Perturbative QCD for the LHC

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As the LHC programme gets going, what is the status of our QCD tools?

Are they where we thought they might be?

Are they where we'd *like* them to be?

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Yes! With several major milestones reached in the past two years.

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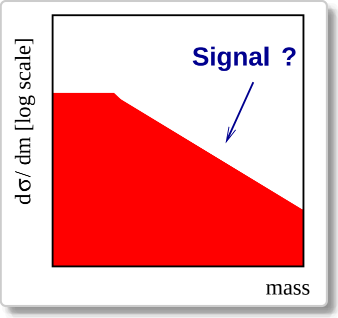
Yes! With several major milestones reached in the past two years.

Are they where we'd *like* them to be?

There's still ample room for progress.

What roles for QCD at the LHC?



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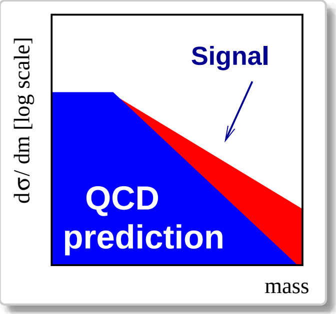

Telling us what the background is, so we can see any excess

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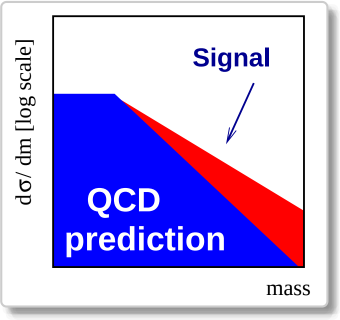

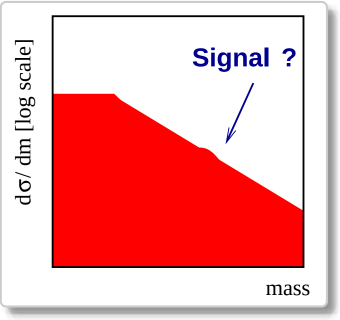

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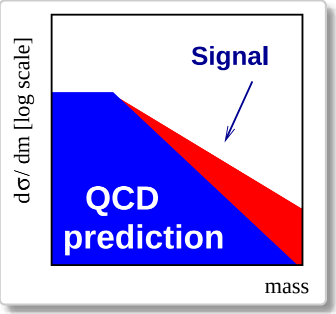

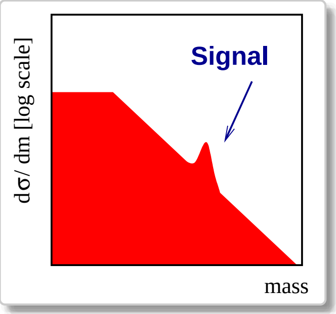

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Teaching us how to reduce the background, sharpen the signal

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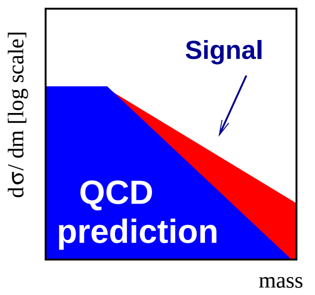

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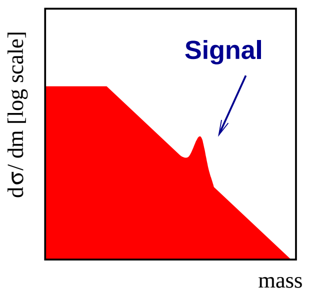

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Constraining any discoveries:

mass

couplings

etc.

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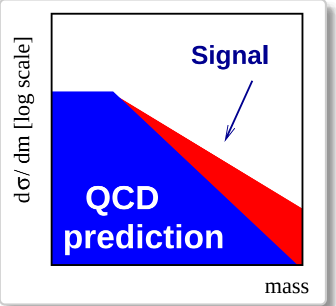

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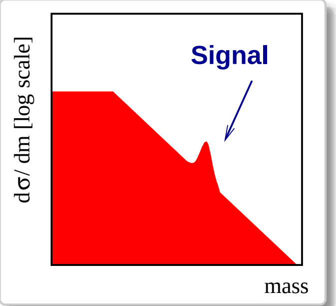

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Constraining any discoveries:

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And as input to nearly all measurements

Monte Carlos

Monte Carlo — *NLO* — *NNLO, etc.* — *Jets*

The most pervasive role of QCD at LHC

Every paper that comes out from the LHC pp physics programme will involve the use of one or more QCD-based parton-shower Monte Carlo event generators: Pythia, Herwig, Sherpa, . . .

For simulating physics signals.

For simulating background signals.

For simulating pileup.

As input to simulating detector respone.

Generations of generators

Original Fortran (77) Generation

Has served us well since 1980's, but now reaching end-of-life

- Herwig 6.5: 11 authors, 60k lines
- Pythia 6.4: $3 + N$ authors, 80k lines — Still the most widely used
- Supplemented with Alpgen/Madgraph (tree-level ME), or MC@NLO/POWHEG (NLO)

New (C++) Generation

After 5–10 years' work, codes now entering early adulthood.

- HERWIG++ 2.4: 14 authors, 250k lines + ThePEG, 3 authors, 110k lines
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F77 → C++; but also improved physics

Pythia 6.4 → Pythia 8.1

- New p_t ordered shower (mass-ordered shower removed)
- Numerous new features for multiple interactions

Herwig 6.5 → Herwig++ 2.4

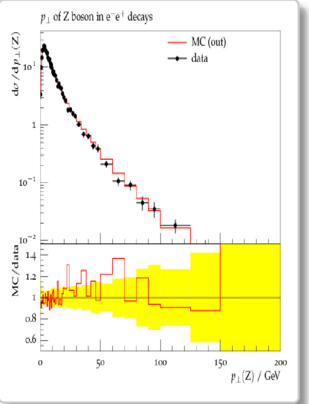
- New angular ordered shower, including better mass treatment
- Several processes at NLO with POWHEG
- Incorporates multiple interactions model

[no F77 version] → **Sherpa 1.2**

- Dipole shower
- Efficient multileg matrix-elements (COMIX), CKKW matching
- Now has own multiple interactions, hadronisation, etc.

$Z\ p_t$ distribution v. Tevatron data

PYTHIA 8



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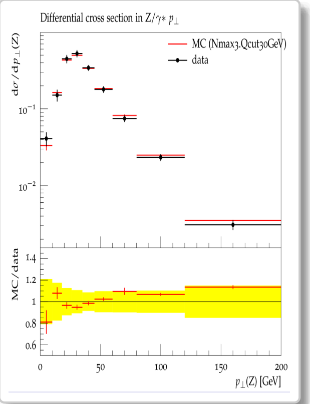
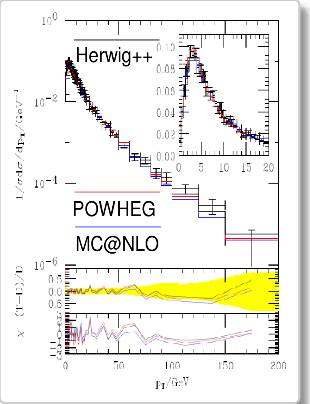


HERWIG++ 2.4



All 3 show good agreement for this basic observable

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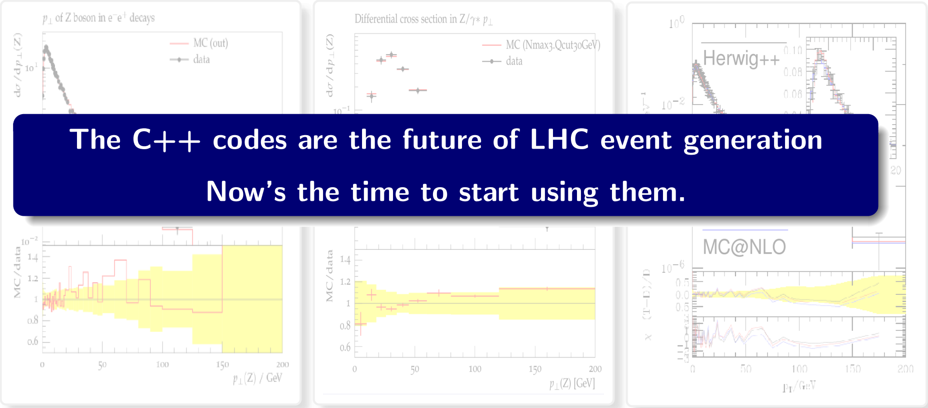

The C++ codes are the future of LHC event generation

Now's the time to start using them.

All 3 show good agreement for this basic observable

NLO calculations

How accurate is perturbative QCD?

$$\sigma = c_0 + c_1\alpha_s + c_2\alpha_s^2 + \ldots$$

$$\alpha_s \simeq 0.1$$

That implies LO QCD (just c_0) should be accurate to within 10%

It isn't

Need NLO in order to have a good guess at normalisation and uncertainties in backgrounds

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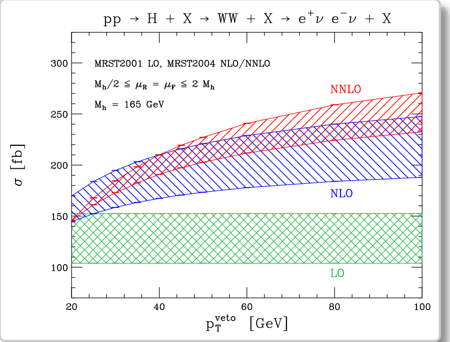

Anastasiou, Melnikov & Petriello '04
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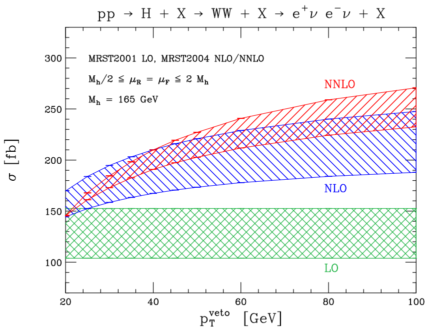

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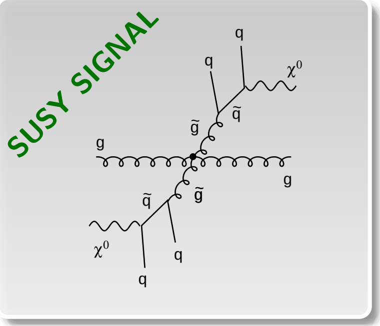
One of the motivations for NLO multijet



SUSY particles often have cascade decays
$\to$ multijet + Missing E_T + X

Signal is broad excess ($\sim$ $\times 5$) over expected (LO) background

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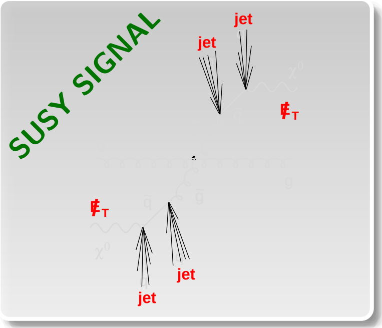

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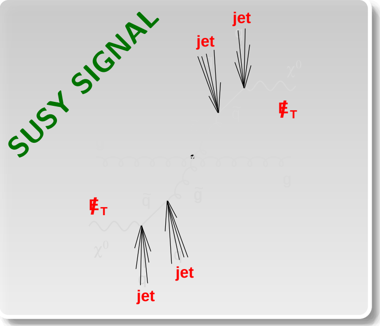

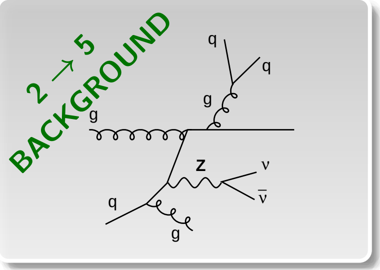

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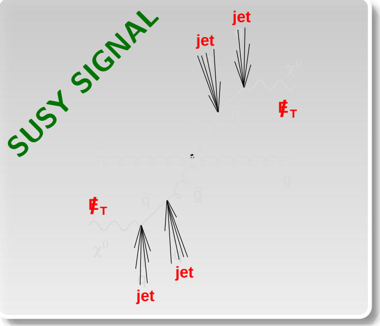

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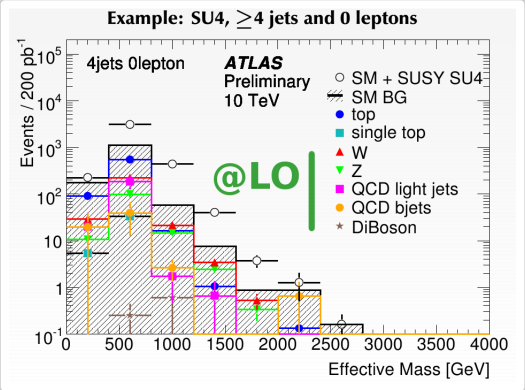
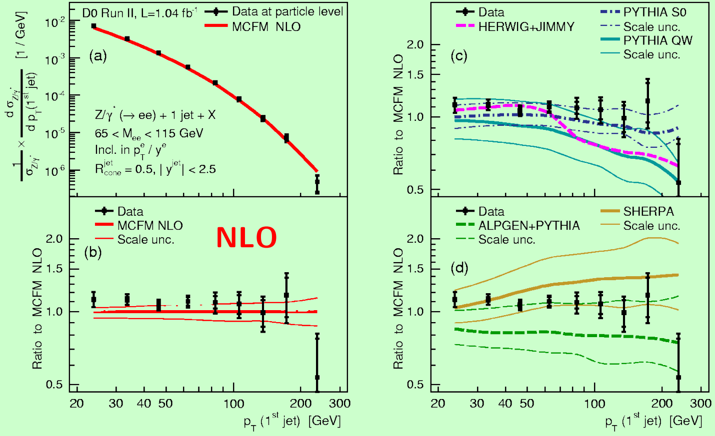


One of the motivations for NLO multijet

Z + jet (p_t of jet)



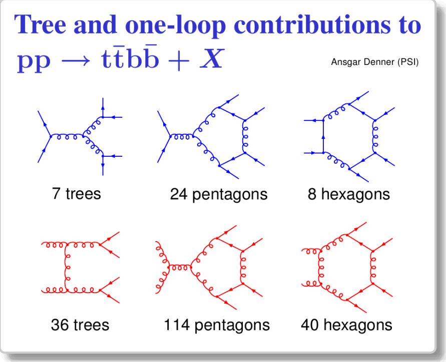
NLO usually gets normalisation & shape correct

NLO bottleneck: 1-loop part

Traditional

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

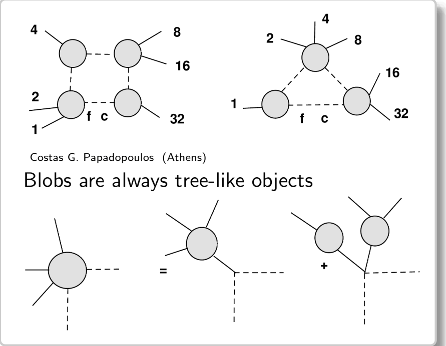
Work hard to reduce integrals to known forms (+ tricks).



Recursive/unitarity methods

Assemble loop-diagrams from individual tree-level diagrams.

Build trees by sticking together simpler tree-level diagrams



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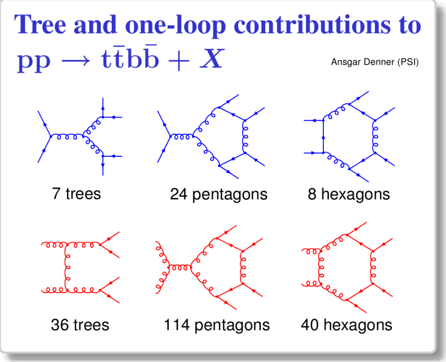

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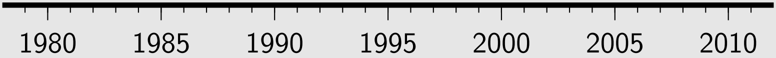
Some main ideas:

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]

The NLO revolution



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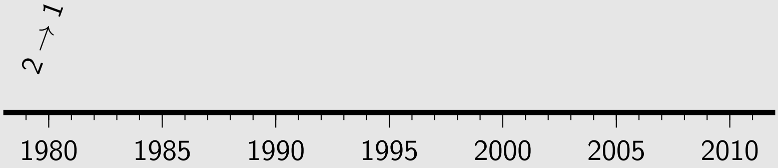
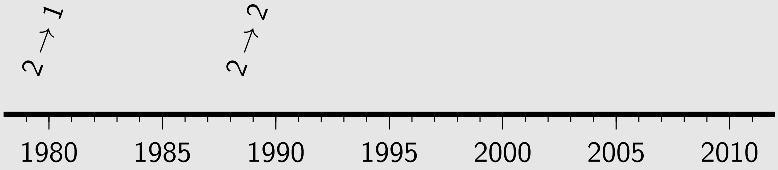


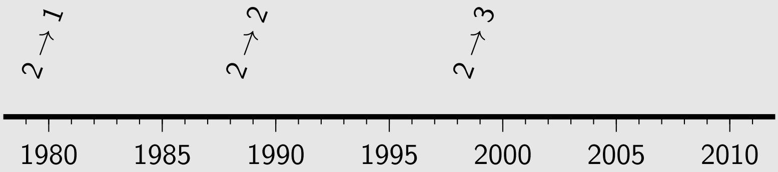
1979: NLO Drell-Yan [Altarelli, Ellis & Martinelli]

The NLO revolution



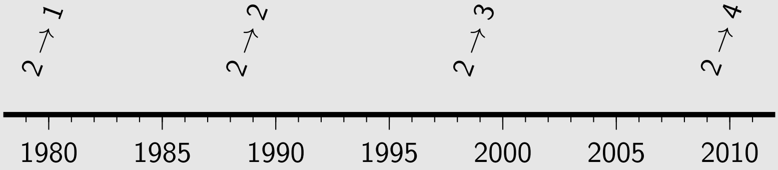
1987: NLO high-p_t photoproduction [Aurenche et al]
1988: NLO $b\bar{b}$, $t\bar{t}$ [Nason et al]
1993: dijets, Vj [JETRAD, Giele, Glover & Kosower]

The NLO revolution



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]
. . .

The NLO revolution



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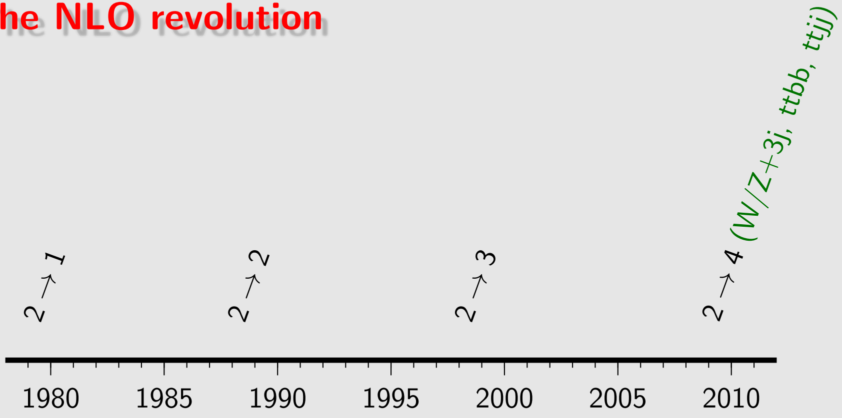

2009: NLO $W+3j$ [Rocket: Ellis, Melnikov & Zanderighi] [unitarity]
2009: NLO $W+3j$ [BlackHat: Berger et al] [unitarity]
2009: NLO $t\bar{t}b\bar{b}$ [Bredenstein et al] [traditional]
2009: NLO $t\bar{t}b\bar{b}$ [HELAC-NLO: Bevilacqua et al] [unitarity]
2009: NLO $q\bar{q} \to b\bar{b}b\bar{b}$ [Golem: Binoth et al] [traditional]
2010: NLO $t\bar{t}jj$ [HELAC-NLO: Bevilacqua et al] [unitarity]
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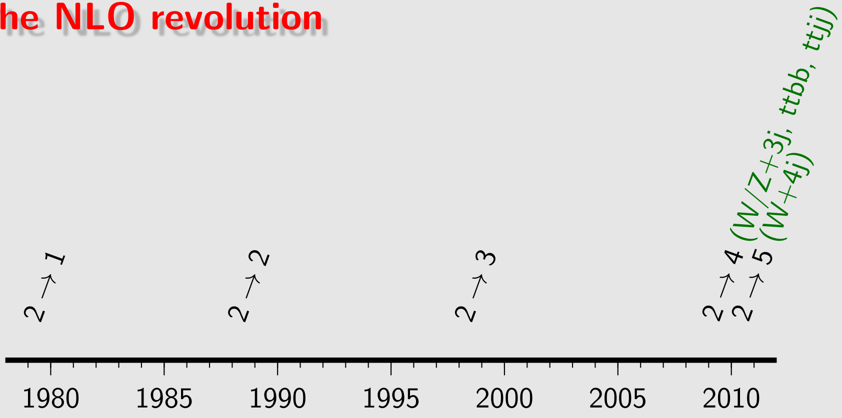
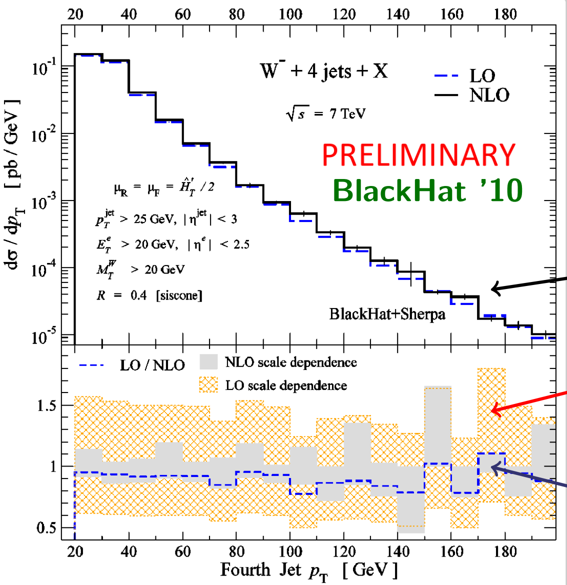


2010: NLO $W+4j$ [BlackHat: Berger et al, preliminary] [unitarity]

NLO $pp \to W + 4$ jets



First (nearly) complete $2 \to 5$ computation
(as needed in our SUSY example)

NLO spectrum of 4th jet!

LO uncertainty

NLO uncertainty

[Currently, leading colour & missing W+6q diags]

NLO multileg outlook

Automation:

A large number of $2 \to 3$ processes have been done manually.

Only some public; e.g. MCFM, NLOJet++

For $2 \to 4$, $2 \to 5$, far too many processes for all to be handled manually.

Among the challenges, **efficiency**, which becomes limiting factor as complexity increases

1 histogram $\sim \mathcal{O}(100)$ CPU days

- because you need to integrate over "more" phase space
- because the amplitudes themselves take longer to evaluate

Or get efficiency gain from graphics cards?

Hagiwara et al '09

Giele, Stavenga & Winter '09-10

Exclusive (hadron-level) quality of Monte Carlo and accuracy of NLO together?

like MC@NLO, POWHEG

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2 developments

MENLOPS: e.g. NLO:Z, LO:Z+1/2/3/...+ parton shower

Hamilton & Nason '10; + work in progress SHERPA

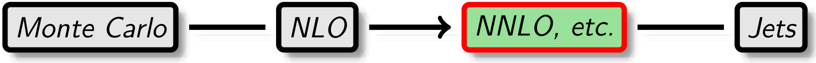
simultaneously NLO:Z & NLO:Z+j + parton shower

Alioli et al, prelim

Generalising this is the current frontier

Monte Carlo ⟷ *NLO* — *NNLO, etc.* — *Jets*

Precision QCD (NNLO, etc.)



Why NNLO / resummation / etc.?

To get precision for the fundamental particles we're studying:

- To better study top, W/Z [Higgs]
- Extract their masses, couplings,
- etc.

For cases where NLO seems crazy

- As can occur for $p_t \gg m_{EW}$ (LHC!)
- In general, with large ratios of scales

Rubin, GPS & Sapeta '10

Here, concentrate on first case, specifically top

Vector Boson Fusion @ NNLO: Bolzoni et al '10

[For more detailed review, see talk by Gehrmann de Ridder]

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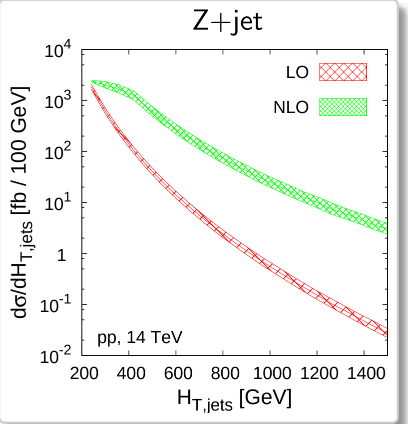

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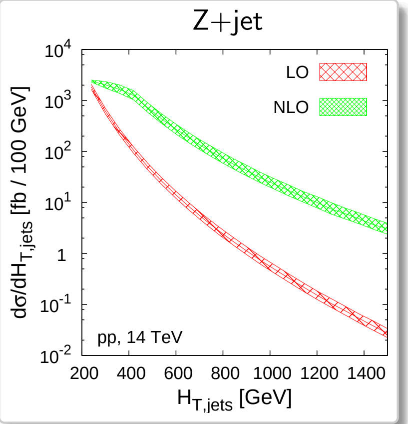

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Top production

"The most interesting known unknown"

in someone's slides (or blog?) — tell me if they were yours

- [Won't talk about:] forward-backward asymmetry, single top
- Mass: nice ideas for a well-defined extraction (because MC extractions give ∼ pole mass, but not obvious how exactly)

  From NLO distribution, Biswas, Melnikov, Schulze '10

  From $\sigma_{t\bar{t}}$, proposal @ Moriond '08; + Moch & Uwer '09

- **Huge effort to calculate cross section accurately**

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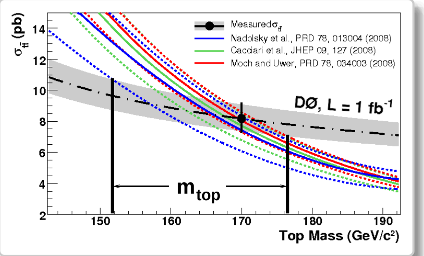

Towards a high precision $t\bar{t}$ cross section

NNLO

- Two-loop diagrams

  high-energy limit:

  Czakon, Mitov & Moch '07

  numerical $q\bar{q} \to t\bar{t}$, Czakon '08

  analytical $q\bar{q} \to t\bar{t}$ (part):

  Bonciani et al '08–'09

  all two-loop poles: Ferroglia et al '09

- One-loop squared

  Körner et al '08, Anastasiou & Aybat '08

- 1-loop $t\bar{t}j$ and real $t\bar{t}jj$

  Dittmaier, Uwer & Weinzierl '07

  Bevilacqua et al '10, Melnikov & Schulze '10

- Learning how to combine terms

  Czakon '10

Alternatively, identify physically relevant contributions:

NNLL (threshold logs)

- Soft $2 \to 2$ structure (massless)

  Mert Aybat, Dixon & Sterman '06

  Becher & Neubert '09

  Gardi & Magnea '09

- Soft $2 \to 2$ structure (massive)

  Kidonakis '09

  Mitov, Sterman & Sung '09

  Becher & Neubert '09

  Beneke, Falgari & Schwinn '09

  Czakon, Mitov & Sterman '09

- Expansion to NNLO

  Beneke et al '09

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  Körner et al '08, Anastasiou & Aybat '08

- 1-loop $t\bar{t}j$ and real $t\bar{t}jj$

  Dittmaier, Uwer & Weinzierl '07

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- Learning how to combine terms

  Czakon '10

All this just part-way to NNLO!

Alternatively, identify physically relevant contributions:

NNLL (threshold logs)

- Soft 2 → 2 structure (massless)

  Mert Aybat, Dixon & Sterman '06

  Becher & Neubert '09

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- Soft 2 → 2 structure (massive)

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  Beneke, Falgari & Schwinn '09

  Czakon, Mitov & Sterman '09

- Expansion to NNLO

  Beneke et al '09

Towards a high precision $t\bar{t}$ cross section

NNLO

- Two-loop diagrams

  high-energy limit:

  Czakon, Mitov & Moch '07

  numerical $q\bar{q} \to t\bar{t}$, Czakon '08

  analytical $q\bar{q} \to t\bar{t}$ (part):

  Bonciani et al '08–'09

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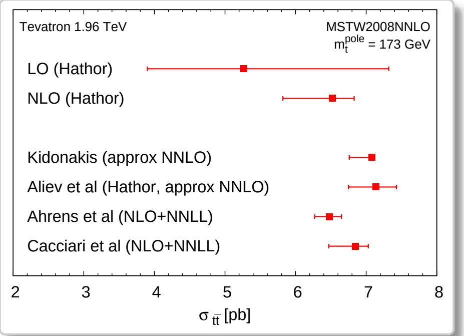
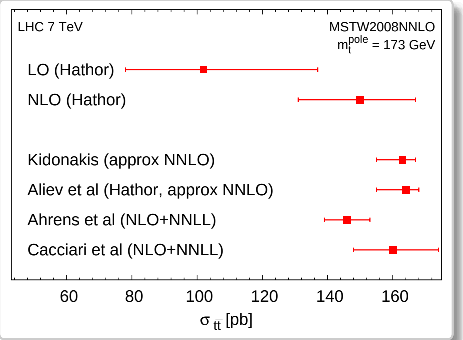
$t\bar{t}$ cross sections

Tevatron 1.96 TeV



LHC 7 TeV



Uncertainties shown are theory (scale) only; no PDF uncertainties

The kinds of differences that are present:

Ahrens et al '10, NNLL+NLO: threshold around $m_{t\bar{t}}$
Aliev et al '10 (Hathor), NNLO approx: threshold around $2m_t$
Procedures for scale dependence and estimating unknown NNLO terms

$t\bar{t}$ cross sections

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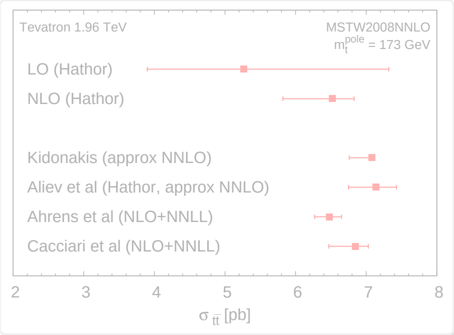

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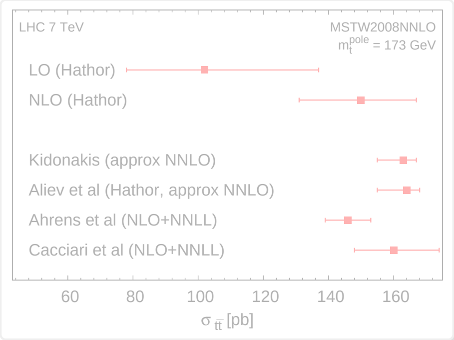

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The kinds of differences that are present:

Much has been learnt about $t\bar{t}$ near threshold

But consensus on cross section & errors not yet reached.

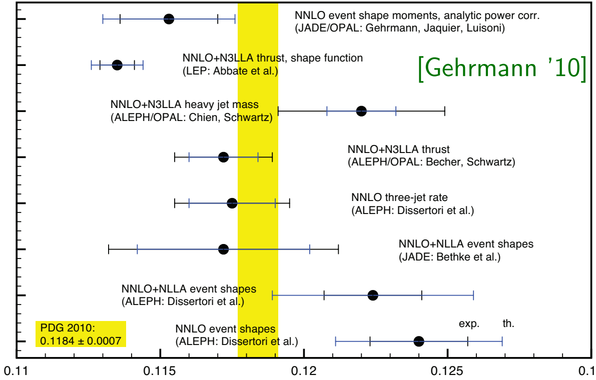
An aside (not directly LHC):
NNLO event shapes in e^+e^-

NNLO in e^+e^-

Big theory progress and much activity for e^+e^- event shapes

- NNLO Gehrmann, Gehrmann de Ridder, Glover & Heinrich '07; Weinzierl '08
- N^3LL (thrust, heavy-jet mass) Becher & Schwartz '08, Chien & Schwartz '10

NNLO α_s fits to e^+e^- event shapes



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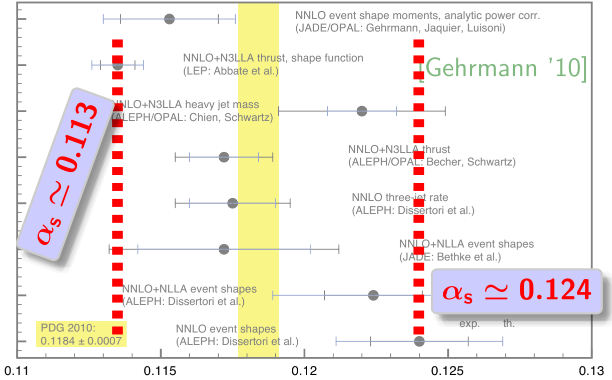
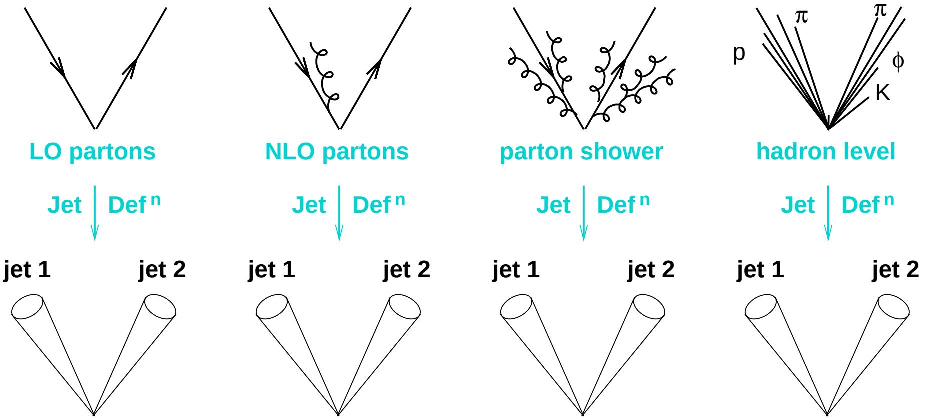


Is non-perturbative QCD the biggest systematic?

Are there lessons for precision pp/p$\bar{\text{p}}$ physics?

Jets

Jets as projections



Projection to jets provides "universal" view of event

A new general-purpose jet algorithm

anti-k_t: repeatedly recombine pair of objects with smallest $d_{ij} = \frac{\Delta R_{ij}^2}{\max(k_{ti}^2, k_{tj}^2)}$

Hard stuff clusters with nearest neighbour

Cacciari, GPS & Soyez '08

[included in FastJet]

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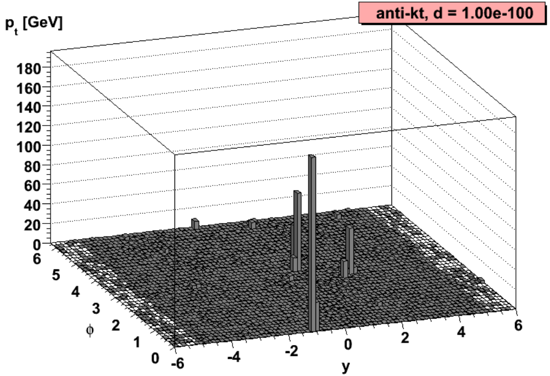

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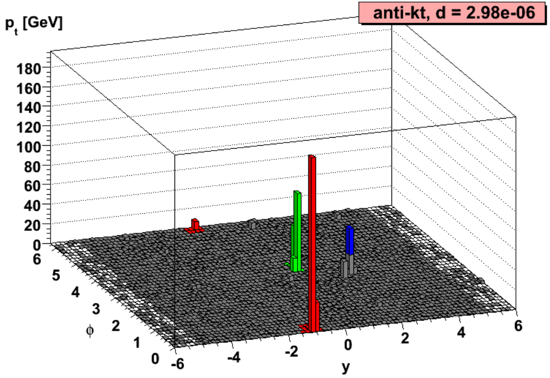

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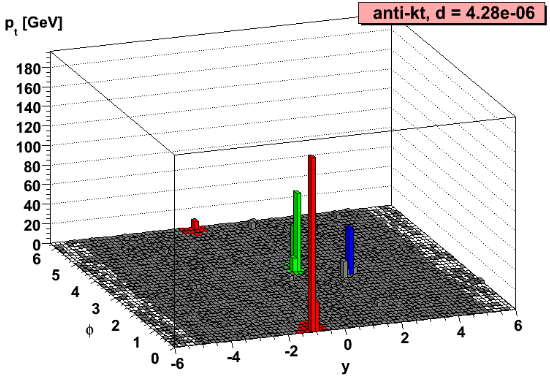

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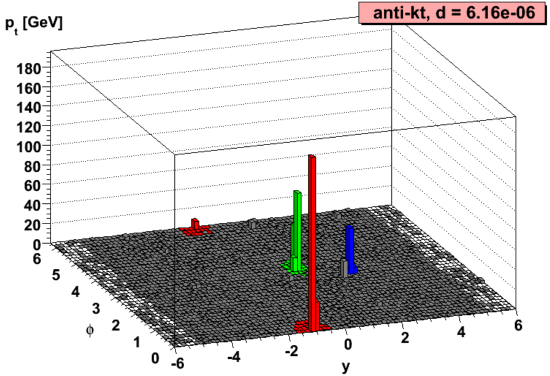

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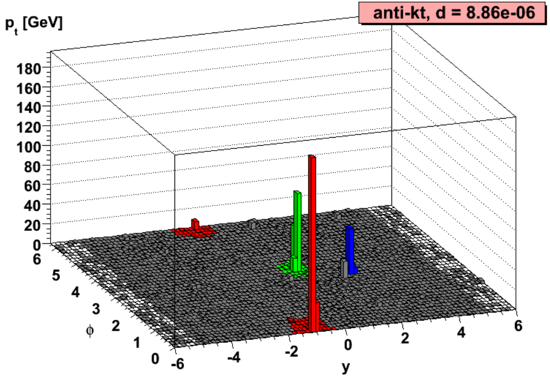

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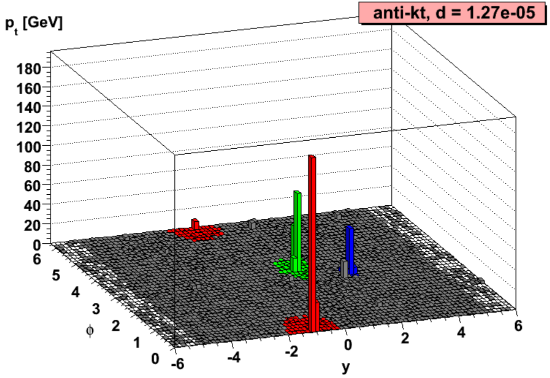

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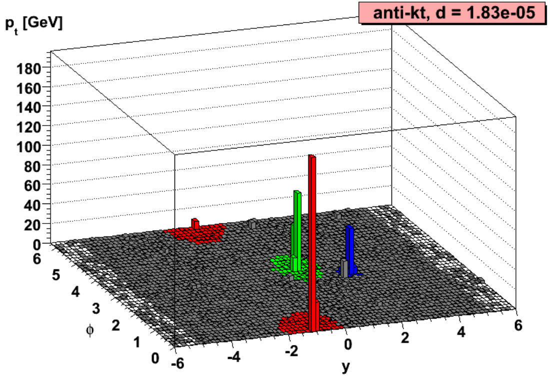

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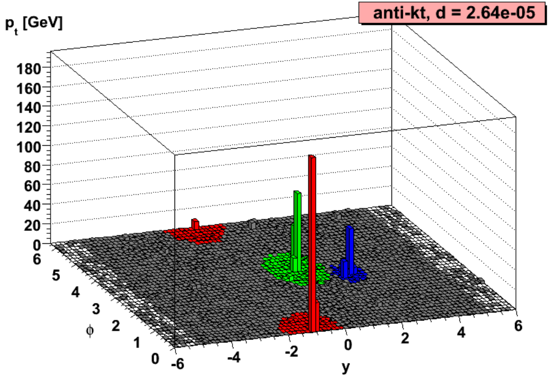

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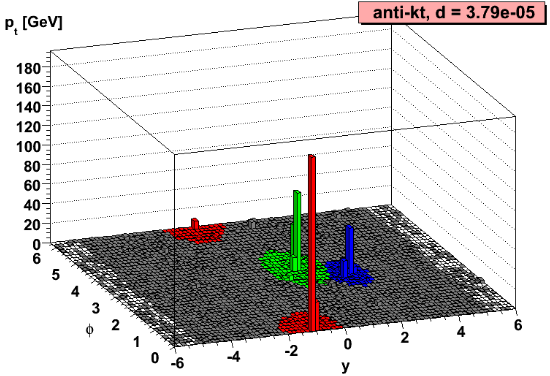

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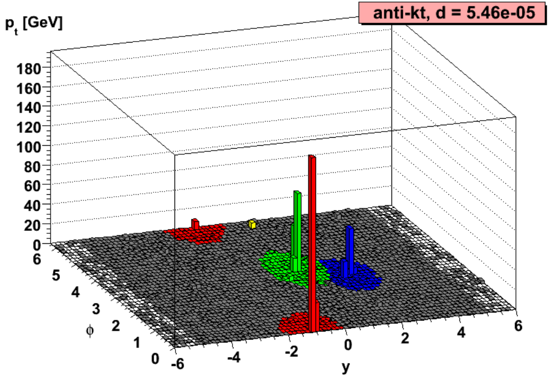

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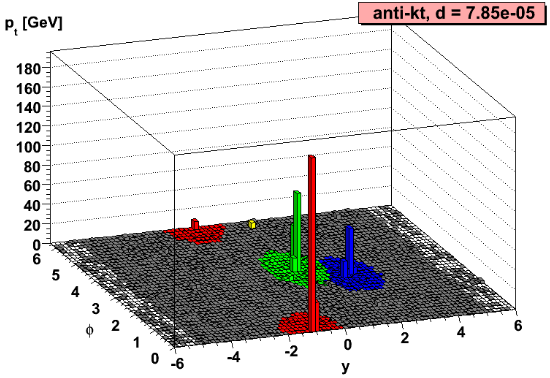
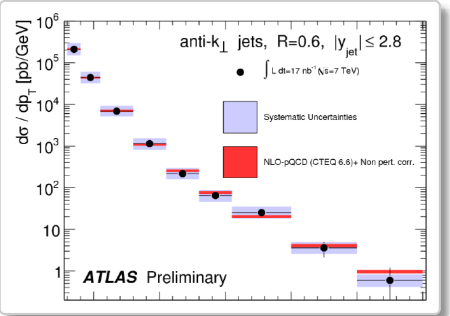
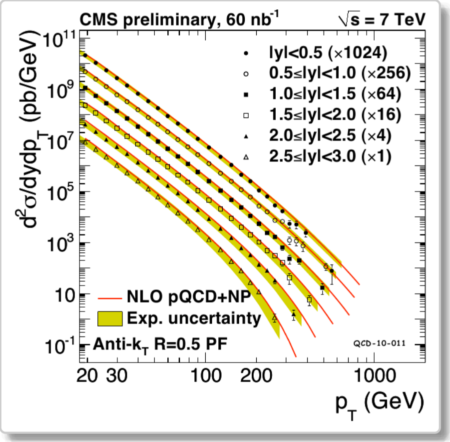


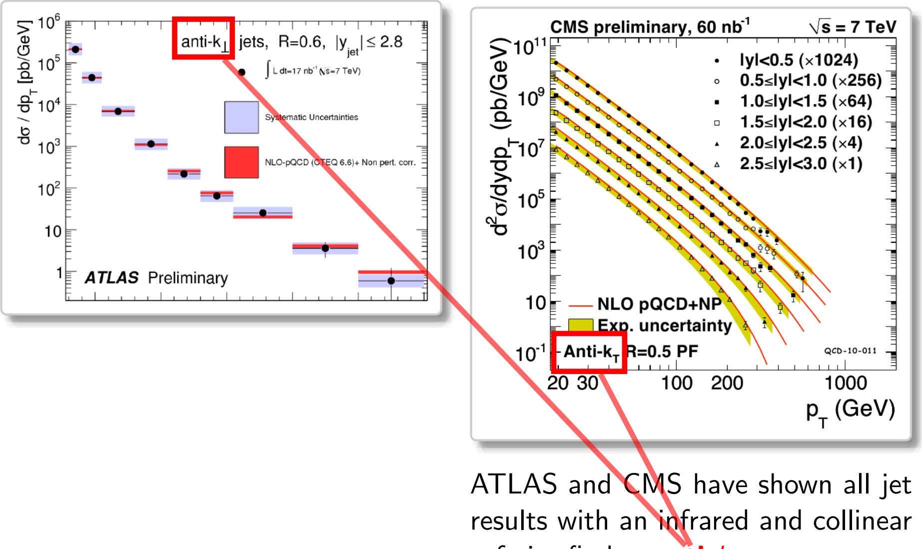
anti-k_t gives cone-like jets without using cones

And is infrared & collinear safe





ATLAS and CMS have shown all jet results with an infrared and collinear safe jet finder, **anti-k_t**;



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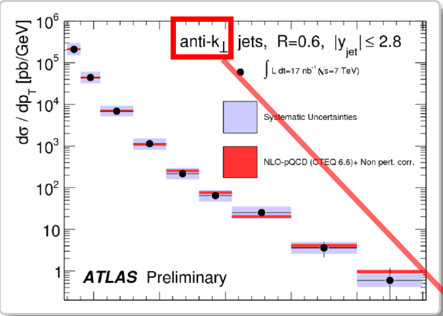
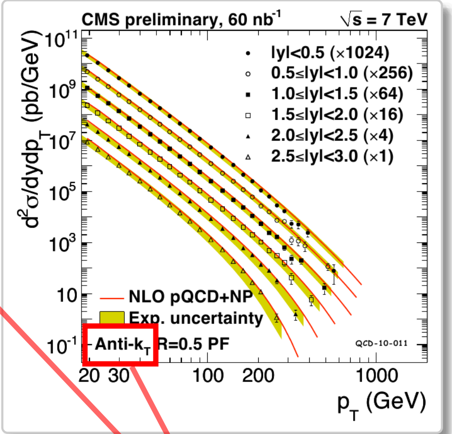
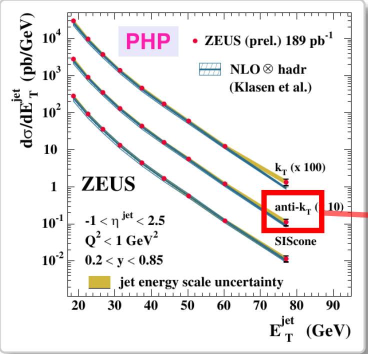
soft junk doesn't change hard jets

NLO calculations are finite







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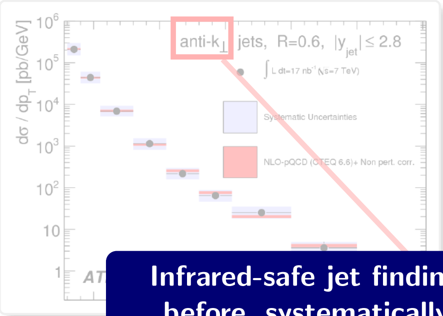

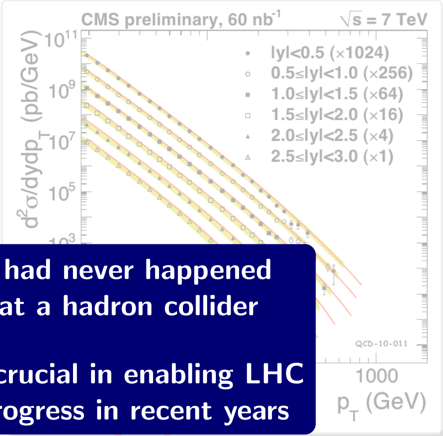

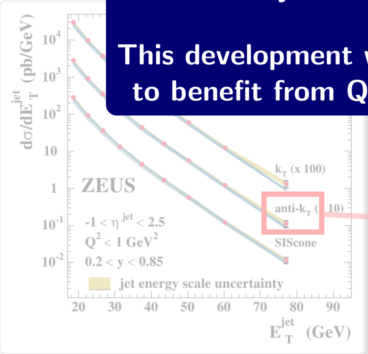

Infrared-safe jet finding had never happened before, systematically, at a hadron collider

This development will be crucial in enabling LHC to benefit from QCD's progress in recent years

ATLAS and CMS have shown all jet results with an infrared and collinear safe jet finder, **anti-k_t**; also used at HERA!

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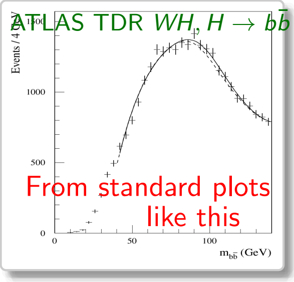
NLO calculations are finite

Jets & boosted searches: X with $p_{tX} \gtrsim m_X$



1) WH, $H \to b\bar{b}$, ATLAS TDR;

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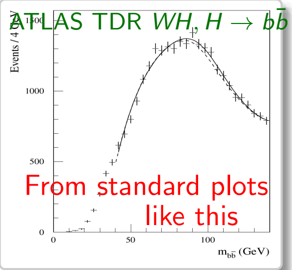

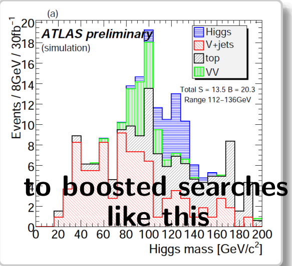

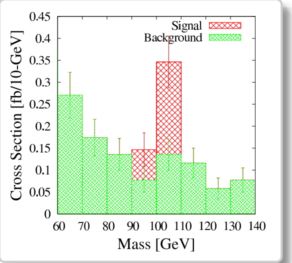

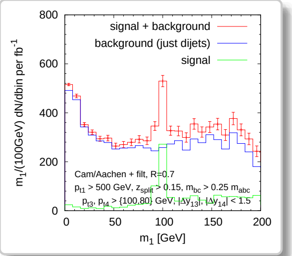

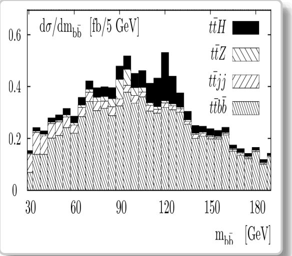

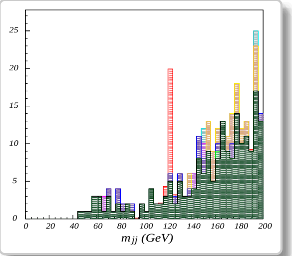

1) WH, $H \to b\bar{b}$, ATLAS TDR; 2) WH, $H \to b\bar{b}$, Butterworth et al '08 & ATLAS '09; 3) Buried Higgs, Falkowski et al '10; 4) $\tilde{\chi}^0 \to qqq$, Butterworth et al '09; 5) $t\bar{t}H$, $H \to b\bar{b}$, Plen et al '09; 6) Buried Higgs, Chen et al '10;

Conclusions

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Several major long-term projects now close to maturity

- The C++ event generators: Herwig++, Sherpa and Pythia 8
- NNPDF global fit with robust error estimates

Breakthroughs:

- NLO calculations, first $2 \to 5$ results (W+4j) Next step: automation
- Jet finding — IR safety; pulling out hadronic signals previously thought impossible

High accuracy:

- Much work on NNLO $t\bar{t}$ and (NNLL) approximations

  And several other processes, e.g. Z/W/H, γj, jj, Vj
- Open questions: estimation of uncertainties; impact of hadronisation

And much else that could not be covered in 30 minutes!

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With thanks for comments, suggestions, conversations and information:

Matteo Cacciari, Aude Gehrmann de Ridder, Gudrun Heinrich, Nikolaos Kidonakis, Giulia Zanderighi

EXTRAS

The three MC++'s

Key differences between PYTHIA 6.4 and 8.1

Old features definitely removed include, among others:
- independent fragmentation
- mass-ordered showers

Features omitted so far include, among others:
- ep, γp and $\gamma\gamma$ beam configurations
- several processes, especially Technicolor, partly SUSY

New features, not found in 6.4 ($\star$ = see below):
- interleaved $p_\perp$-ordered MI + ISR + FSR evolution
- richer mix of underlying-event processes (γ, J/ψ, DY, ...)

$\star$ possibility for two selected hard interactions in same event
$\star$ allow rescattering in MI framework
$\star$ hard scattering in diffractive systems
$\star$ several new processes, within and beyond SM
- possibility to use one PDF set for hard process and another for rest

$\star$ up-to-date decay data and LO PDF sets

Sjöstrand @ MC4LHC Readiness Workshop, March '10

The three MC++'s

Herwig++

- The new Herwig++ program now provides a full simulation of lepton-lepton, lepton-hadron and hadron-hadron collisions with many improvements over its FORTRAN predecessor:
  - New angular ordered parton shower with better theoretical control and mass treatment;
  - Many processes at NLO in the POWHEG approach;
  - Multiple scattering model of the underlying event;
  - Better treatment of BSM physics models;
  - Improved simulation of tau and hadron decays.

CERN 29th March 6

Richardson @ MC4LHC Readiness Workshop, March '10

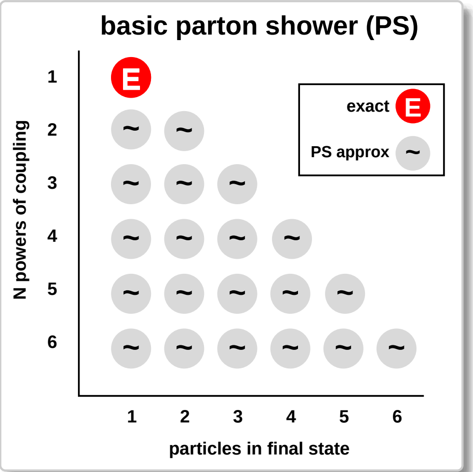
The three MC++'s

A brief introduction [SHERPA]

- SHERPA has been under development since the late 1990's
  - In the beginning, borrowed and re-implemented physics from others: virtuality-ordered parton shower - APACIC++, underlying event like PYTHIA 6.2
  - Helicity amplitudes for matrix elements - AMEGIC++
  - Fragmentation/hadron decays through link to PYTHIA routines
- Constructed from scratch, in C++
  - Mainly done by diploma and PhD students
- Replaced physics modules one-by-one.
- Status in SHERPA 1.2: by now independent of other code
  - Virtuality-ordered shower replaced by dipole shower,
  - Berends-Giele matrix elements,
  - Own version of cluster fragmentation AHADIC++,
  - Huge own library of hadron and τ-decays,
  - QED radiation through YFS formalism,
  - Only UE modelling still along the line of Sjostyrand-van der Zijl, PYTHIA 6.2.
- A full-fledged independent event generator

Krauss @ MC4LHC Readiness Workshop, March '10

NLO and Monte Carlo?



A trend towards more elements included **exactly** in Monte Carlo

- PS: the original
- ME+PS — Ideas from mid '90's, CKKW '01, MLM
- NLO+PS — MC@NLO '02, POWHEG '04

What's new?

- ME + NLO + PS (MENLOPS) — Hamilton & Nason '10

What's still unsolved?

- NLO + NLO + (...) + PS — specific implementations: Lavesson & Lonnblad '08 (e^+e^-), Alioli et al [prelim. Z&Z+j]

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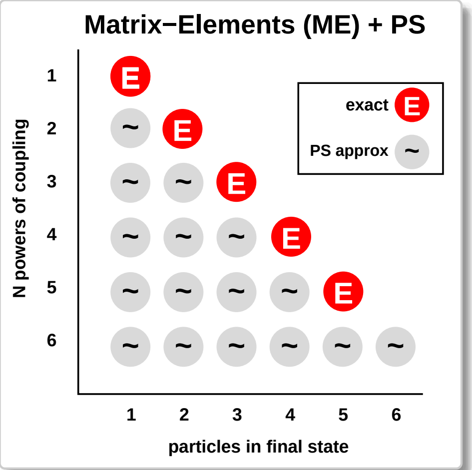

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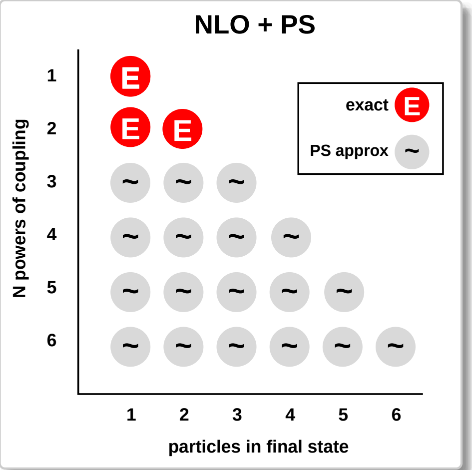

A trend towards more elements included **exactly** in Monte Carlo

- PS: the original
- ME+PS — Ideas from mid '90's
  CKKW '01, MLM
- NLO+PS
  MC@NLO '02, POWHEG '04

What's new?

- ME + NLO + PS (MENLOPS)
  Hamilton & Nason '10

What's still unsolved?

- NLO + NLO + (...) + PS
  specific implementations: Lavesson & Lonnblad '08 (e^+e^-)
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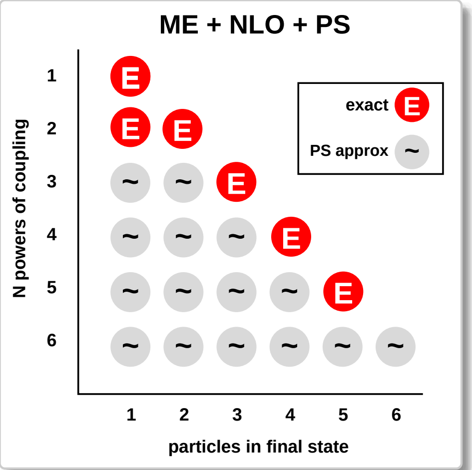

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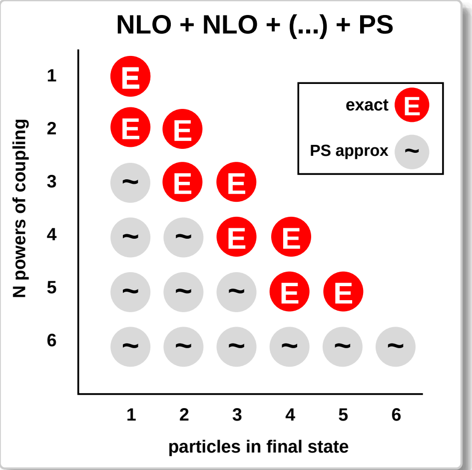

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Parton Distribution Functions (PDFs)

PDFs

PDFs go into every LHC prediction and calculation, from Monte Carlo event generation, through to precision studies.

Protons are the initial state; quarks and gluons interact

Of several groups, so far CTEQ and MSTW have dominated the Global Fit Industry, albeit with a decade-old worry about their procedures:

How well-founded are their uncertainty estimates?
($\delta\chi^2$ choice, parametrisations, . . .)

The barrier to entry for new players is high:

- PDF evolution
- Calculation of cross sections for many DIS and *pp* observables
- Proper statistical treatment of all (correlated) experimental errors
- Fitting a couple of thousand data points, from myriad sources

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2010: NNPDF goes global + adds heavy quarks

Statistical treatment is transparent

Generate 'replica' datasets.

For each one, fit a replica PDF

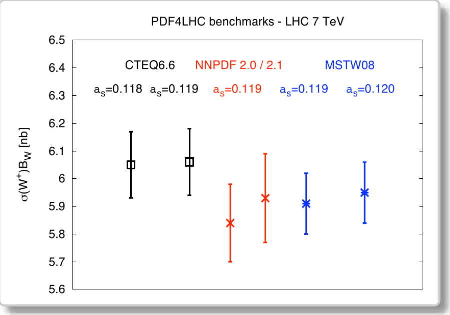
Sample over ensemble of PDFs to get error on cross section.

Neural networks provide flexible parametrisation of the PDFs

Avoid biases from manual choice of functional form

Genetic algorithms to handle fits with large numbers of parameters

$\sigma(pp \to W^+)$, LHC7 [NNPDF]



Provides significant added confidence in our understanding of PDF uncertainties

What's still missing with PDFs?

Theory uncertainties

For a wide range of experimentally well-measured observables, theory uncertainties are limiting factor in extracting parameters of the theory (masses, couplings, etc.).

Theory uncertainties are currently being left out from global PDF fits

I would be surprised if NLO theory uncertainties $\ll$ exp. ones

Maybe not a problem at NNLO?

Only MSTW have NNLO right now

This should (in my opinion) become a high priority for PDF fits.