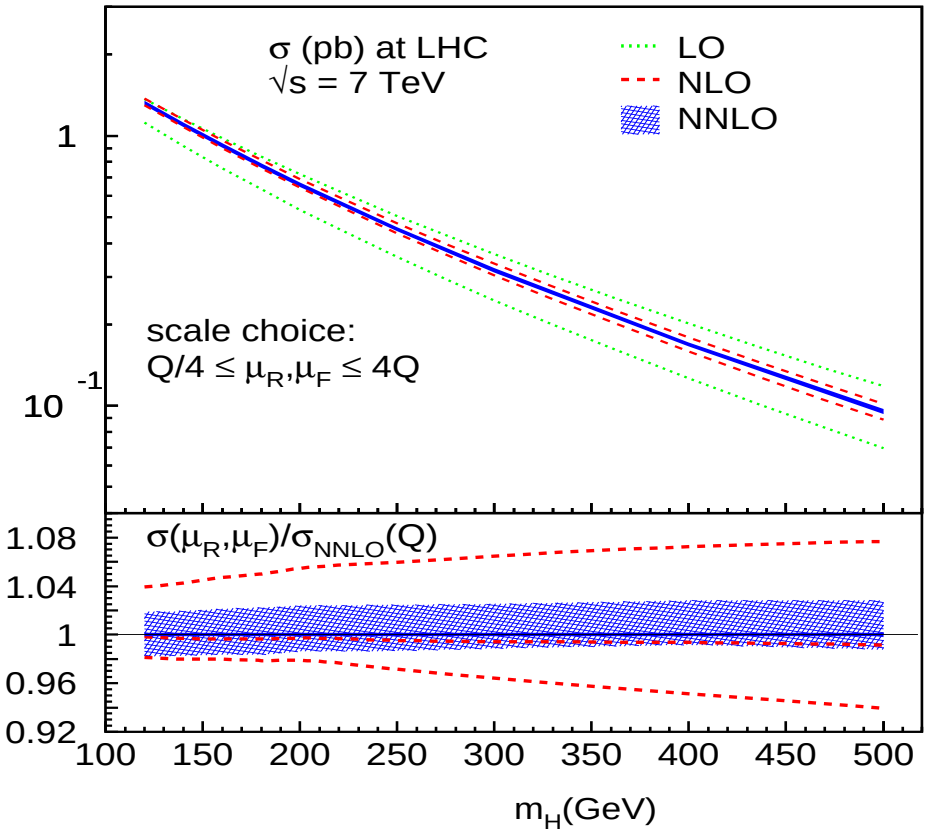
✗ VV, $t\bar{t}$, inclusive jets, etc.

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.

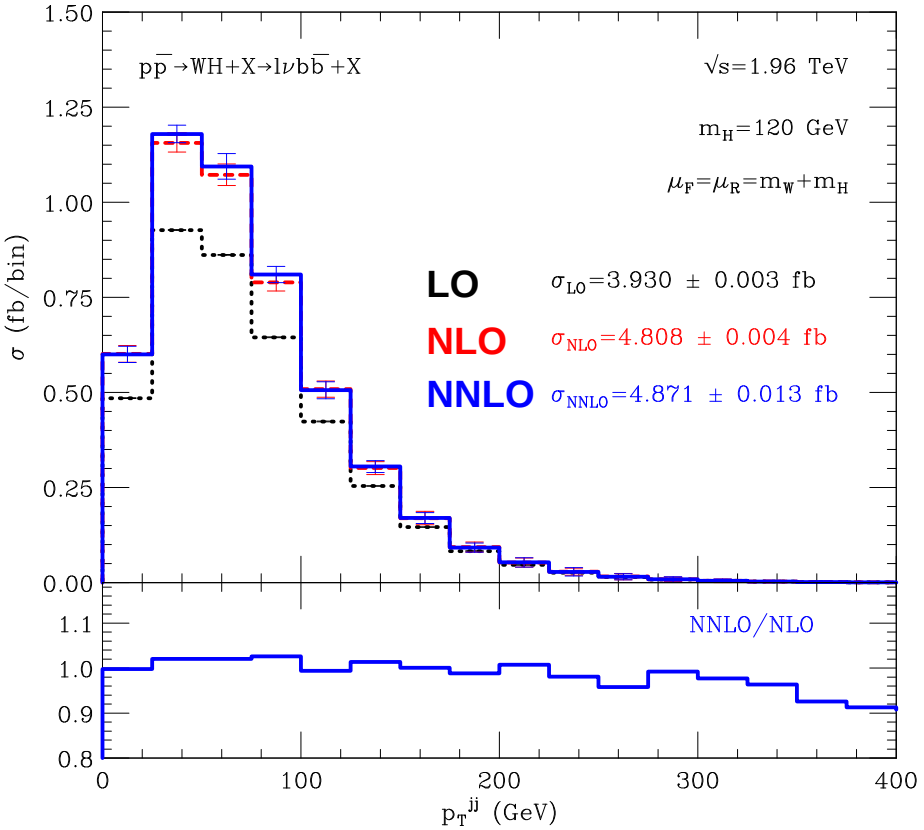
NNLO: crucial for precision

New in 2010: **NNLO VBF→H**



Bolzoni, Maltoni, Moch & Zaro

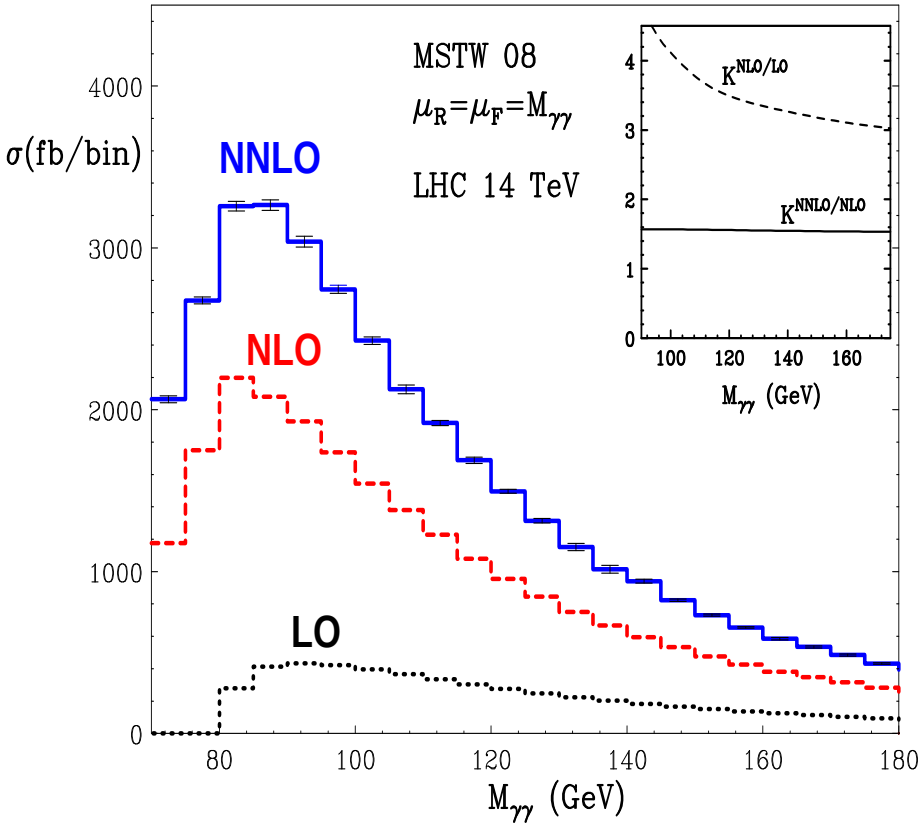
New in 2011: **NNLO WH (differential)**



Ferrera, Grazzini & Tramontano

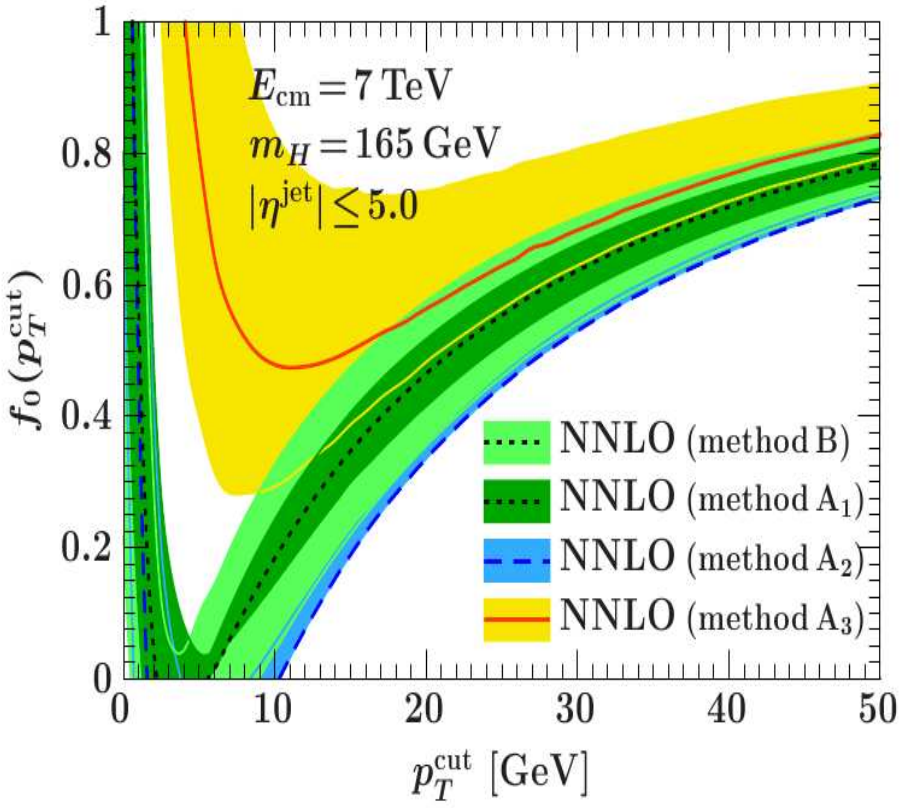
NNLO: yet not always reassuring

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



Catani et al

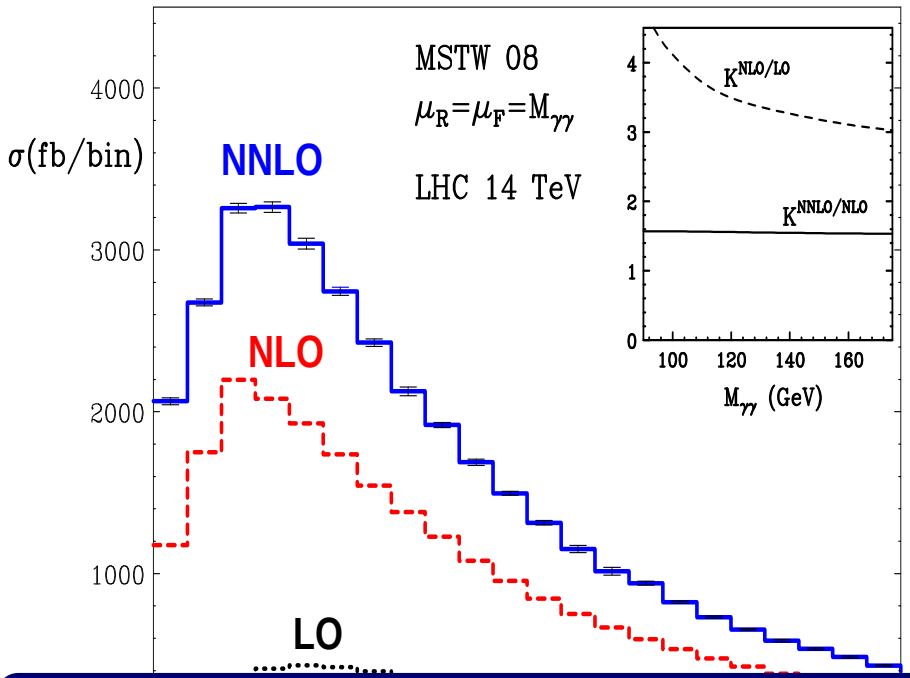
Higgs jet veto efficiency



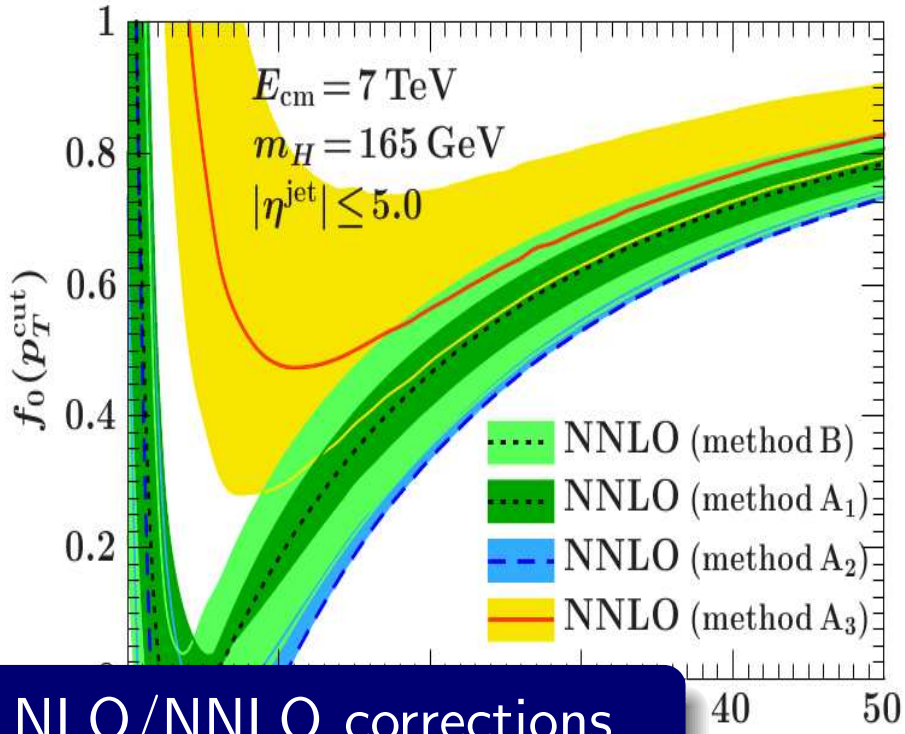
analyses by Stewart & Tackmann '12
+ Banfi, GPS & Zanderighi '12
using FeHiP/HNNLO

NNLO: yet not always reassuring

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 $gg \to H$ case.

mann '12

lerighi '12

/HNNLO

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

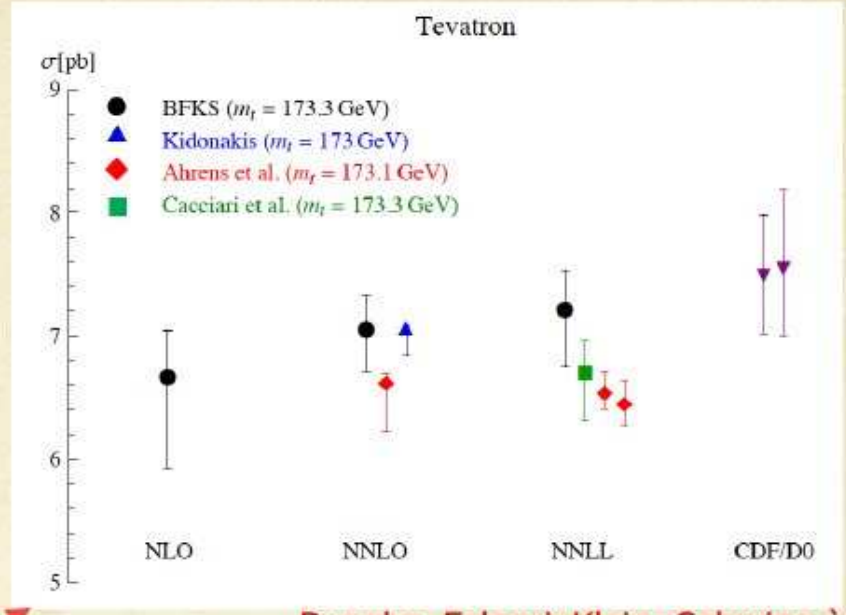
Nason, Dawson, Ellis '88
Beenakker et al '89

... 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)

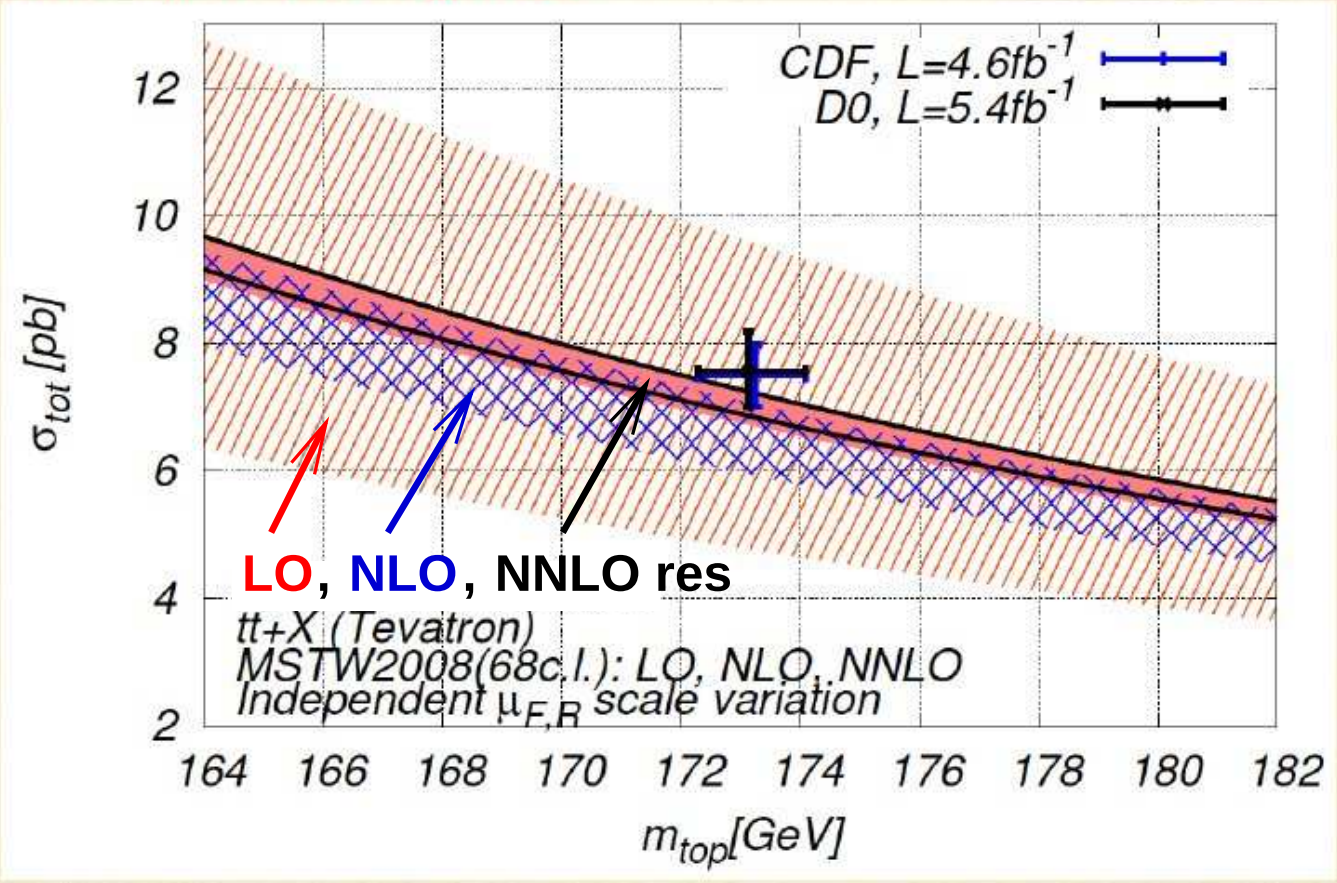
Cacciari, Czakon, Mangano, Mitov, Nason `11

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

Good perturbative convergence:

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

P. Baernreuther et al arXiv:1204.5201



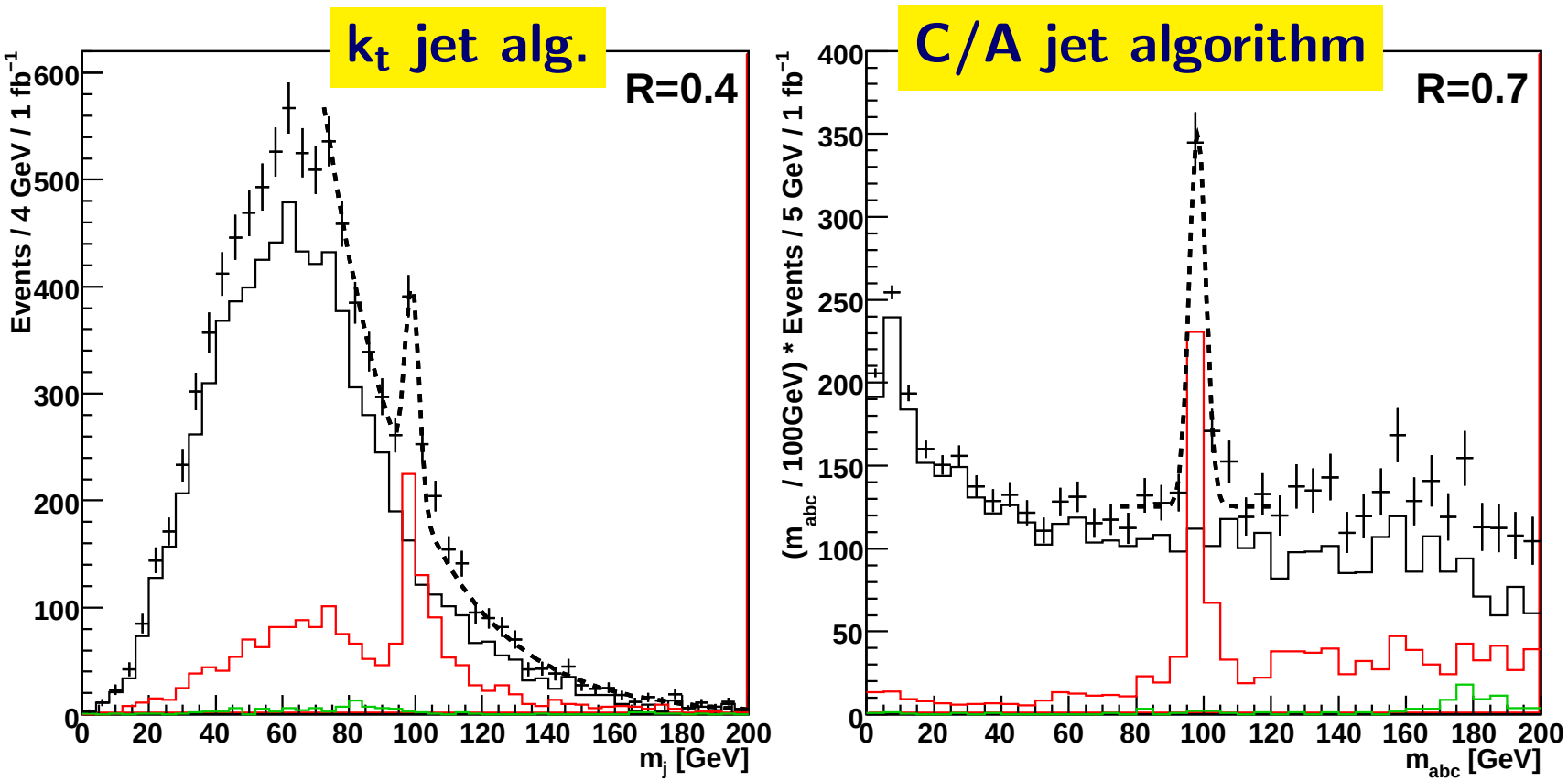
- ✓ Good overlap of various orders (LO, NLO, NNLO).
- ✓ Suggests our (restricted) independent scale variation is good

Looking at data differently

Are we using all possible handles to analyse data?

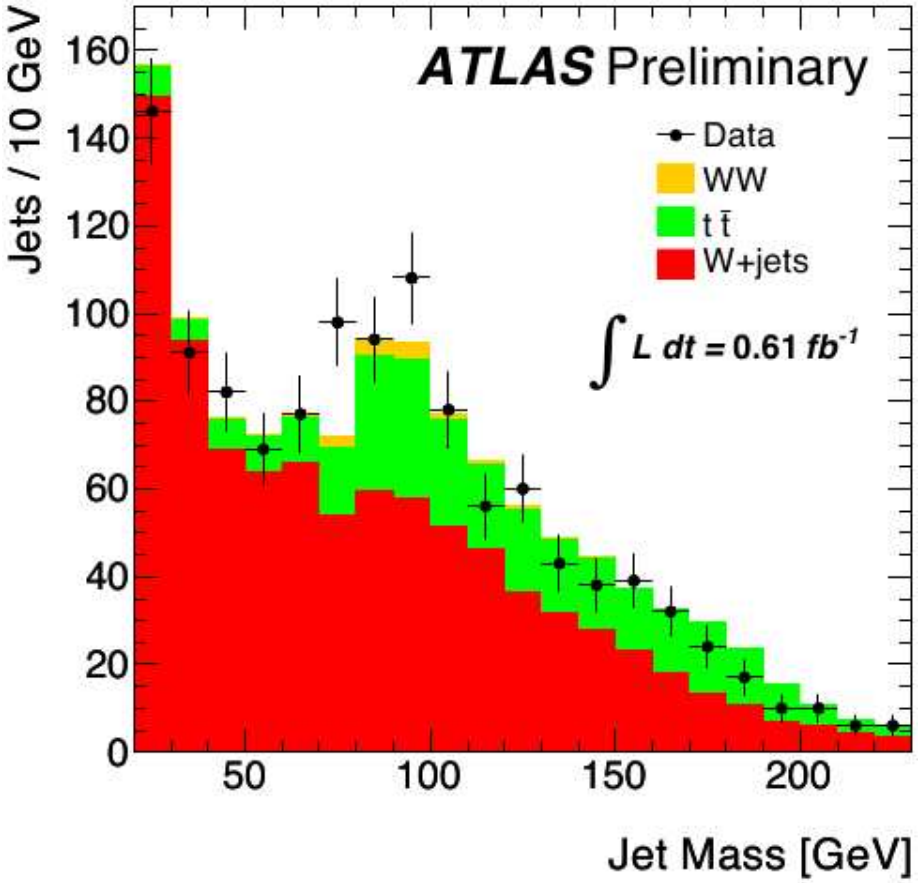
A new sub-field has emerged, "Boost", for finding boosted tops/Z/H/etc.

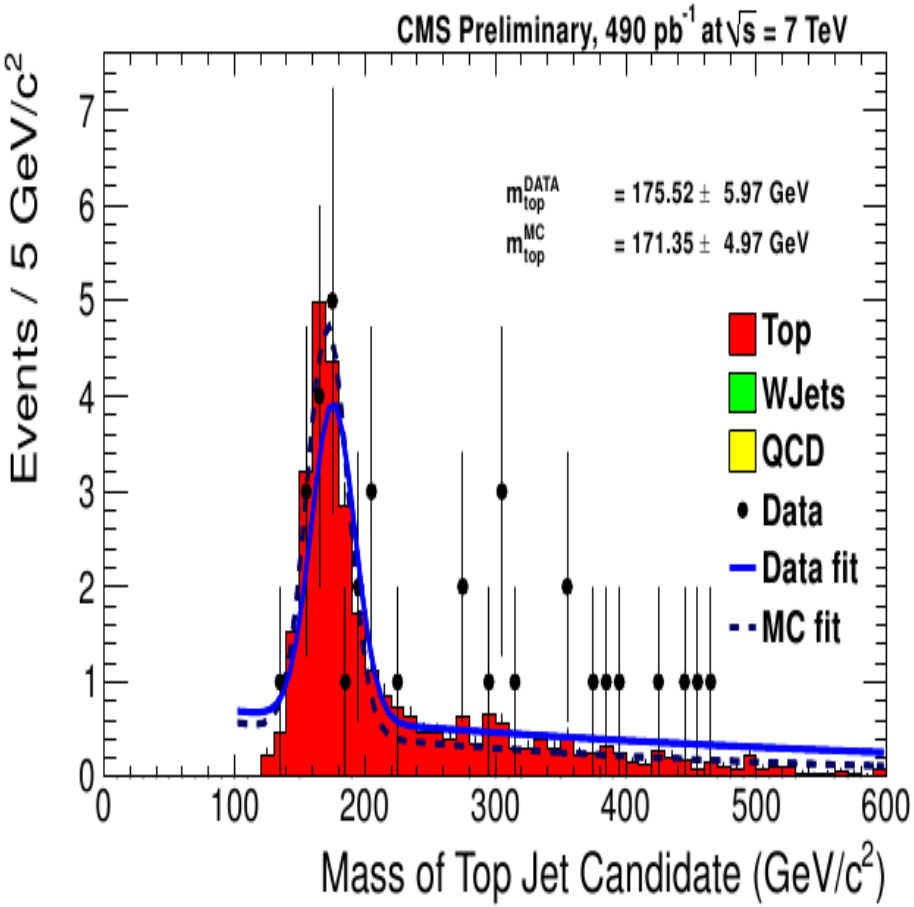
It's teaching us that there are many ways of looking at events, and QCD can educate us about the "best" ways.

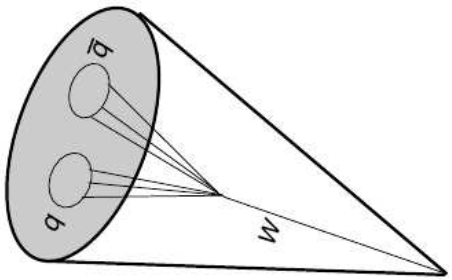


[Search for R-parity violating $\chi^0 \to qqq$; Butterworth, Ellis, Raklev & GPS '09]

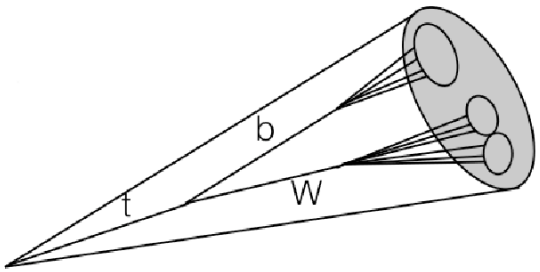
Experimental progress on boosted objects





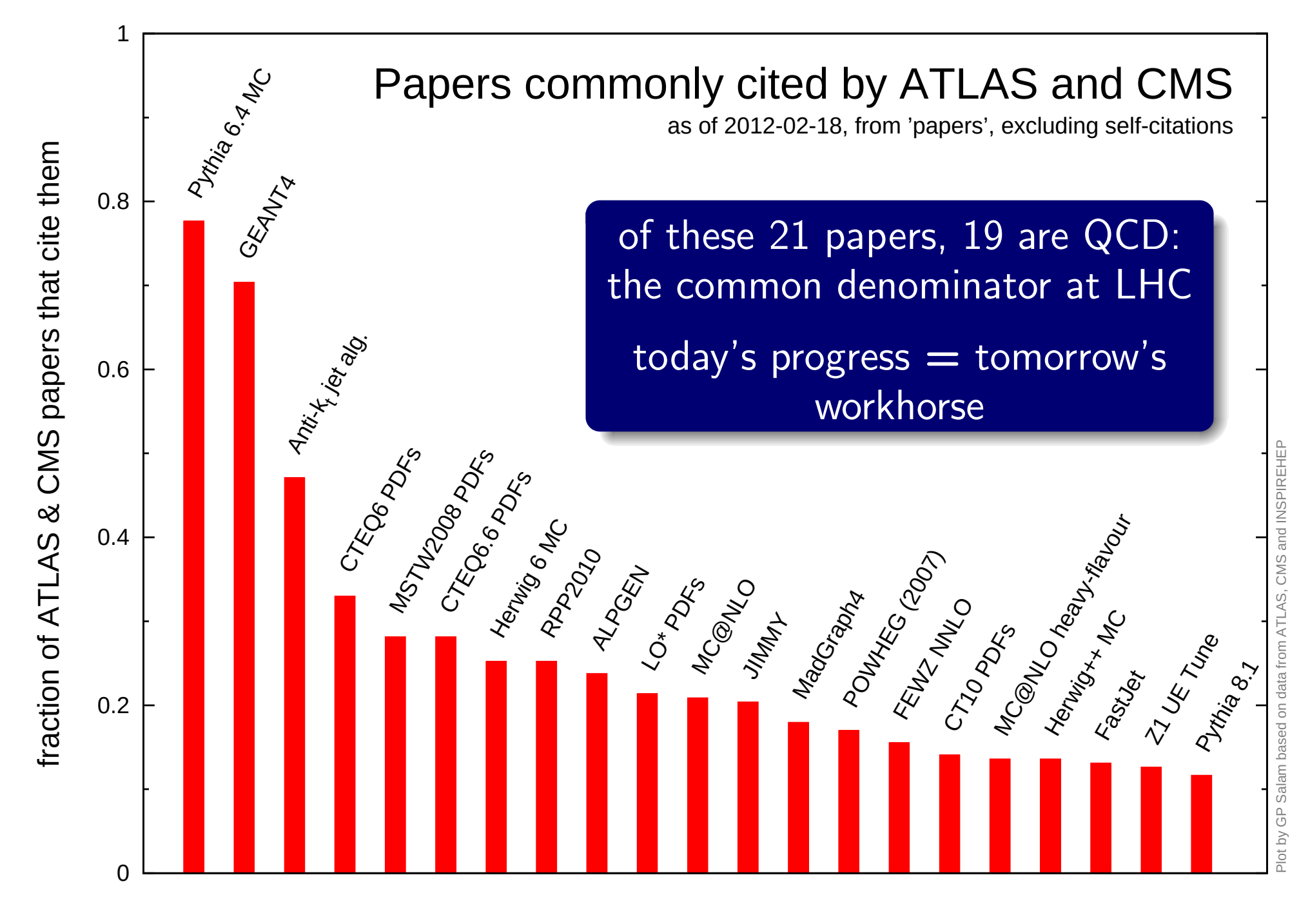


with BDRS two-body tagger



with CMS top tagger

Closing

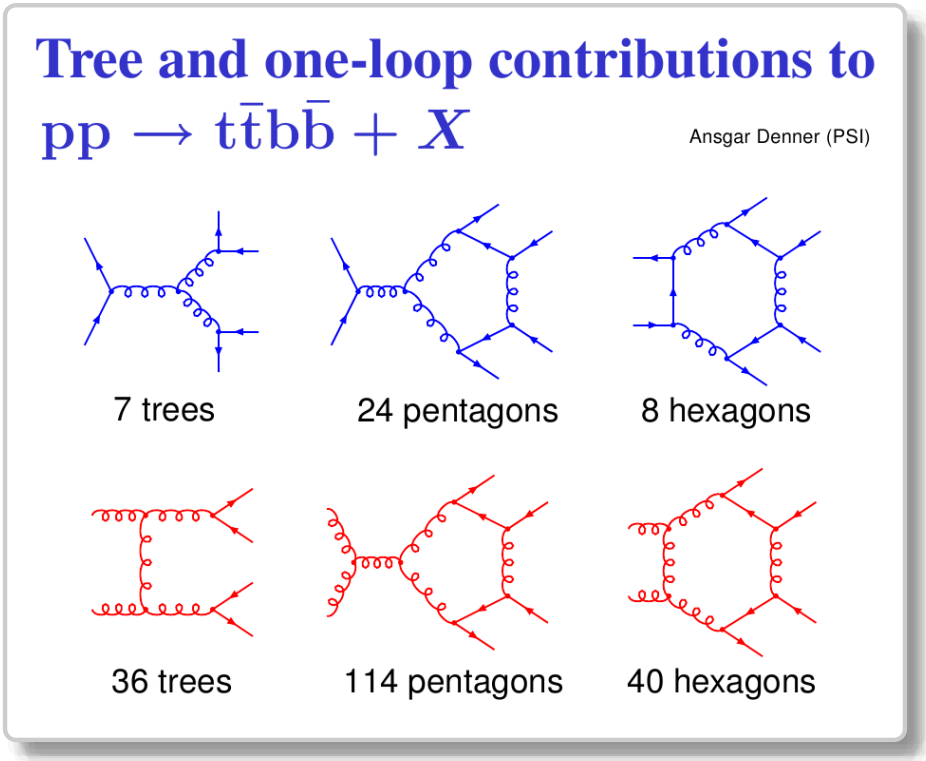

Papers commonly cited by ATLAS and CMS
as of 2012-02-18, from 'papers', excluding self-citations
fraction of ATLAS & CMS papers that cite them
1
0.8
0.6
0.4
0.2
0
Pythia 6.4 MC
GEANT4
Anti-k$_t$ jet alg.
CTEQ6 PDFs
MSTW2008 PDFs
CTEQ6.6 PDFs
Herwig 6 MC
RPP2010
ALPGEN
LO* PDFs
MC@NLO
JIMMY
MadGraph4
POWHEG (2007)
FEWZ NNLO
CT10 PDFs
MC@NLO heavy-flavour
Herwig++ MC
FastJet
Z1 UE Tune
Pythia 8.1
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.

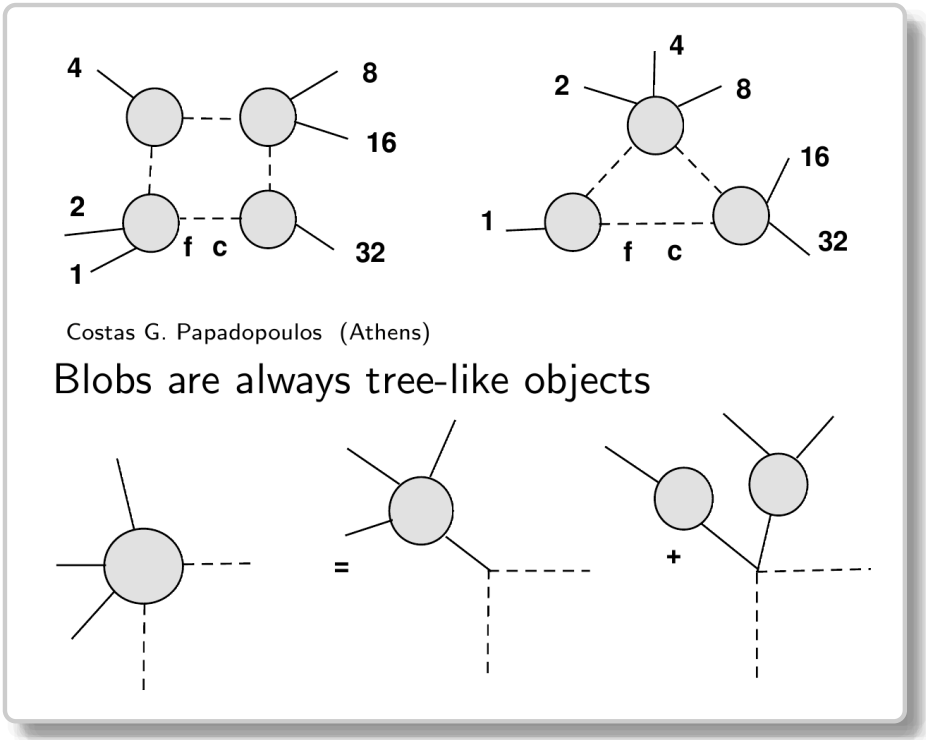
Work hard to reduce integrals to known forms (+ tricks).



Recursive/unitarity methods

Assemble loop-diagrams from individual tree-level diagrams.

Build trees by sticking together simpler tree-level diagrams



NLO bottleneck: 1-loop part

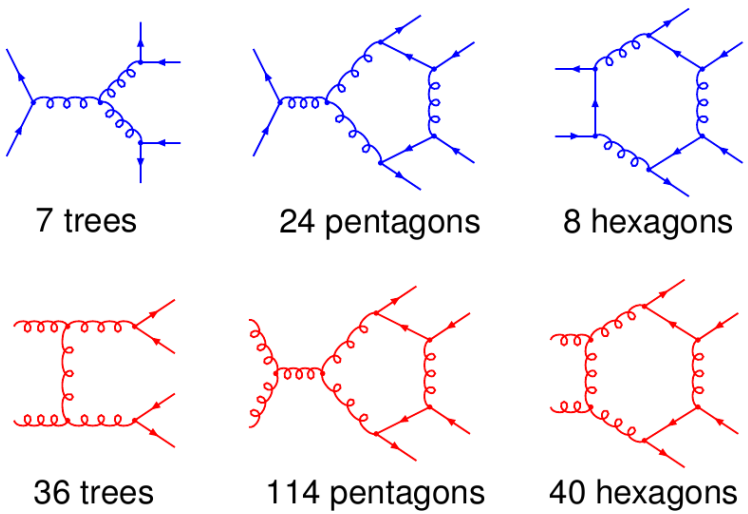
Traditional

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

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

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

Ansgar Denner (PSI)



Recursive/unitarity methods

Assemble loop-diagrams from individual tree-level diagrams.

Build trees by sticking together simpler tree-level diagrams

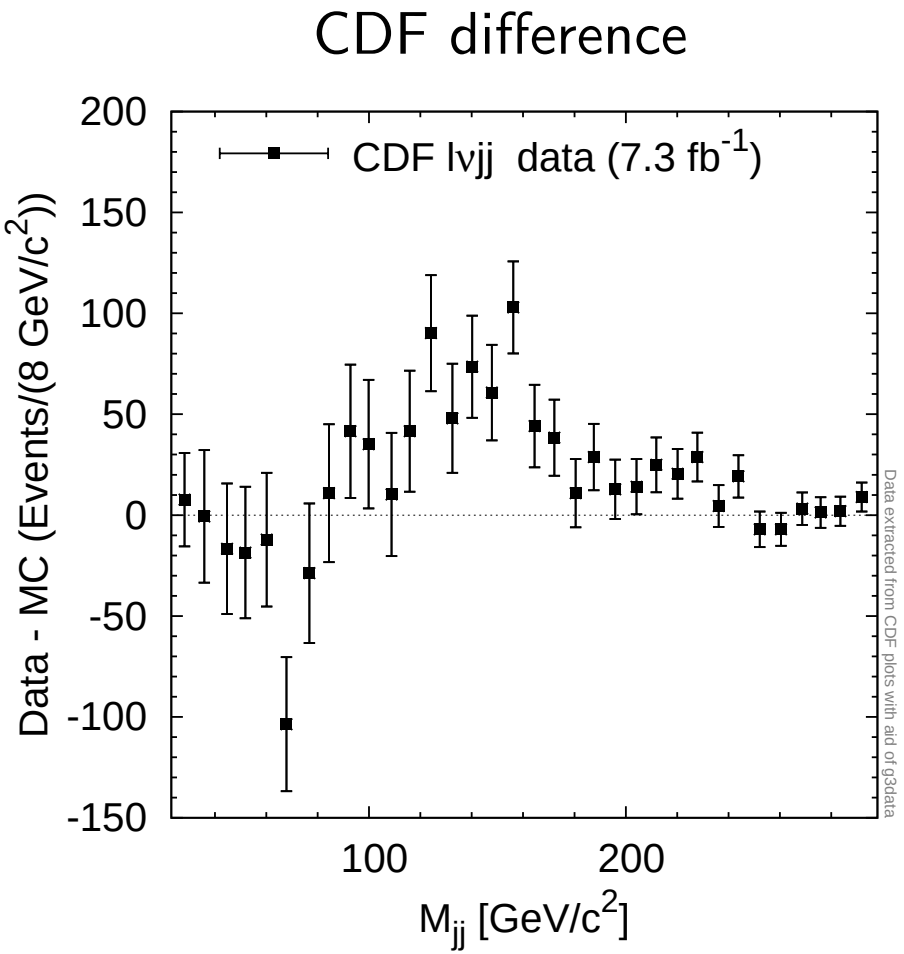
Some main ideas:

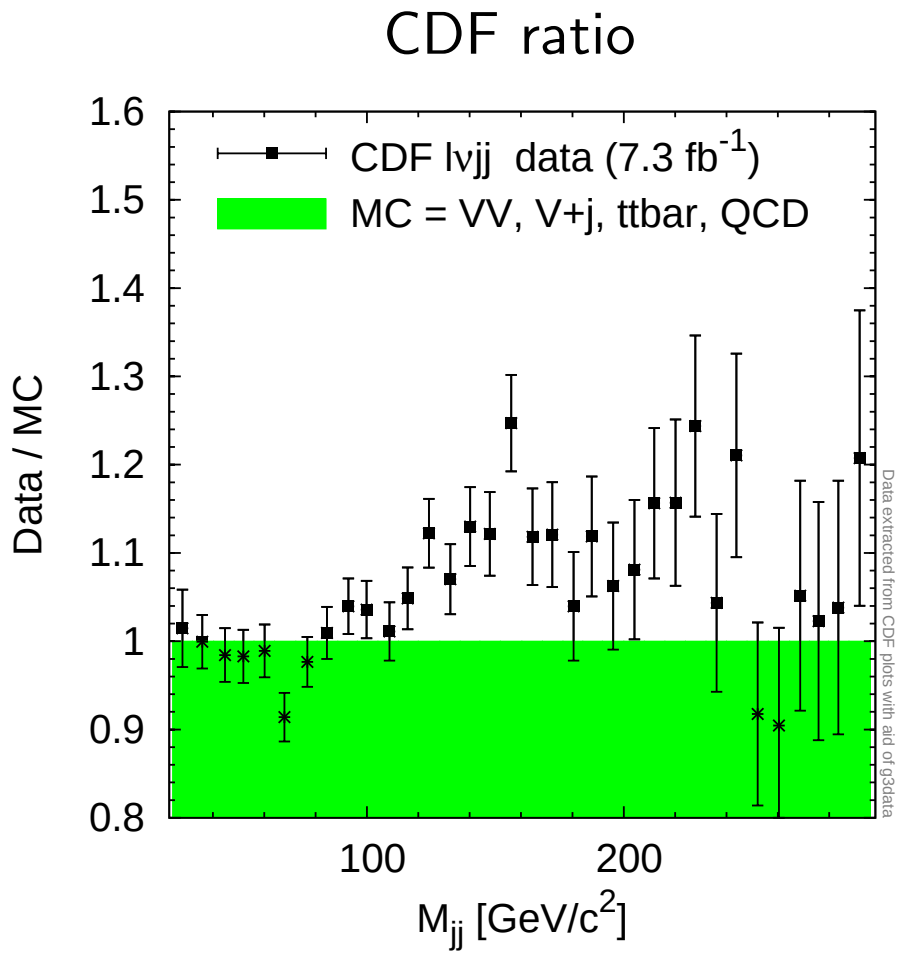
Bern, Dixon & Kosower '93
[sewing together trees]

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

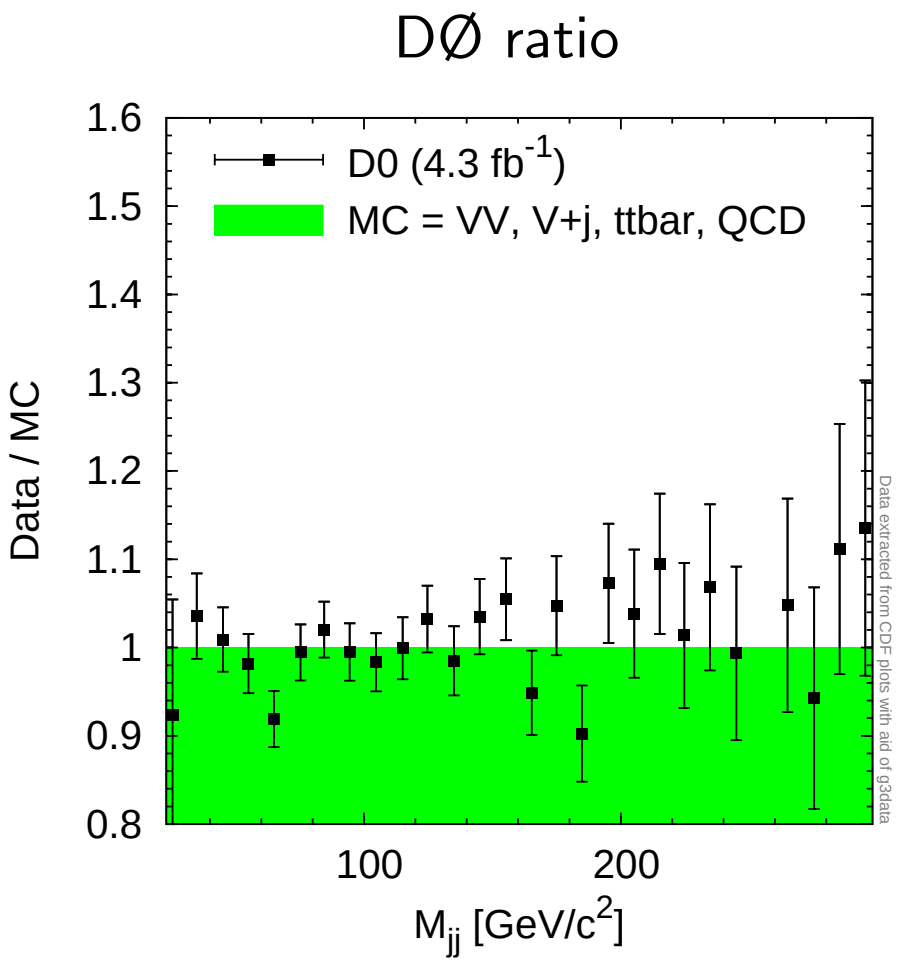
Ossola, Pittau & Papadopoulos '06
[handful of loop momentum choices give full amplitude]

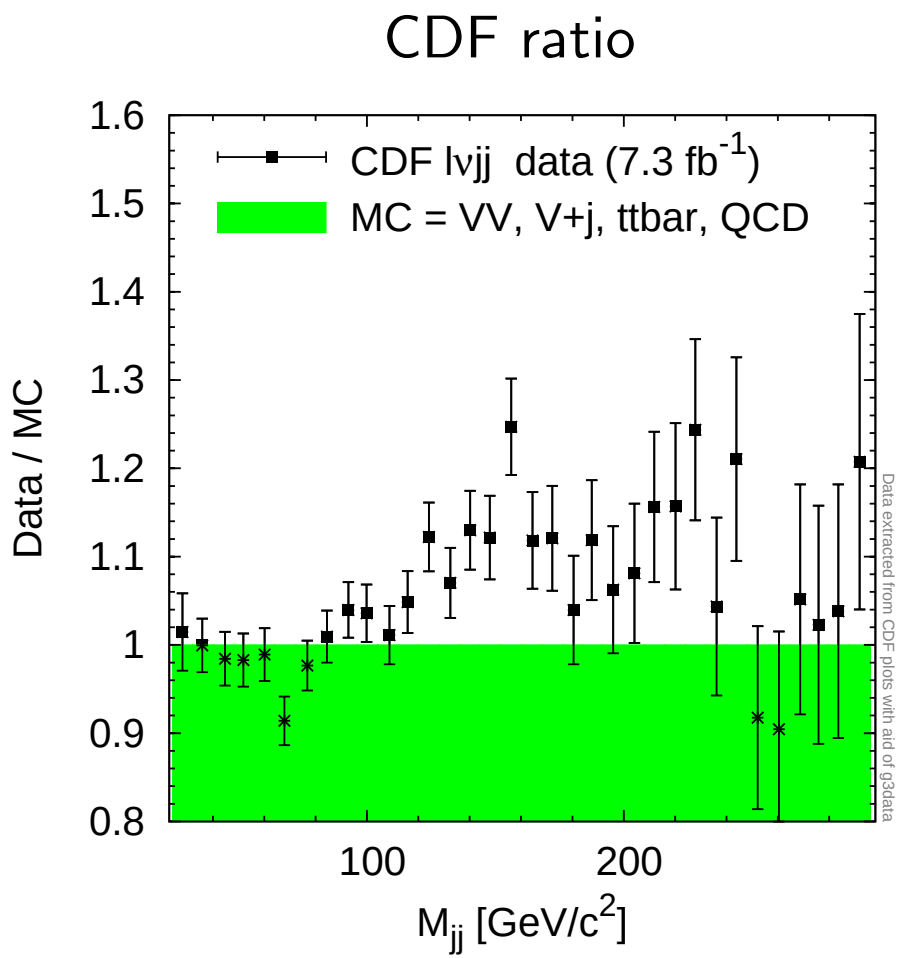
CDF Wjj: difference wrt MC v. ratio to MC

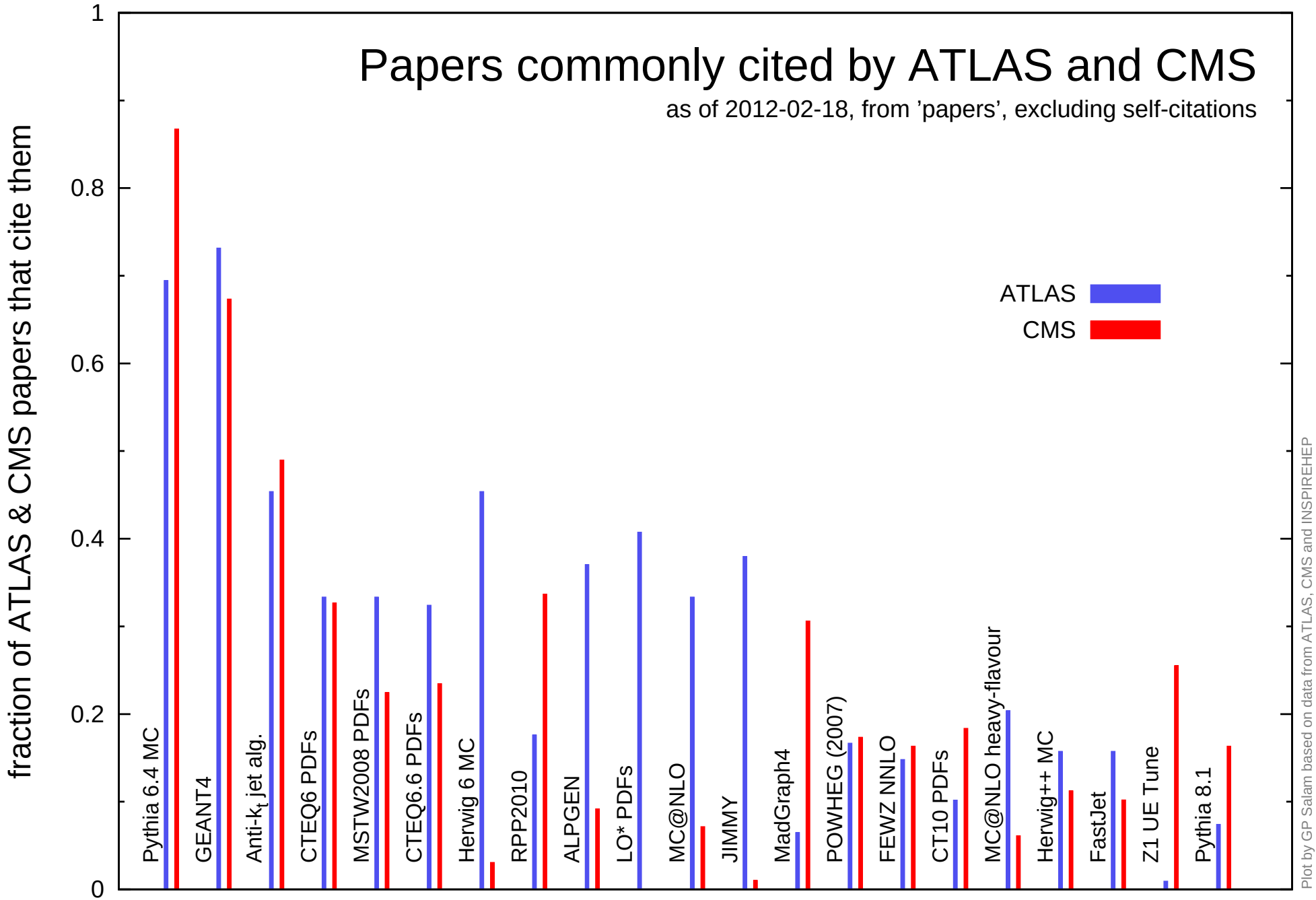




Wjj ratio to MC, DØ v. CDF



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