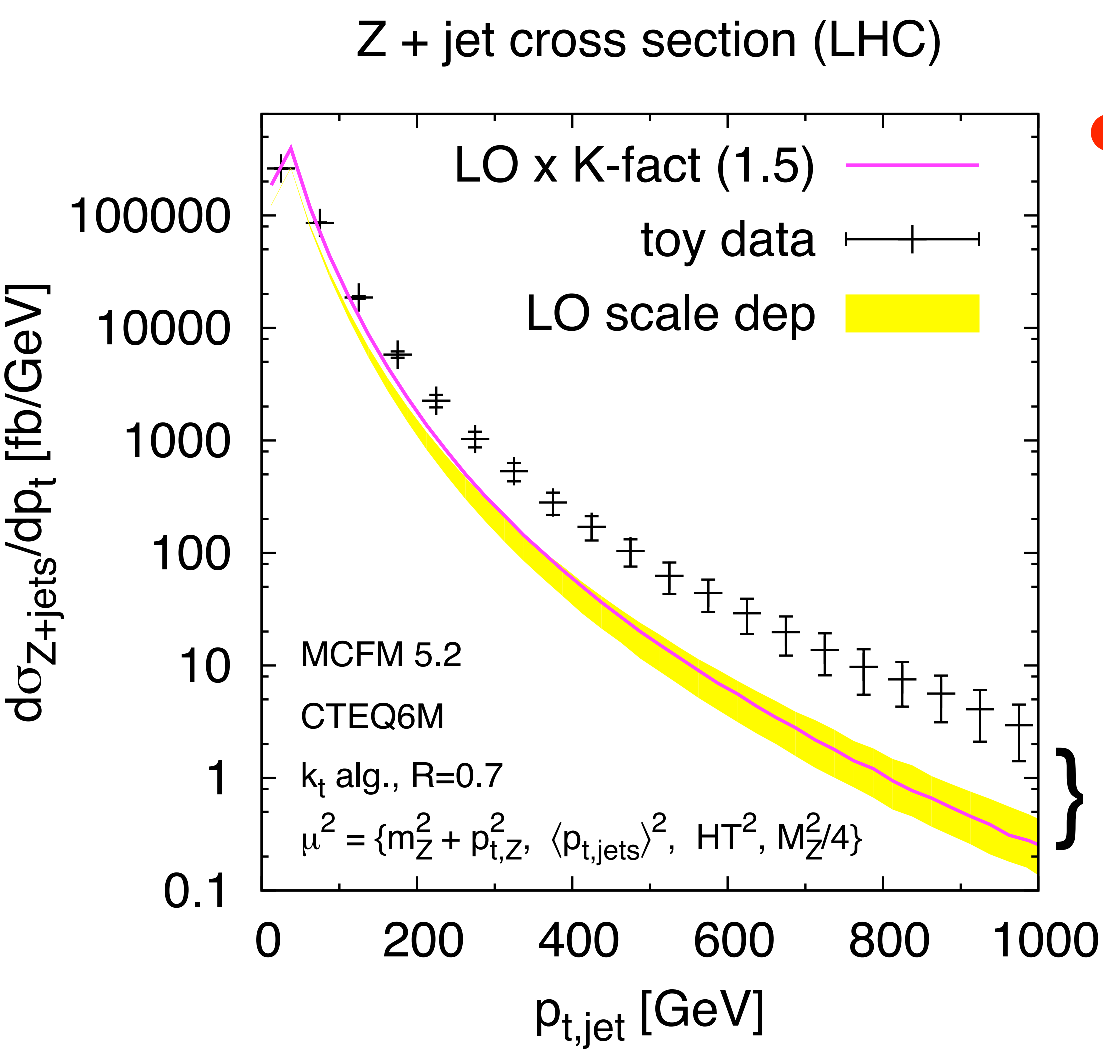
Phenomenology for LHC: A (Selective) Status Report

Bryan Webber
UNIVERSITY OF CAMBRIDGE 800 YEARS 1209 ~ 2009

- Higher-order calculations
- Monte Carlos
- Jet algorithms
- Beyond Standard Model

Higher-order calculations

Need for NLO



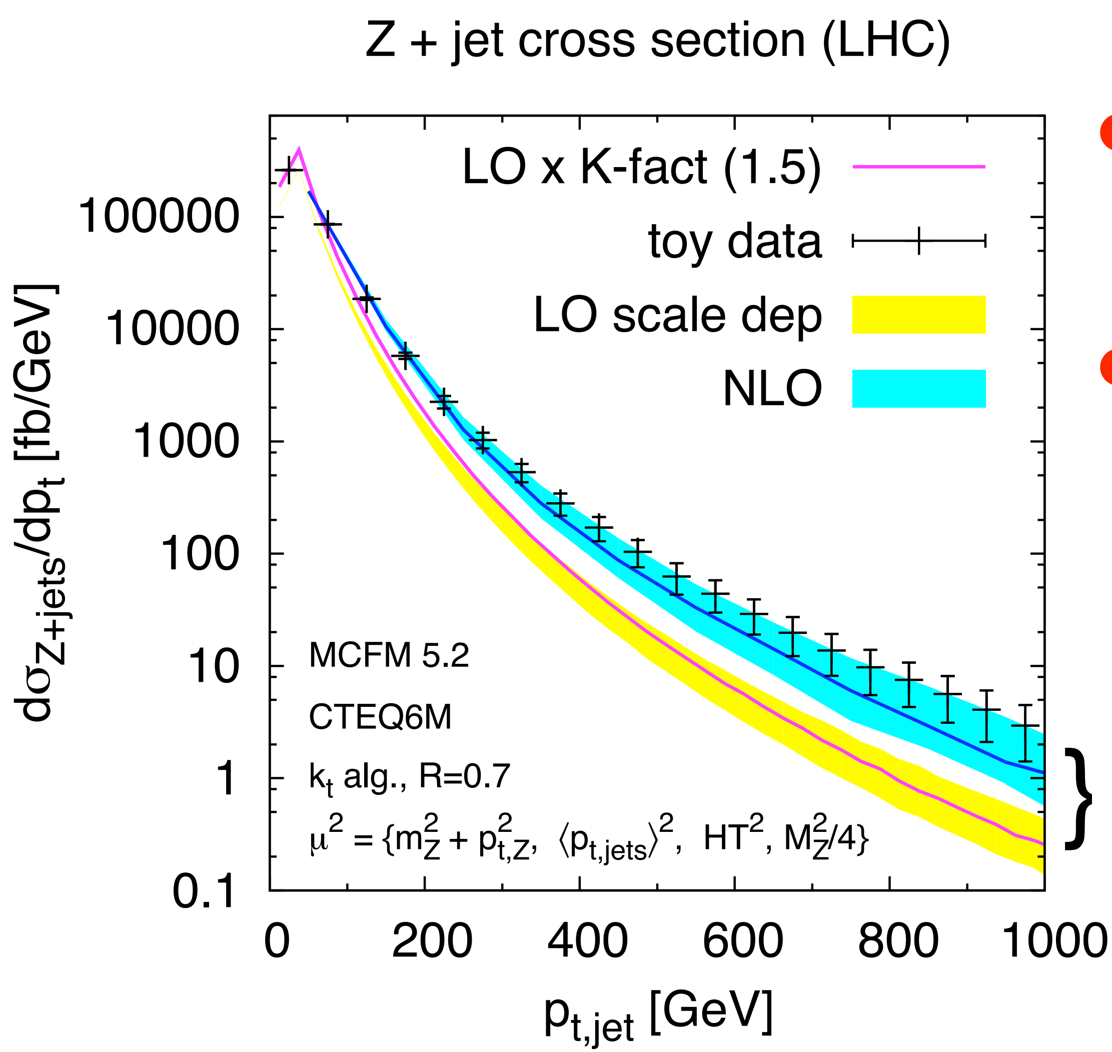
- LO rescaled to fit cross section

} x10 excess → discovery?

Zanderighi

Butterworth, Davison, Rubin, Salam

Need for NLO



- LO rescaled to fit cross section can be misleading!
- E.g. new channels at NLO

$$qq \rightarrow Zqq$$

} Sorry, just NLO!

Zanderighi

Butterworth, Davison, Rubin, Salam

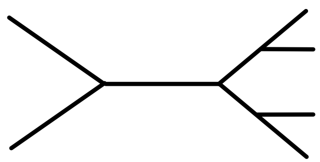
Les Houches 2007 wish list

Process ($V \in \{Z, W, \gamma\}$)	Comments
Calculations completed since Les Houches 2005	
1. $pp \to VV$jet	WWjet completed by Dittmaier/Kallweit/Uwer [3]; Campbell/Ellis/Zanderighi [4] and Binoth/Karg/Kauer/Sanguinetti (in progress)
2. $pp \to$ Higgs+2jets	NLO QCD to the gg channel completed by Campbell/Ellis/Zanderighi [5]; NLO QCD+EW to the VBF channel completed by Ciccolini/Denner/Dittmaier [6, 7]
3. $pp \to V\,V\,V$	ZZZ completed by Lazopoulos/Melnikov/Petriello [8] and WWZ by Hankele/Zeppenfeld [9]
Calculations remaining from Les Houches 2005	
4. $pp \to t\bar{t}\,b\bar{b}$	relevant for $t\bar{t}H$
5. $pp \to t\bar{t}$+2jets	relevant for $t\bar{t}H$
6. $pp \to VV\,b\bar{b}$,	relevant for VBF $\to H \to VV$, $t\bar{t}H$
7. $pp \to VV$+2jets	relevant for VBF $\to H \to VV$ VBF contributions calculated by (Bozzi/)Jäger/Oleari/Zeppenfeld [10–12]
8. $pp \to V$+3jets	various new physics signatures
NLO calculations added to list in 2007	
9. $pp \to b\bar{b}b\bar{b}$	Higgs and new physics signatures
Calculations beyond NLO added in 2007	
10. $gg \to W^*W^*$ $\mathcal{O}(\alpha^2\alpha_s^3)$	backgrounds to Higgs
11. NNLO $pp \to t\bar{t}$	normalization of a benchmark process
12. NNLO to VBF and Z/γ+jet	Higgs couplings and SM benchmark
Calculations including electroweak effects	
13. NNLO QCD+NLO EW for W/Z	precision calculation of a SM benchmark

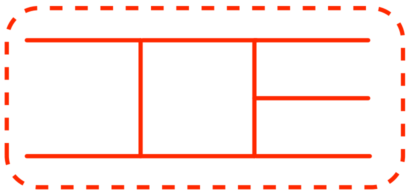
Table 1: The updated experimenter's wishlist for LHC processes

NLO calculations

Ingredients for N-particle NLO calculation:



- ☑ tree graph rates with N+1 partons
  → soft/collinear divergences
- ☐ virtual correction to N-leg process
  → divergence from loop integration
- ☑ set of subtraction terms



bottleneck

Status of NLO:

- ☑ 2 → 2: all known (or easy) in SM and beyond
- ☑ 2 → 3: very few processes left

  [but: often do not include decays, newest codes mostly private]
- ☐ 2 → 4: barely touched ground [$q\bar{q} \to t\bar{t}\, b\bar{b}$]

  Bredenstein, Denner, Dittmaier, Pozzorini '08

Done since 2007

- Most physics results done from Feynman diagram approach:
  - QCD corrections to vector boson pair production (W^+W^-, $W^{\pm}Z$ & ZZ) via vector boson fusion (VBF). (Jager, Oleari, Zeppenfeld)+(Bozzi)
  - QCD and EW corrections to Higgs production via VBF. (Ciccolini, Denner, Dittmaier)
  - $pp \to$ Higgs+2 jets. (via gluon fusion Campbell, Ellis, Zanderighi), (via weak interactions Ciccolini, Denner, Dittmaier). $pp \to$ Higgs+3 jets (leading contribution) (Figy, Hankele, Zeppenfeld).
  - $pp \to t\bar{t}H$. (Beenakker, Dittmaier, Krämer, Plümper, Spira, Zerwas), (Dawson, Jackson, Reina, Wackeroth)
  - $pp \to ZZZ$, (Lazopoulos, Petriello, Melnikov) $pp \to t\bar{t}Z$+(McElmurry)
  - $pp \to WWZ, WWW$ (Hankele, Zeppenfeld, Campanario, Oleari, Prestel)
  - $pp \to WW+j+X$. (Campbell, Ellis, Zanderighi). (Dittmaier, Kallweit, Uwer)
  - $pp \to W/Z\, b\bar{b}$ (Febres Cordero, Reina, Wackeroth),
  - $pp \to t\bar{t}+jet$ (Dittmaier,Uwer,Weinzierl),
  - $q\bar{q} \to t\bar{t} + b\bar{b}$ (Bredenstein,Denner,Dittmaier,Pozzorini),

Done with new techniques

- Past year progress using unitarity and related techniques,
  - $gg \to gggg$ amplitude. (Bern,Dixon,Kosower), (Britto,Feng,Mastrolia), (Bern,Bjerrum-Bohr,Dunbar,H.I.), (Berger,Bern,Dixon,Forde,Kosower), (Bedford,Brandhuber,Spence,Travaglini) (Xiao,Yang,Zhu) ,(Berger,Bern,Dixon,Forde,Kosower), (Giele,Kunszt,Melnikov)
  - Lots of gluons (Giele,Zanderighi), (Berger, Bern, Dixon, Febres Cordero, Forde,H.I., Kosower, Maître)
  - 6 photons (Nagy, Soper), (Ossola, Papadopoulos, Pittau), (Binoth, Heinrich, Gehrmann, Mastrolia)
  - $pp \to ZZZ, WZZ, WWZ, ZZZ$ (Binoth, Ossola, Papadopoulos, Pittau),
  - $gg \to t\bar{t}g$ using D-Dimensional Unitarity (Ellis,Giele,Kunszt,Melnikov)
- Numerical packages under construction:
  - BlackHat Berger, Bern, Dixon, Febres Cordero, Forde, H.I., Kosower, Maître
  - CutTools Ossola, Papadopoulos, Pittau
  - Rocket Ellis, Giele, Kunszt, Melnikov, Zanderighi

Thanks to H.I.=Harald Ita

BlackHat

Berger, Bern, Dixon, Febres Cordero, Forde, Ita, Kosower, Maitre

BlackHat: *A C++ implementation of on-shell techniques for 1-loop amplitudes*

- Portability (standard libraries for unix systems)
- Modularity (object oriented)
- Malleability (to accept several routines – numerics and analytics)
- Numerical precision and efficiency
- Ready to use with existing Monte Carlo programs
  - Work in progress with automated real dipole subtraction from Sherpa (*with T. Gleisberg*)

HELAC/CutTools

Cafarella, van Hameren, Kanaki, Ossola, Papadopoulos, Pittau, Worek

- Automatic 1-loop computation of all 2→4 wish-list processes

$$\begin{aligned} q\bar{q}, gg &\rightarrow t\bar{t}b\bar{b},\ b\bar{b}b\bar{b},\ W^+W^-b\bar{b},\ t\bar{t}gg \\ q\bar{q}' &\rightarrow Wggg,\ Zggg \end{aligned}$$

- All masses, colours and helicities treated exactly

- Still need to combine with LO 2→5 processes, subtraction terms and efficient MC integration

Rocket

Ellis, Giele, Kunszt, Melnikov, Zanderighi

Rocket:* an F90 package which fully automates the calculation of virtual amplitudes via tree level recursion + D-unitarity

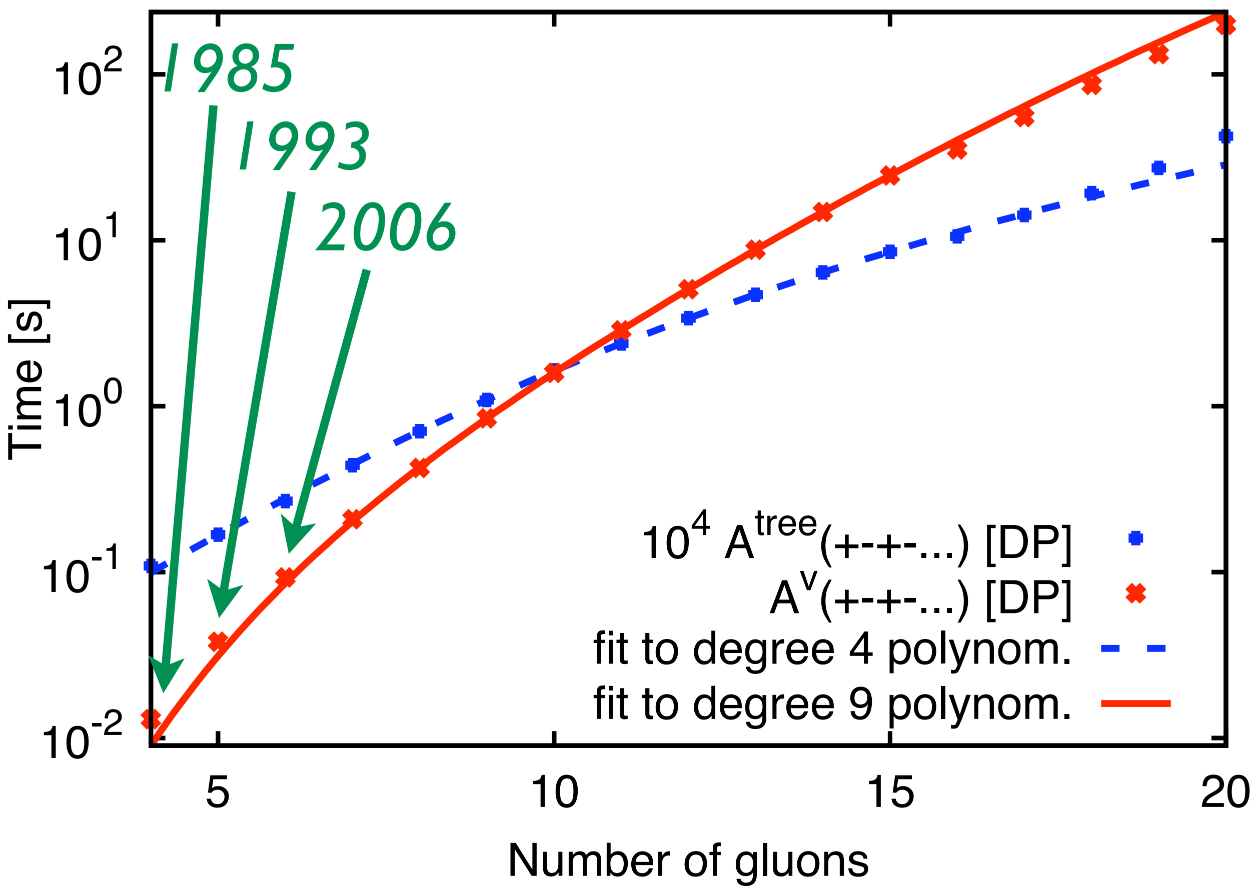
First step: use only three and four-gluon vertices
⇒ pure gluonic amplitudes

Input: arbitrary number of gluons and their arbitrary helicities (+/-)

Output: (un)-renormalized virtual amplitude in FDH or t'HV scheme

* From the Italian Rucola, Recursive Unitarity Calculation of One-Loop Amplitudes

gg → (N-2)g at 1-loop



QCDloop

QCDloop: A repository for one-loop scalar integrals

This is a repository of one-loop scalar Feynman integrals, evaluated close to four dimensions. For integrals with all massive internal lines the integrals are all known, both analytically and numerically. This website therefore concentrates on integrals with some internal masses vanishing; in general, these integrals contain infra-red and collinear singularities which are here regulated dimensionally. The integrals are described in a PDF file for every known integral. The general divergent box integral can be calculated using one of sixteen basis integrals which are given here. The general divergent triangle integral can be calculated using one of six triangle basis integrals which are also given here. The browser must be set to use hypertex-aware tool, such as Acrobat reader, and for best viewing, should open the pdf files in the browser. For general notation for the loop integrals click here

- Box integrals definitions and generalities
  - Basis set of 16 divergent box integrals
  - Index of all box integrals currently in the repository
- Triangle integrals
  - Basis set of 6 divergent triangle integrals
  - Finite triangle integrals
- Bubble integrals
- Tadpole integral

The results in this web-site are also available in the paper arXiv:0712.1851 by R.K. Ellis and G. Zanderighi
The corresponding fortran 77 code which calculates an arbitrary one-loop scalar integral, finite or divergent can be downloaded, QCDLoop-1.8.tar.gz (version 1.8, date 2008-Nov-07). If you encounter any problems with the code, please notify the authors.

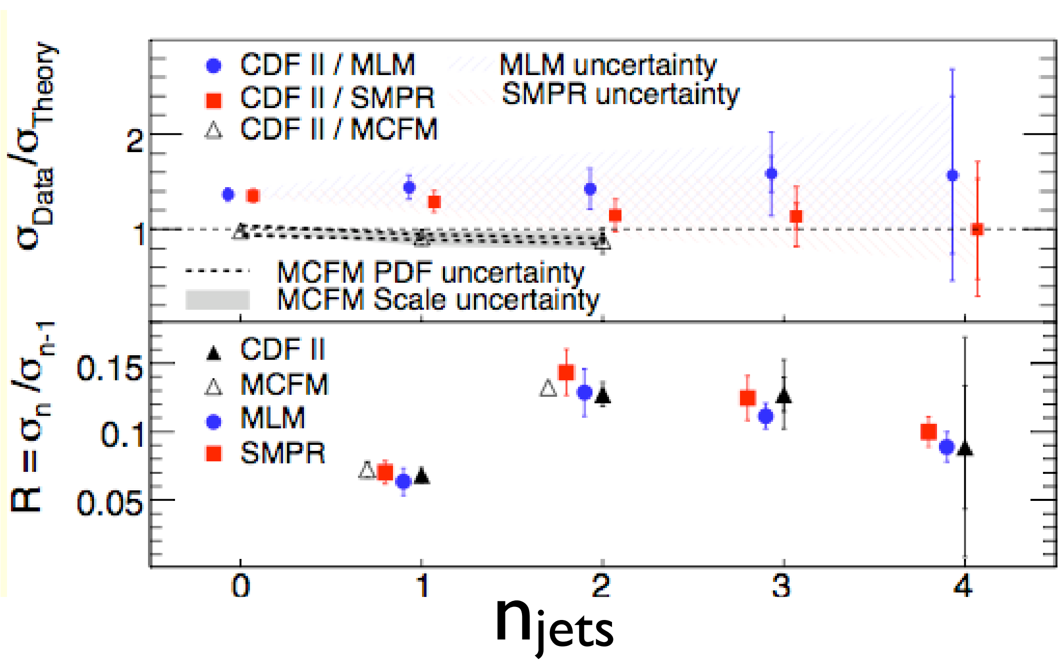
We gratefully acknowledge comments on previous versions of the code from
Andre van Hameren, Francesco Tramontano, Kirill Melnikov, Gudrun Heinrich, Adrian Signer, and Markus Schulze.

Example: W+3 jets

Need to evaluate two amplitudes

$$0 \to \bar{u}\, d\, g\, g\, g\, W^+$$ → 1203 +104 Feynman diagrams

$$0 \to \bar{u}\, d\, \bar{Q}\, Q\, g\, W^+$$ → 258 +18 Feynman diagrams



New!

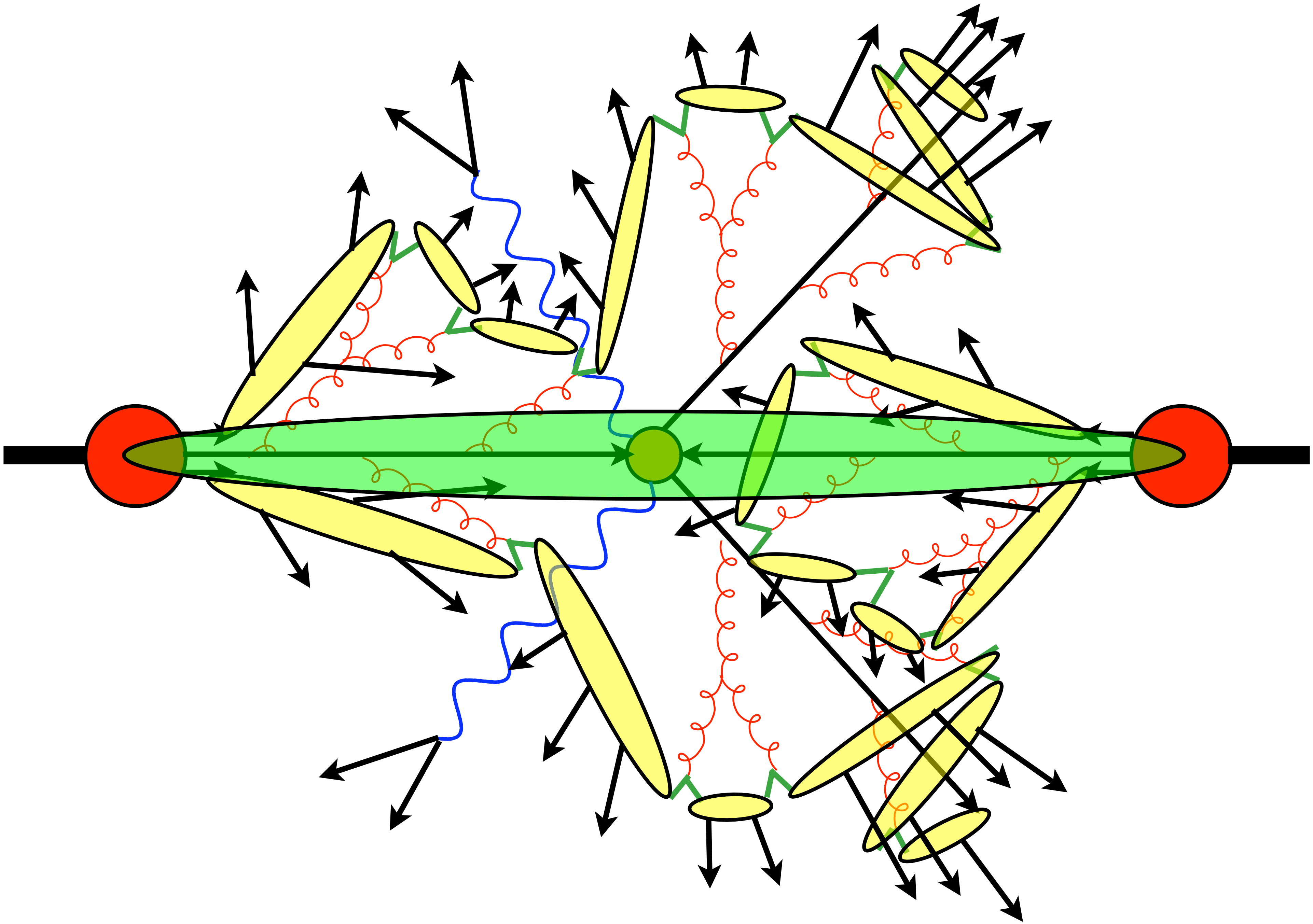
All amplitudes in 0810.2762

[Ellis, Giele, Kunszt, Melnikov, GZ]

Thanks to GZ=Giulia Zanderighi

Monte Carlos

LHC event structure



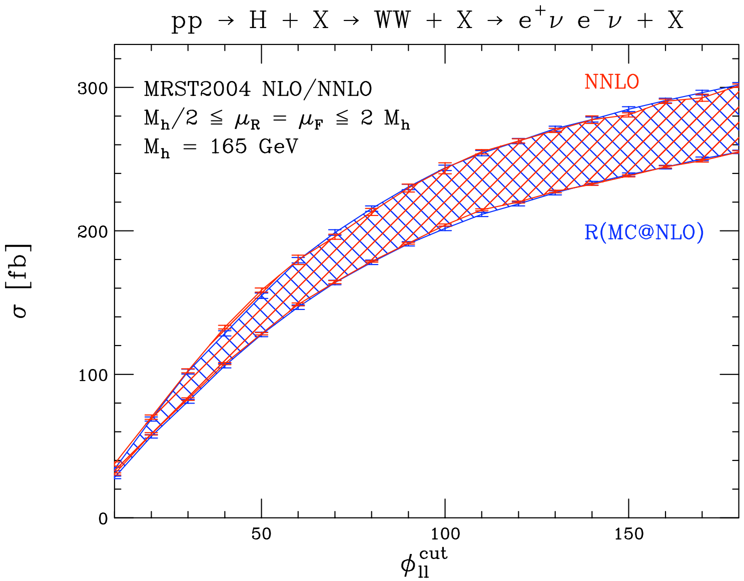
MC event generators

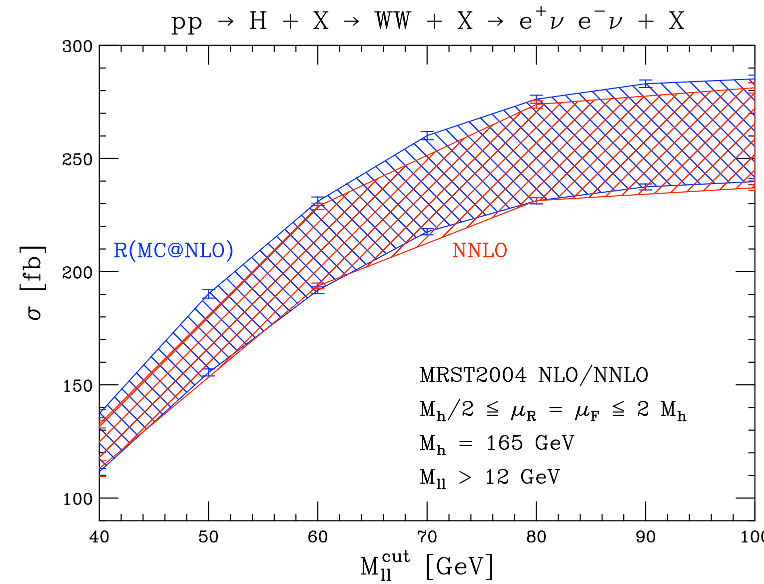
- **HERWIG**
  - Angular-ordered shower, cluster hadronization
  - v6 Fortran; Herwig++
- **PYTHIA**
  - Virtuality/k_T-ordered shower, string hadronization
  - v6 Fortran; v8 C++
- **SHERPA**
  - Virtuality/dipole-ordered shower, string/cluster hadronization
  - C++

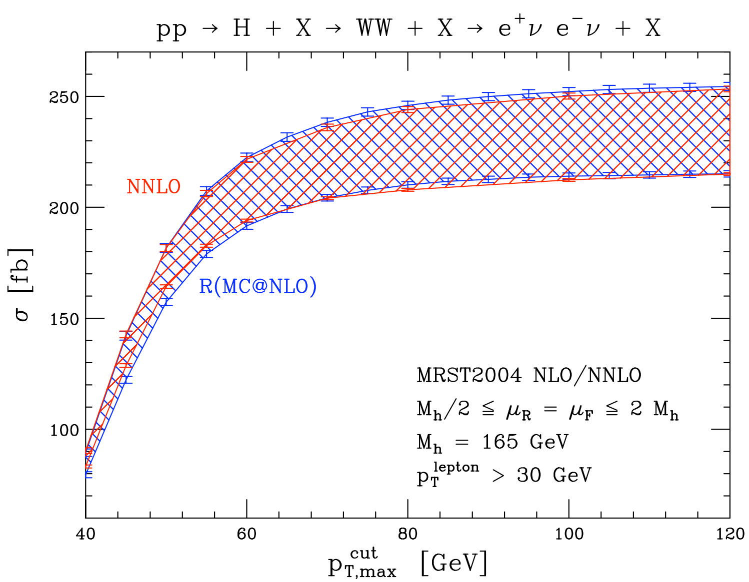
ME-MC Matching

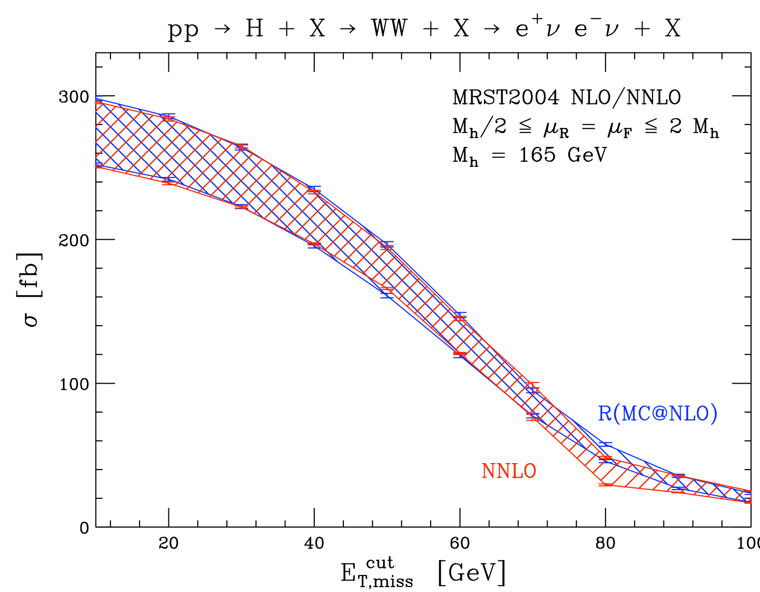
- Two rather different objectives:
- Matching parton showers to NLO matrix elements, without double counting
  - MC@NLO — Frixione, BW
  - POWHEG — Nason
- Matching parton showers to LO n-jet matrix elements, minimizing jet resolution dependence
  - CKKW — Catani, Krauss, Kühn, BW
  - Dipole — Lönnblad
  - MLM Matching — Mangano

H→WW: MC@NLO vs NNLO





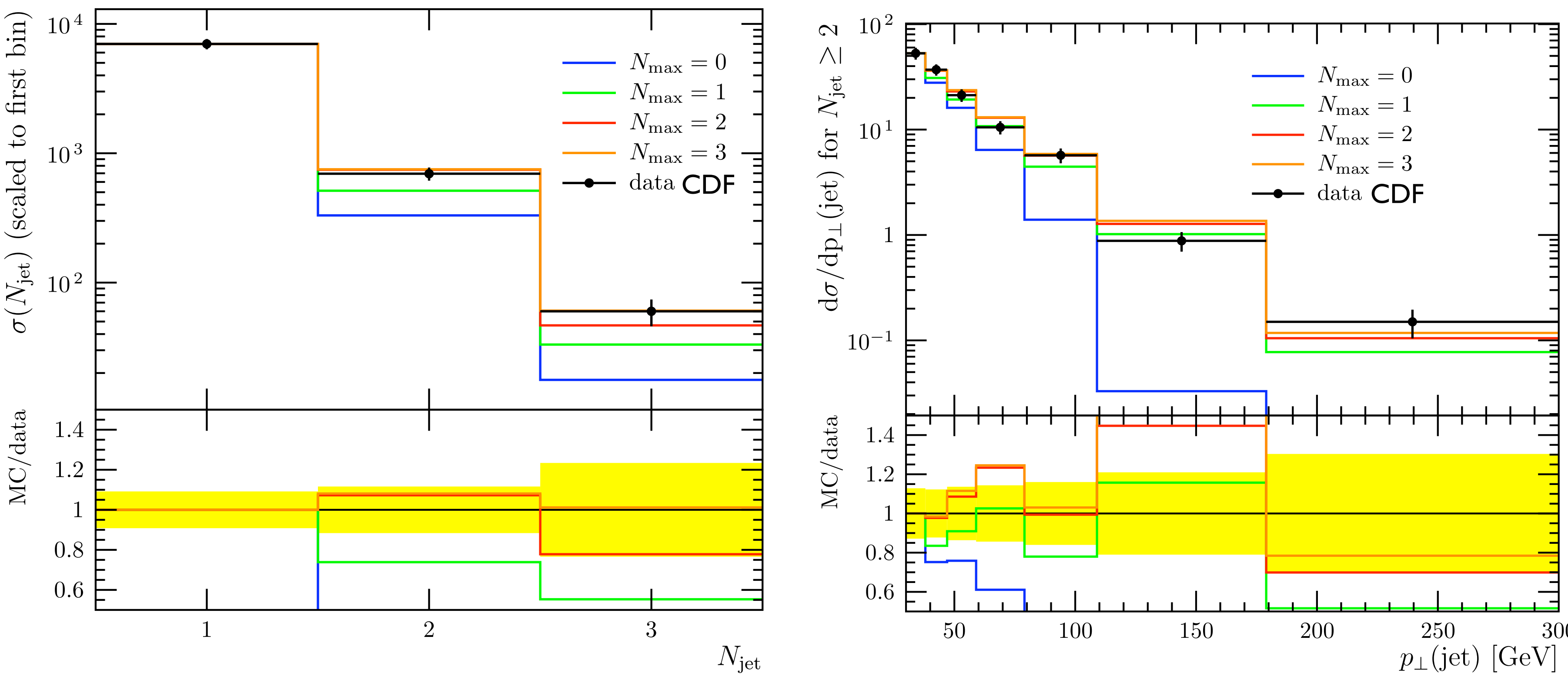




C Anastasiou, G Dissertori, F Stöckli & BW, JHEP03(2008)017 [arXiv:0801.2682]

CKKW matching

- $p\bar{p} \to e^+e^-X\,,\ 66 < m_{ee} < 116\,\mathrm{GeV}$



SHERPA: S Höche, F Krauss, S Schumann & F Siegert, arXiv:0903.1219

Herwig++ v2.3

- **Authors:**
  - CERN/Manchester
    - Mike Seymour
  - Durham
    - Peter Richardson, David Grellscheid, Martyn Gigg*, Jon Tully*
  - Karlsruhe
    - Stefan Gieseke, Manuel Bähr*, Simon Plätzer*
  - Louvain
    - Keith Hamilton•

• Postdoc

* PhD Student

Hard subprocesses

- We provide our own set of basic processes, currently

$$e^+e^- \to Z^0,\ e^+e^- \to q\bar{q},$$
$$e^+e^- \to h^0e^+e^-,\ e^+e^- \to h^0\nu_e\bar{\nu}_e$$
DIS (NC and CC)
Minimum Bias
$$\text{QCD } 2 \to 2,\ pp \to t\bar{t},$$
$$pp \to (\gamma, Z^0) \to \ell^+\ell^-,\ pp \to W^\pm \to \ell^\pm\nu_\ell,$$
$$pp \to (Z^0, W^\pm) + \text{jet}$$
$$pp \to h^0,\ pp \to h^0 + \text{jet},$$
$$pp \to h^0 + W^\pm, pp \to h^0 + Z^0$$
$$pp \to \gamma + \text{jet},\ pp \to \gamma\gamma\ ,$$

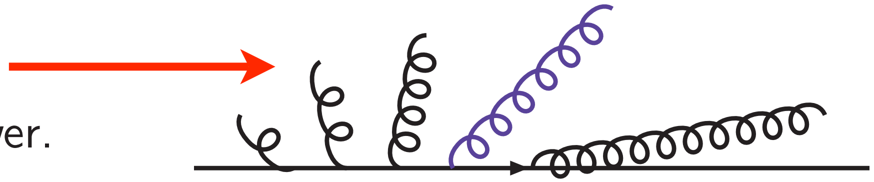
(New from 2.3)

- Many processes available with POWHEG NLO matching.
- `LesHouchesFileReader` enables to read in and process any hard event generated by parton level event generators (`MadGraph/MadEvent`, `AlpGen`, `VBFNLO`, `CompHEP`, `WHIZARD`, ...).
- Exception: BSM Physics. Production and (long) cascade decay chains with spin correlations.

Herwig++ will probably never such a large library of built–in hard matrix elements as its predecessor.

POWHEG matching

- Alternative method to match NLO computations with parton shower Monte Carlos, proposed by P. Nason.
- Generates hardest (highest p_T) emission first.
- Uses modified Sudakov FF for this emission, full NLO recovered upon expansion in α_S.
- `Herwig++` angular-ordered Parton Shower may first emit fairly soft, large angle gluons, then higher p_T later
- *Truncated Shower* adds in this radiation afterwards.
- Finally evolution with vetoed 'ordinary' Parton Shower.



Method avoids Phase Space division into hard/soft region. 'Hardest' emission may also be soft/collinear.

[Nason, JHEP 11 (2004) 040, Frixione, Nason, Oleari, JHEP 11 (2007) 070]

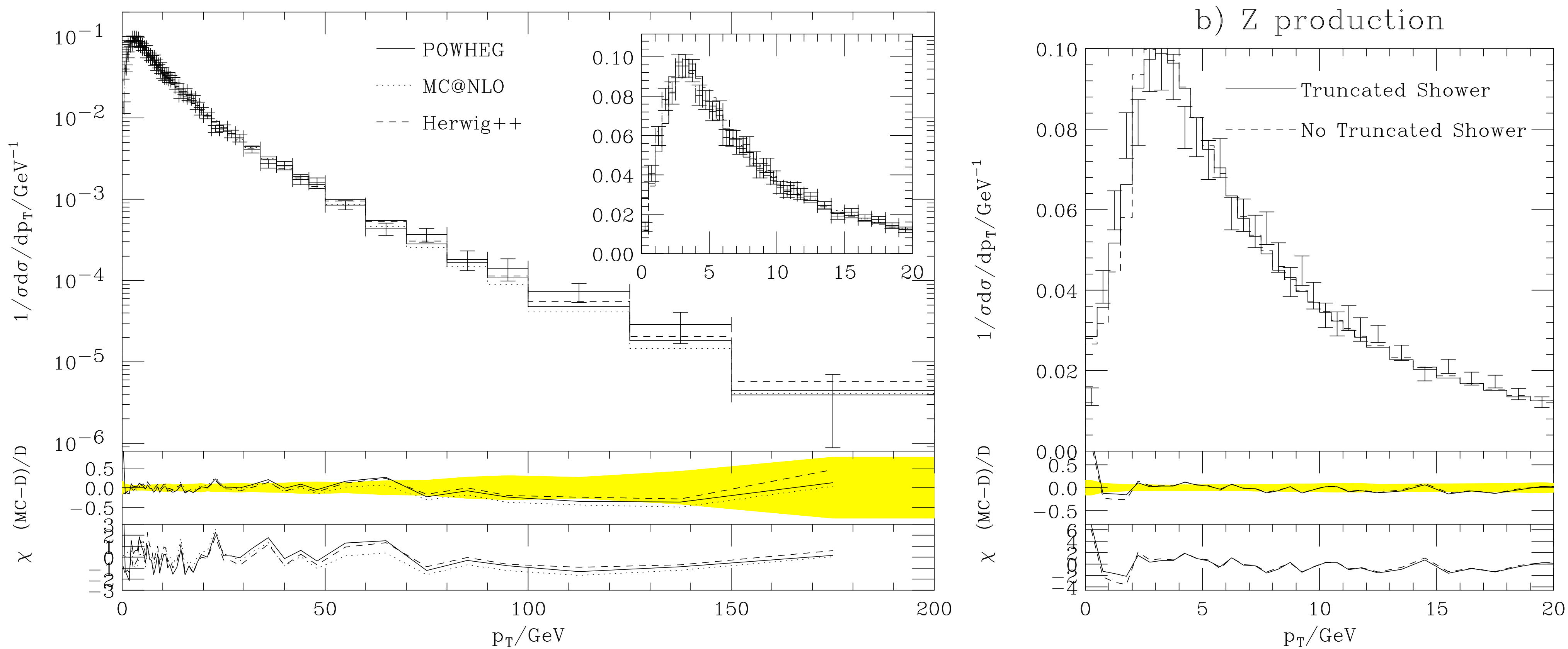
POWHEG in Herwig++

Shipped with v2.3:

- Drell–Yan type, $\gamma * /Z^0$ and $W^\pm$ production.
- Decay of $\gamma * /Z^0/W^\pm$.
- Higgs in gg fusion.
- Higgs in association with $W^\pm$ or Z^0.

With truncated shower. Examples provided.

POWHEG in Herwig++ with full truncated shower.



[K. Hamilton, P. Richardson, J. Tully, 0806.0290]

Effect of truncated shower here very small.

Herwig++ Particle Properties DataBase

This is the production version of the Herwig++ particle properties database. This replaces the storage of particle properties as a text file to improve maintainance and accessiblity.

This is the version of the database which was used to generate the particle properties for Herwig++ version 2.1. The baryon properties were not taken from the database for this release.

The database currently contains 487 particles and 6872 decay modes.

The information is available in a number of forms

- The particles numerically listed according to the PDG code
- The particles listed according to the multiplets taken from the PDG
- The decayers
- The Width Generators
- The Mass Generators
- The references
- Generate the input files for event generation

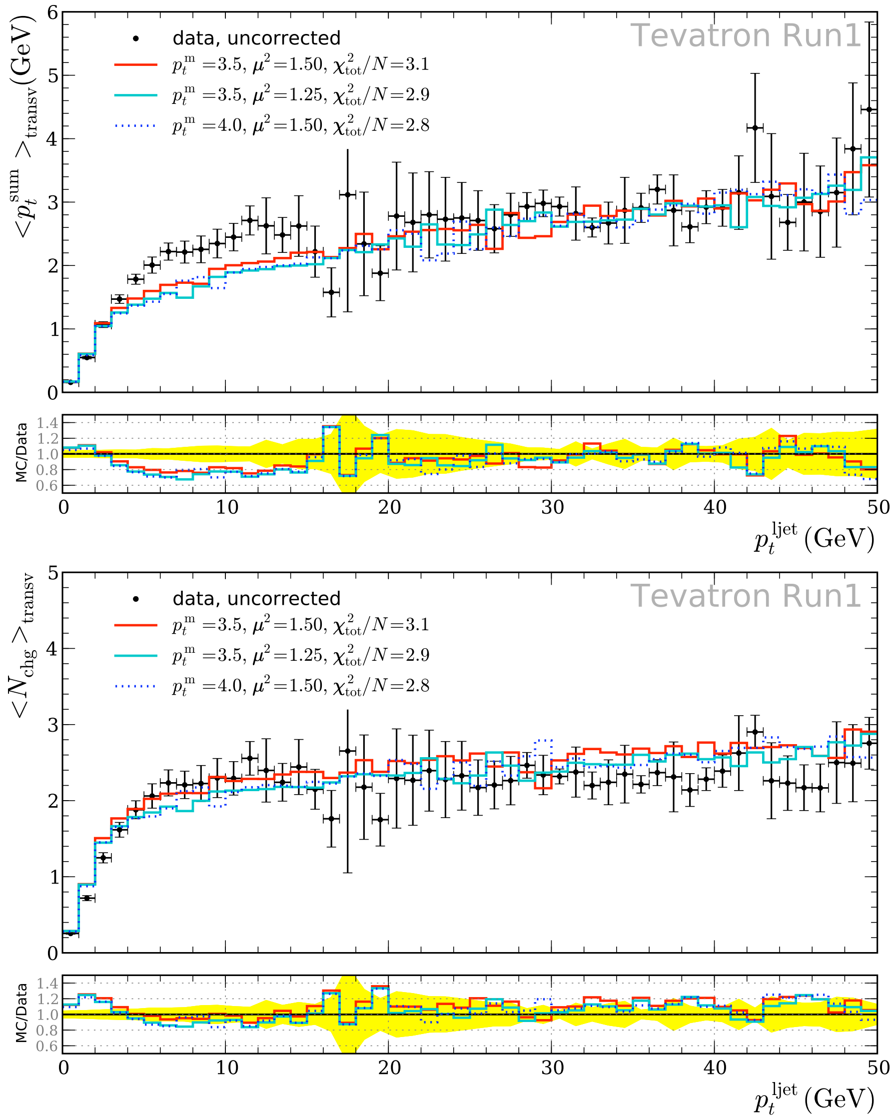
The contents of the database can be altered by following the links in the particle table or particle descriptions or by selecting an option below

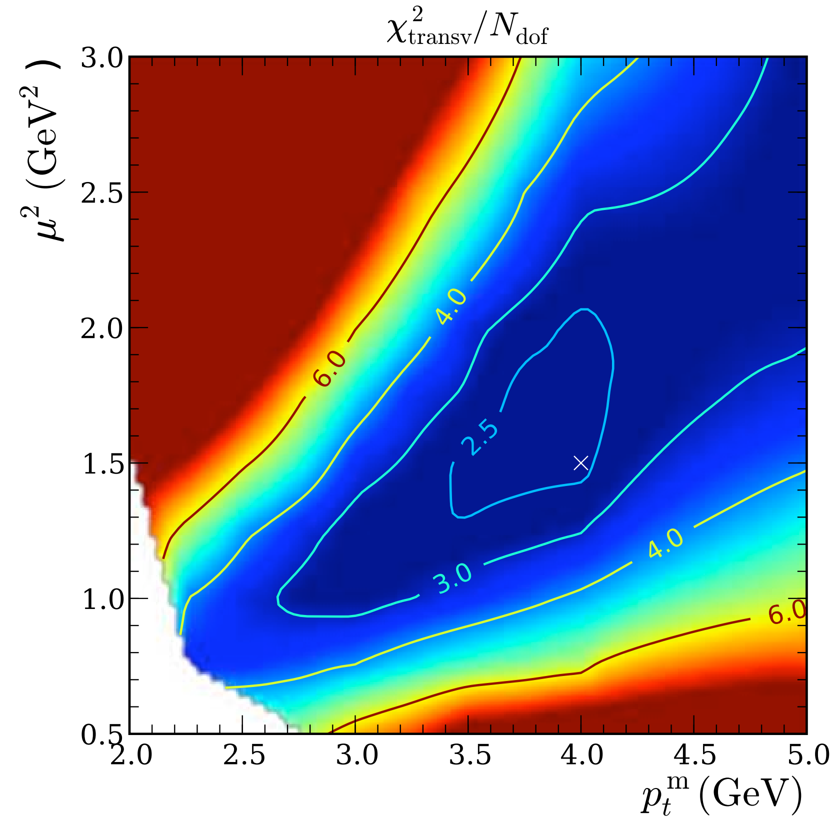
- Add or modify a particle: 0
- Add a decay mode for particle with id: 0

http://www.ippp.dur.ac.uk/~richardn/particles/

Underlying event

Fit of new soft component model to TVT Run 1 data.



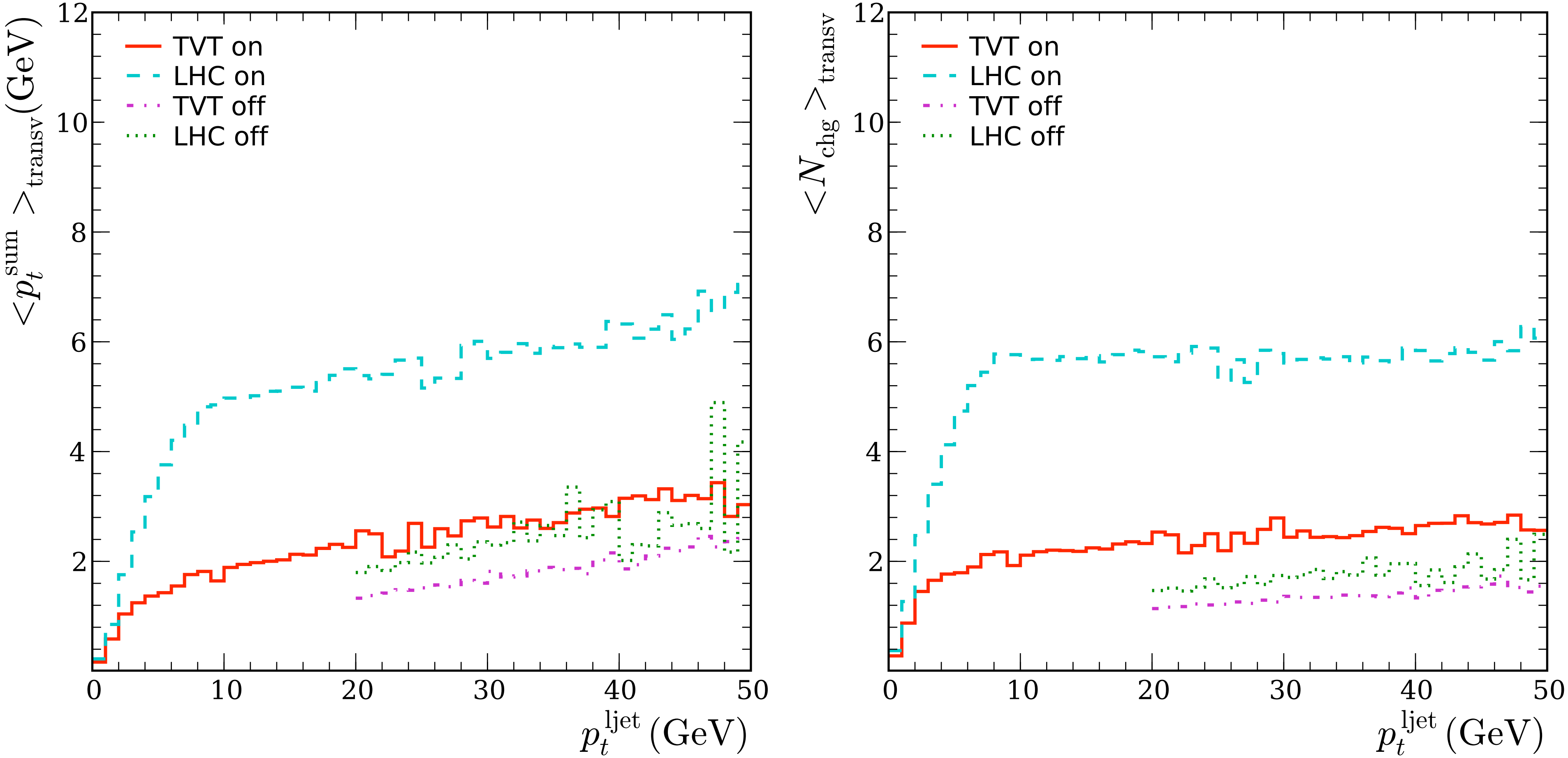


Freedom in hard parameter space.

Soft parameters fixed by $\sigma_{\rm tot}$ and $b_{\rm el}$.

[M. Bähr, PhD thesis (Karlsruhe)]

Underlying event at LHC



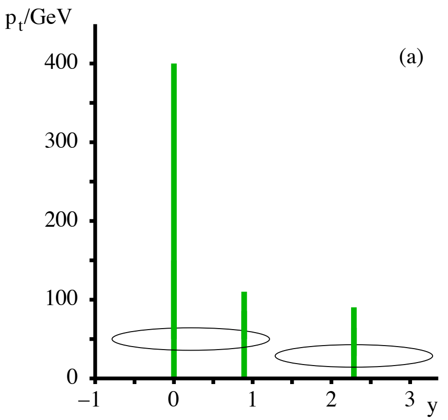
[M. Bähr, PhD thesis (Karlsruhe)]

Jet algorithms

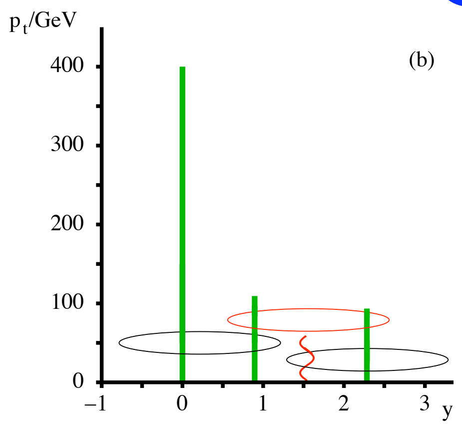
Cones vs Recombination

- Cone algorithms
  - Intuitive, clear jet structure
  - Complicated; problems with IR safety
  - Solved by SISCone — Salam, Soyez
- Recombination algorithms (k_T etc.)
  - Simple, IR safe
  - Slow; messy jet structure
  - Solved by FastJet & anti-k_T — Cacciari, Salam, Soyez

Cone algorithms

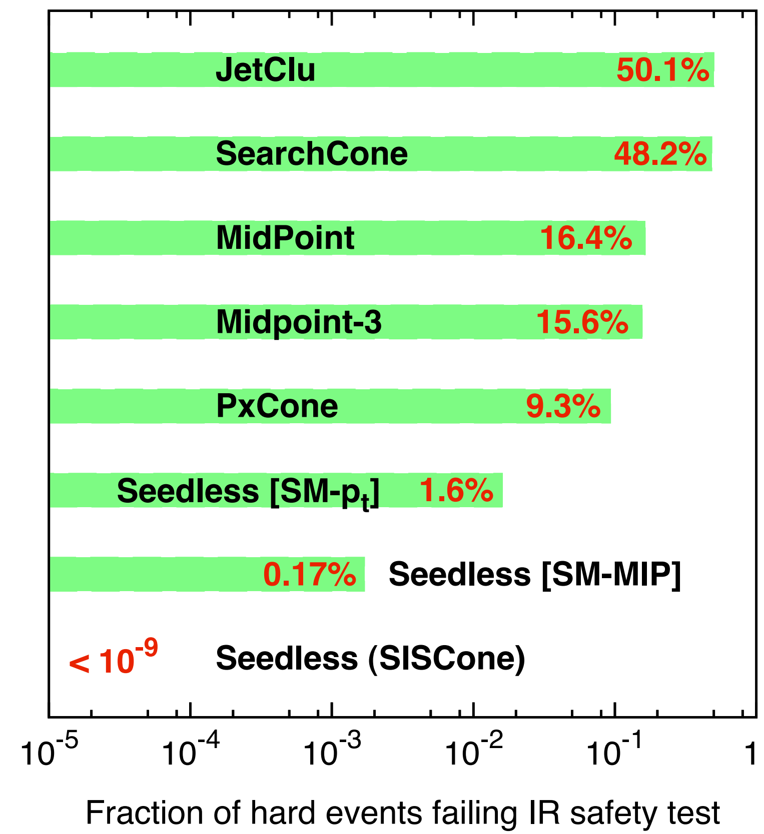


Midpoint

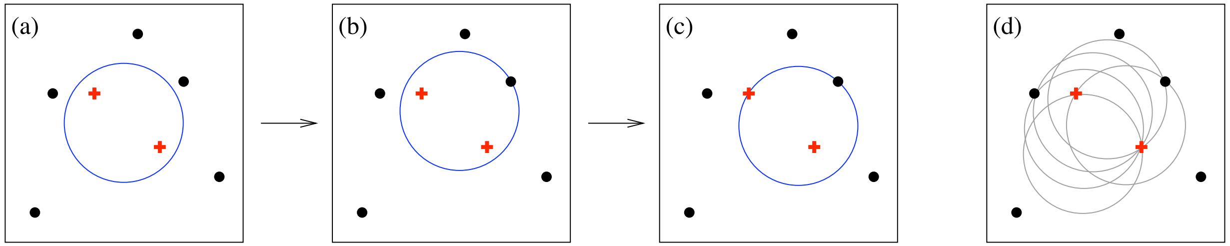


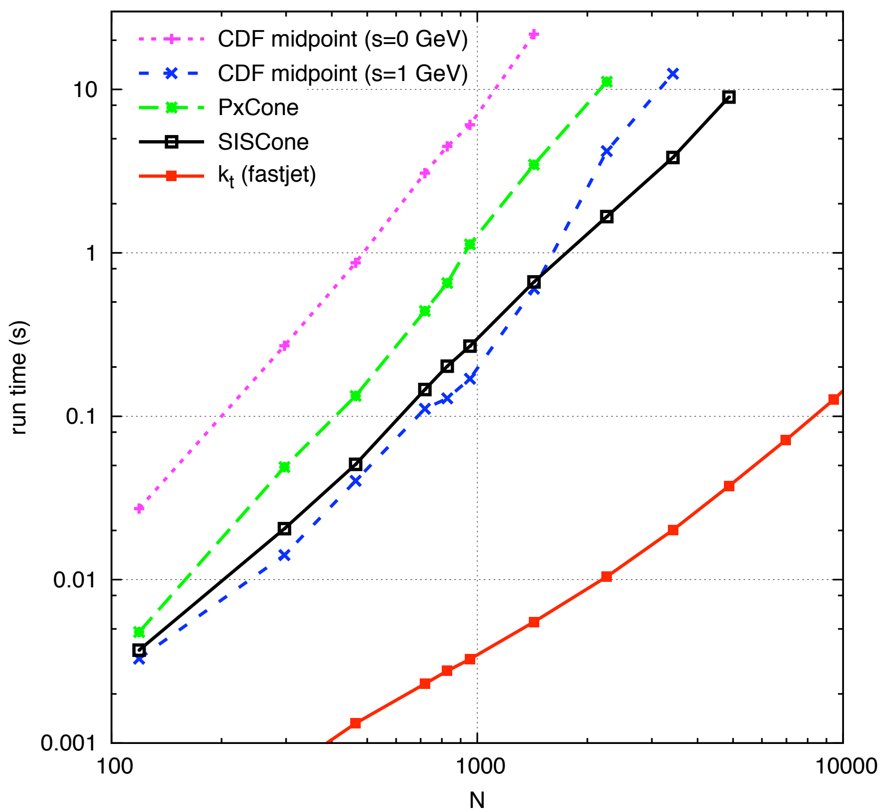
Midpoint + soft

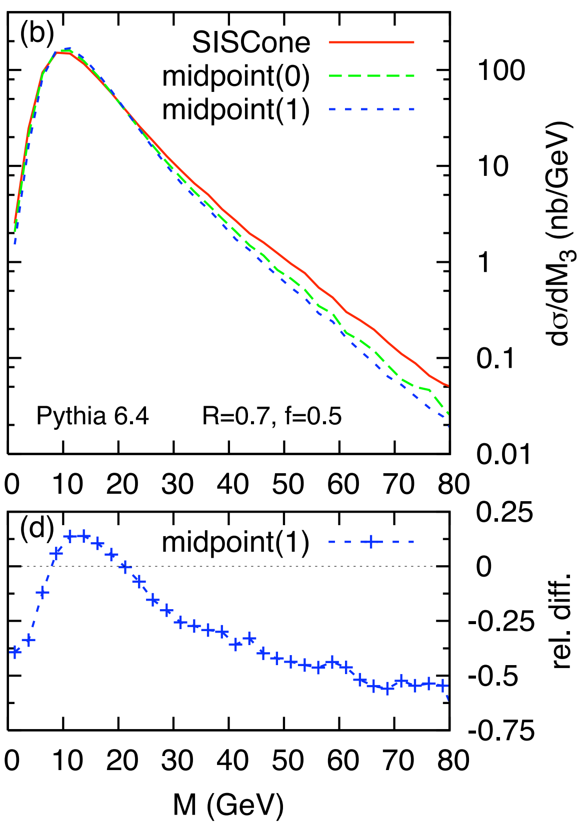
Algorithm	Type	IR unsafe
JetClu	Seeded, no midpoints	2h+1s [9]
SearchCone	Seeded, search cone [21], midpoints	2h+1s [1]
MidPoint	Seeded, midpoints (2-way)	3h+1s [1]
MidPoint-3	Seeded, midpoints (2-way, 3-way)	3h+1s
PxCone	Seeded, midpoints (n-way), non-standard SM	3h+1s
Seedless [SM-p_t]	Seedless, SM uses p_t	4h+1s[a]
Seedless [SM-MIP]	Seedless, SM merges identical protojets	4h+1s[b]
Seedless [SISCone]	Seedless, SM of algorithm 3	no



SISCone


(a)
(b)
(c)
(d)


CDF midpoint (s=0 GeV)
CDF midpoint (s=1 GeV)
PxCone
SISCone
k_t (fastjet)
run time (s)
N
0.001
0.01
0.1
1
10
100
1000
10000


(b)
SISCone
midpoint(0)
midpoint(1)
Pythia 6.4
R=0.7, f=0.5
$d\sigma/dM_3$ (nb/GeV)
(d)
midpoint(1)
rel. diff.
M (GeV)

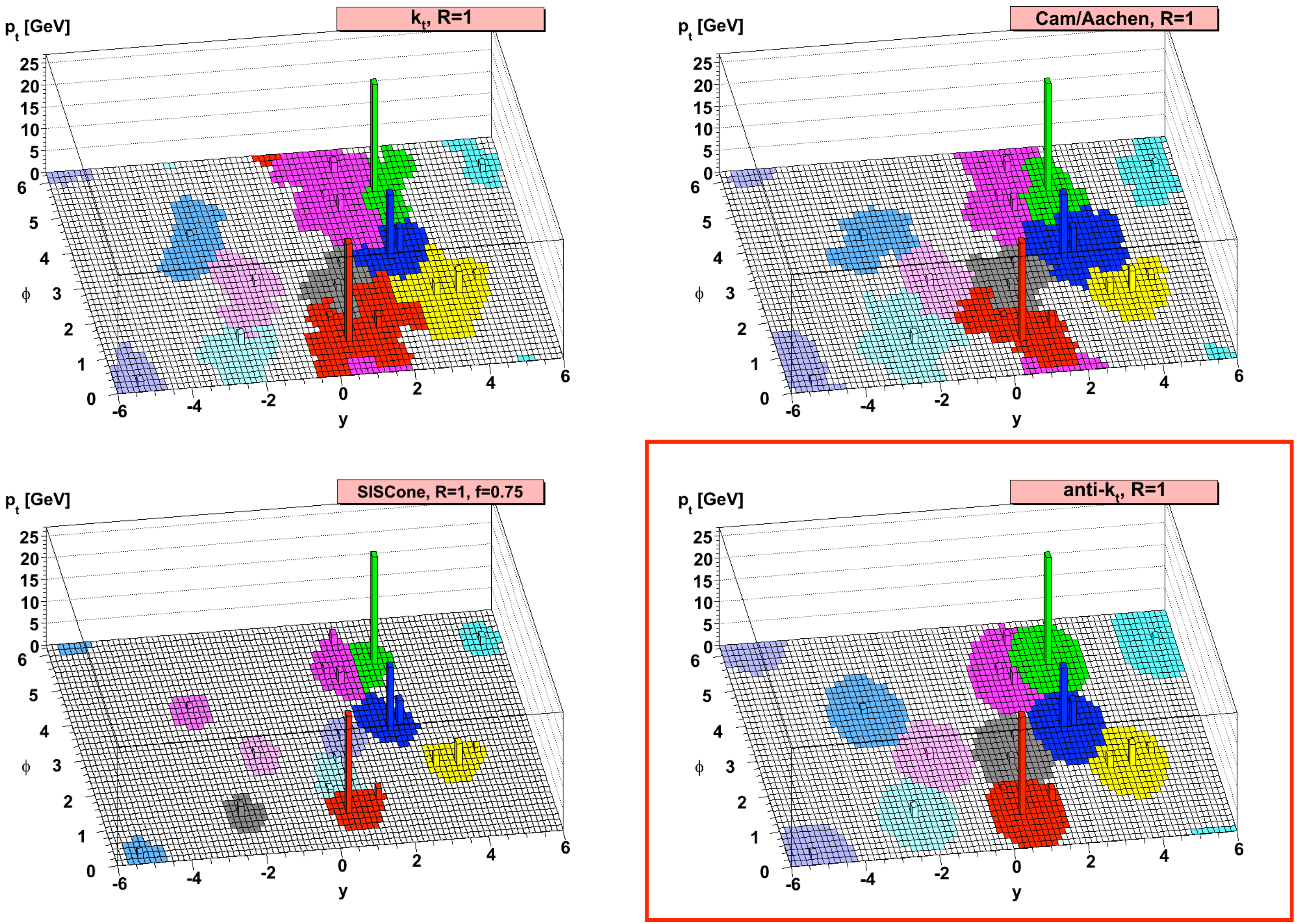
Recombination algorithms

- $d_{ij} = \min\{k_{Ti}^p, k_{Tj}^p\} \Delta R_{ij}/R\,, \quad d_{iB} = k_{Ti}^p$

  $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$

  - p>0 ➞ k_T/Durham
  - p=0 ➞ Cambridge-Aachen
  - p<0 ➞ anti-k_T

Anti-k_T algorithm



Beyond Standard Model

Phenomenological MSSM

Djouadi, Kneur, Moultaka

- Assume (at weak scale):
  - No SUSY $\not{CP}$ → real parameters
  - No tree-level FCNC → sfermion masses and trilinears diagonal
  - 1st & 2nd generation sfermion universality
- This leave 20 MSSM (+5 SM) parameters (+sign μ)
- Computing power and techniques are now available to explore this huge parameter space!

Profumo, Yaguna
Berger, Gainer, Hewett, Rizzo
AbdusSalam, Allanach, Feroz, Hobson, Quevedo

- AbdusSalam et al. adopt a strictly Bayesian approach
  - ➔ Flat or log prior distributions of sfermion masses (range 100 GeV - 4 TeV)
  - ➔ Gaussian errors for observables and SM parameters
  - ➔ Output is relative likelihood and Bayesian evidence
- Nested sampling method computes these efficiently

  Skilling; Feroz & Hobson
  - ➔ Computing resources feasible (~16 CPU-yr)
- Similar approach applied to cMSSM

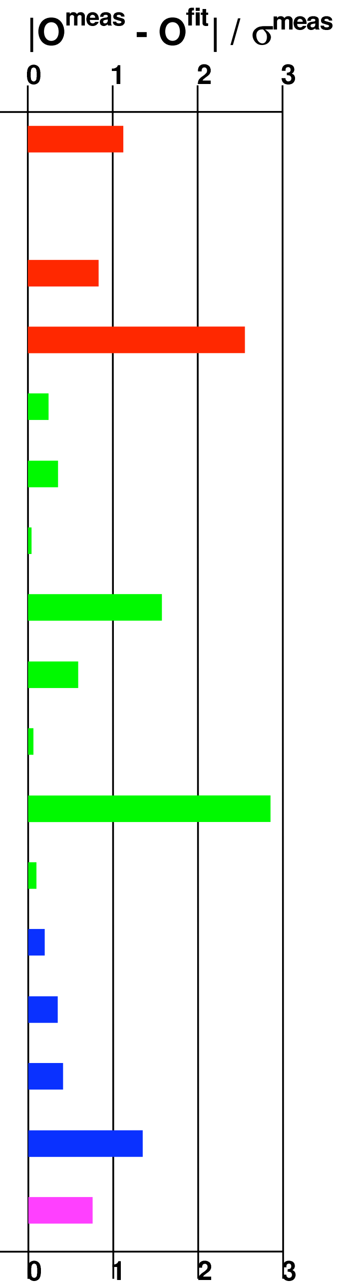
  de Austri, Feroz, Hobson, Roszkowski, Trotta

pMSSM parameters

Parameter	Description	Nat prior fit	Log prior fit
M_1	Bino mass	-2947.1	-250.01
M_2	Wino mass	-1297.0	-3017.3
M_3	Gluino mass	-2397.1	-641.94
$m_{\tilde{e}_L} = m_{\tilde{\mu}_L}$	1st/2nd gen. L_L slepton	1039.7	174.42
$m_{\tilde{\tau}_L}$	3rd gen. L_L slepton	2640.3	993.17
$m_{\tilde{e}_R} = m_{\tilde{\mu}_R}$	1st/2nd gen. E_R slepton	2301.2	200.73
$m_{\tilde{\tau}_R}$	3rd gen. E_R slepton	3747.8	3529.8
$m_{\tilde{u}_L} = m_{\tilde{d}_L} = m_{\tilde{c}_L} = m_{\tilde{s}_L}$	1st/2nd gen. Q_L squark	877.88	164.67
$m_{\tilde{t}_L} = m_{\tilde{b}_L}$	3rd gen. Q_L squark	2300.6	2321.4
$m_{\tilde{u}_R} = m_{\tilde{c}_R}$	1st/2nd gen. U_R squark	3026.9	1514.8
$m_{\tilde{t}_R}$	3rd gen. U_R squark	2617.7	2904.7
$m_{\tilde{d}_R} = m_{\tilde{s}_R}$	1st/2nd gen. D_R squark	1368.3	328.61
$m_{\tilde{b}_R}$	3rd gen. D_R squark	1053.9	1267.8
A_t	top quark trilinear	-1962.6	650.69
A_b	b-quark trilinear	-3540.9	5727.0
A_τ	τ-quark trilinear	4724.6	3196.4
$A_e = A_\mu$	μ-quark trilinear	2153.8	2950.8
m_{H_1}	up-type Higgs doublet	2548.3	3445.0
m_{H_2}	down-type Higgs doublet	882.31	668.83
$\tan\beta$	Higgs vevs ratio	5.2	21.0
m_t	top quark mass	173.37	175.31
m_Z	Z-boson mass	91.186	91.190
$m_b(m_b)^{\overline{MS}}$	b-quark mass	4.164	4.25877
$1/\alpha_{em}(m_Z)^{\overline{MS}}$	e-coupling constant	127.95	127.91
$\alpha_s(m_Z)^{\overline{MS}}$	s-coupling constant	0.11678	0.11609
sign(μ)	sign of Higgs mixing	-1	-1

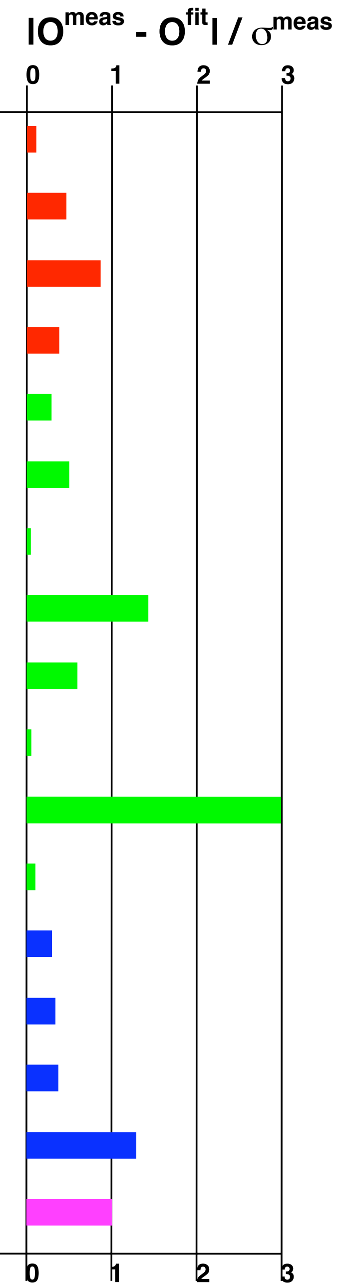
Input observables

Observable	Measurement	Fit (flat prior)
m_W [GeV]	80.399 ± 0.025	80.37092
Γ_Z [GeV]	2.4952 ± 0.00251	2.49520
$\sin^2 \theta^{eff}_{lep}$	0.2324 ± 0.0012	0.23140
$\delta(g-2)_\mu \times 10^{10}$	30.20 ± 9.02	7.15359
R^0_l	20.767 ± 0.025	20.76085
R_b	0.21629 ± 0.00066	0.21605
R_c	0.1721 ± 0.0030	0.17222
A_e	0.1513 ± 0.0021	0.14799
A_b	0.923 ± 0.020	0.93487
A_c	0.670 ± 0.027	0.66831
A^b_{FB}	0.0992 ± 0.0016	0.10376
A^c_{FB}	0.0707 ± 0.035	0.07418
$BR(b \to s\gamma) \times 10^4$	3.55 ± 0.42	3.63154
$R_{BR(B_u \to \tau\nu)}$	1.11 ± 0.32	0.99864
$R_{\Delta M_{B_s}}$	1.15 ± 0.40	0.98640
Δ_{0^-}	0.0375 ± 0.0289	0.07636
$\Omega_{CDM}h^2$	0.1143 ± 0.0200	0.09923



Input observables

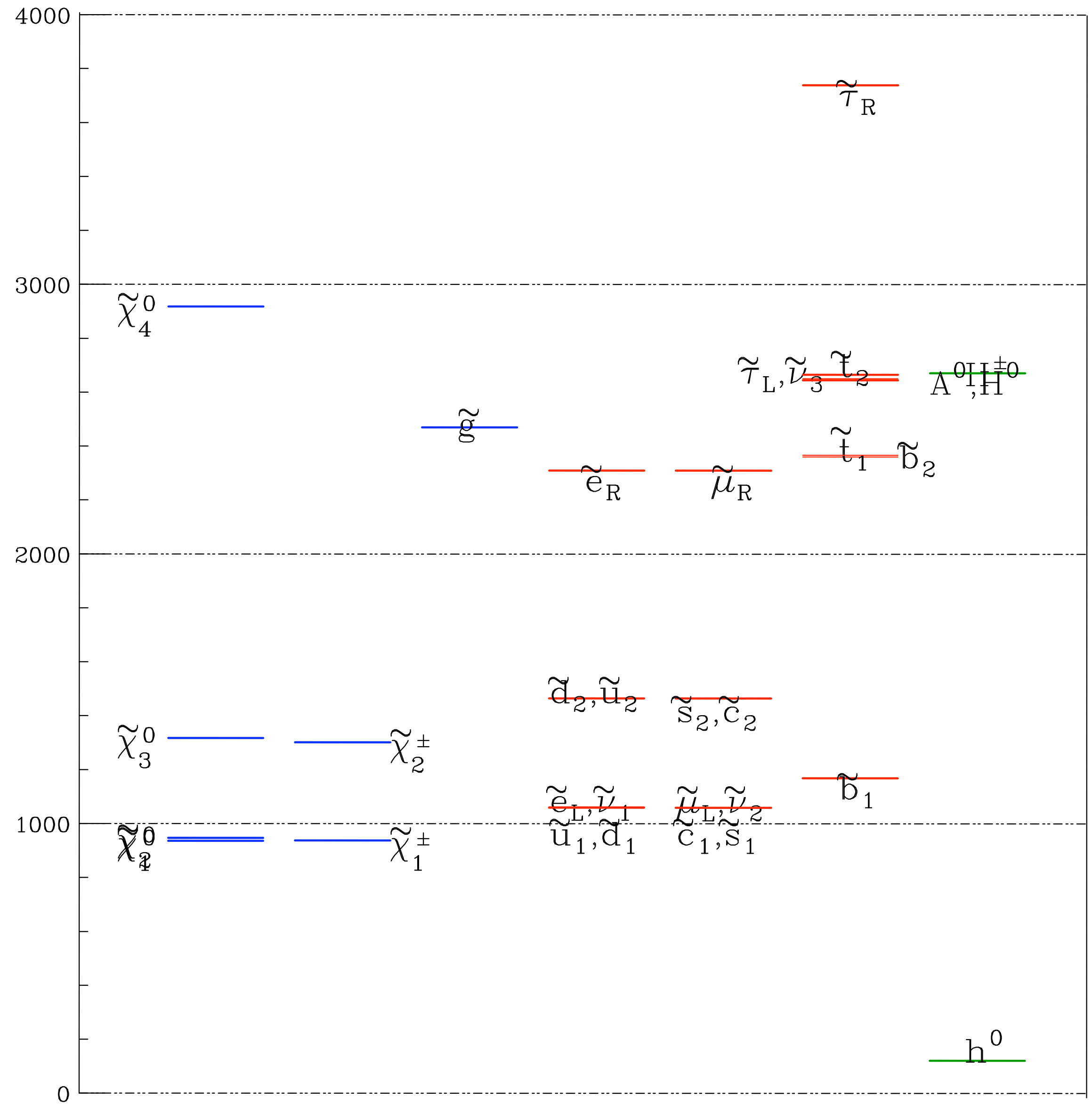
Observable	Measurement	Fit (log prior)
m_W [GeV]	80.399 ± 0.025	80.40175
Γ_Z [GeV]	2.4952 ± 0.00251	2.49637
$\sin^2 \theta^{eff}_{lep}$	0.2324 ± 0.0012	0.23136
$\delta(g-2)_\mu \times 10^{10}$	30.20 ± 9.02	26.73551
R^0_l	20.767 ± 0.025	20.75968
R_b	0.21629 ± 0.00066	0.219617
R_c	0.1721 ± 0.0030	0.17225
A_e	0.1513 ± 0.0021	0.14830
A_b	0.923 ± 0.020	0.93488
A_c	0.670 ± 0.027	0.68508
A^b_{FB}	0.0992 ± 0.0016	0.10399
A^c_{FB}	0.0707 ± 0.035	0.07436
$BR(b \to s \gamma) \times 10^4$	3.55 ± 0.42	3.42260
$R_{BR(B_u \to \tau \nu)}$	1.11 ± 0.32	0.99952
$R_{\Delta M_{B_s}}$	1.15 ± 0.40	0.99873
Δ_{0^-}	0.0375 ± 0.0289	0.07480
$\Omega_{CDM}h^2$	0.1143 ± 0.0200	0.13443



Best fit spectra

	Nat prior	Log prior
$\tilde{e}_L, \tilde{\mu}_L$	1062	271
$\tilde{e}_R, \tilde{\mu}_R$	2310	251
$\tilde{\tau}_L$	2651	1033
$\tilde{\tau}_R$	3740	3530
$\tilde{u}_1, \tilde{c}_1$	1059	384
$\tilde{u}_2, \tilde{c}_2$	3067	1527
$\tilde{t}_1$	2361	2354
$\tilde{t}_2$	2665	2903
$\tilde{d}_1, \tilde{s}_1$	1060	383
$\tilde{d}_2, \tilde{s}_2$	1465	419
$\tilde{b}_1$	1169	1296
$\tilde{b}_2$	2367	2351
χ_1^0	936	243
χ_2^0	947	770
χ_3^0	1317	781
χ_4^0	2918	2864
$\chi_1^\pm$	937	765
$\chi_2^\pm$	1301	2916
A_0, H_0	2671	3529
$H^\pm$	2673	3531
$\tilde{g}$	2470	735
$\tilde{\nu}_{1,2}$	1058	255
$\tilde{\nu}_3$	2645	1018
h	121	119

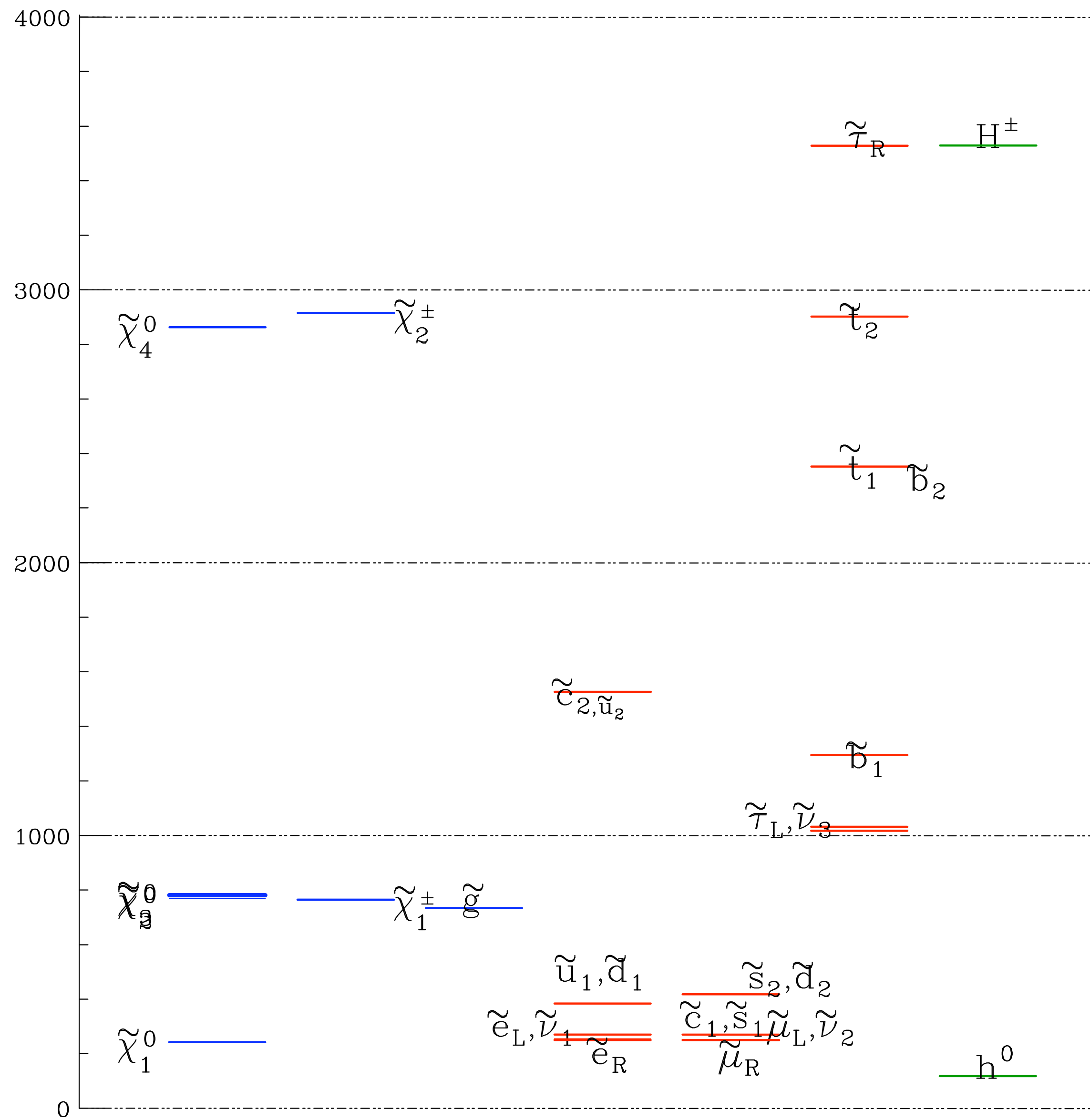
Flat prior



Best fit spectra

	Nat prior	Log prior
$\tilde{e}_L, \tilde{\mu}_L$	1062	271
$\tilde{e}_R, \tilde{\mu}_R$	2310	251
$\tilde{\tau}_L$	2651	1033
$\tilde{\tau}_R$	3740	3530
$\tilde{u}_1, \tilde{c}_1$	1059	384
$\tilde{u}_2, \tilde{c}_2$	3067	1527
$\tilde{t}_1$	2361	2354
$\tilde{t}_2$	2665	2903
$\tilde{d}_1, \tilde{s}_1$	1060	383
$\tilde{d}_2, \tilde{s}_2$	1465	419
$\tilde{b}_1$	1169	1296
$\tilde{b}_2$	2367	2351
χ_1^0	936	243
χ_2^0	947	770
χ_3^0	1317	781
χ_4^0	2918	2864
$\chi_1^\pm$	937	765
$\chi_2^\pm$	1301	2916
A_0, H_0	2671	3529
$H^\pm$	2673	3531
$\tilde{g}$	2470	735
$\tilde{\nu}_{1,2}$	1058	255
$\tilde{\nu}_3$	2645	1018
h	121	119

Log prior



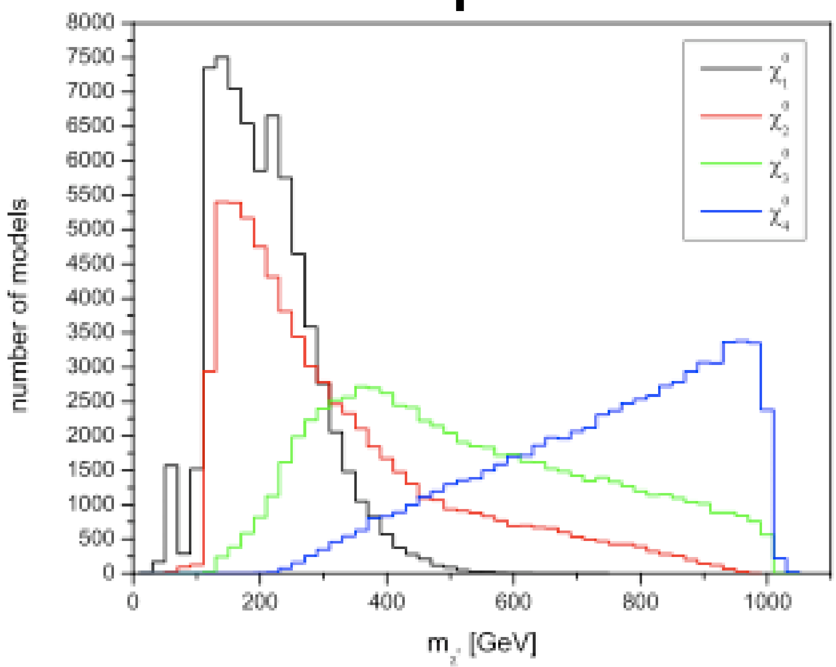
- Berger et al. adopt a more statistical approach
    - Flat or log prior distributions ~10^7 points/models
    - Allowed intervals for observables, central values for SM parameters
    - Models simply accepted or rejected

- Less prior dependence found (but not Bayesian analysis)

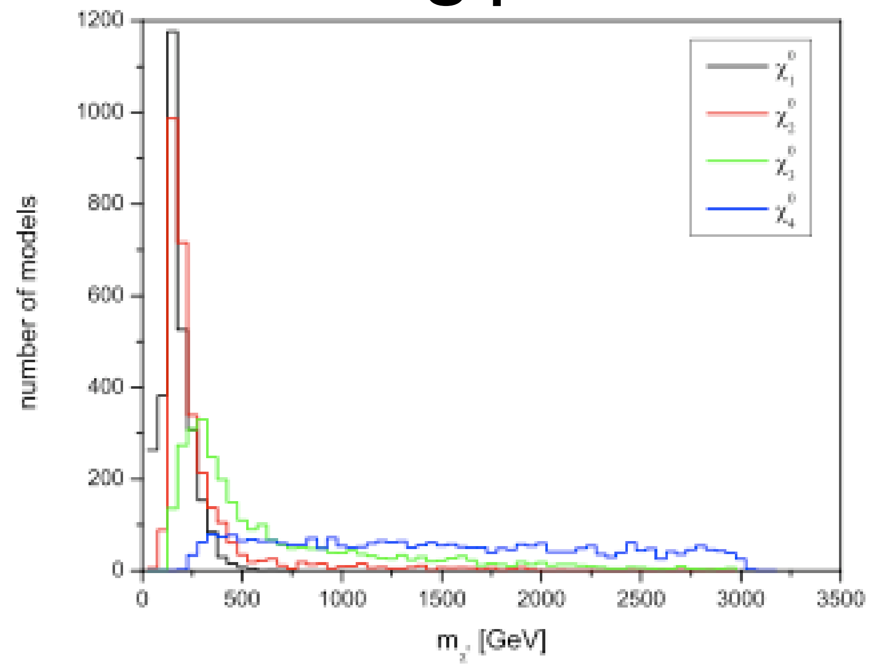
- C.f. earlier work (flat prior only) by Profumo & Yaguna

Neutralino masses

Flat prior



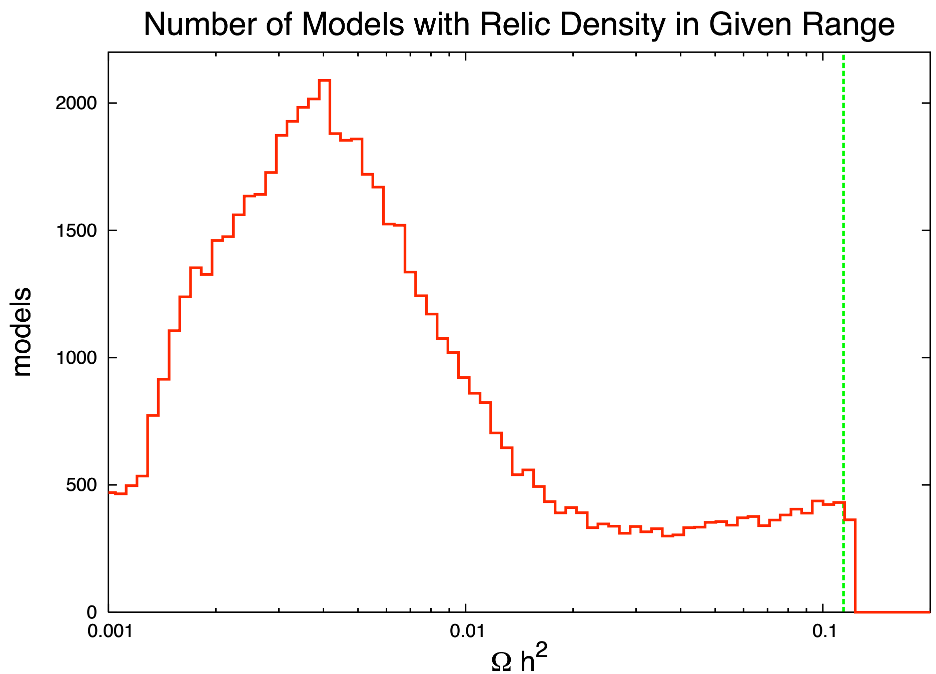
Log prior



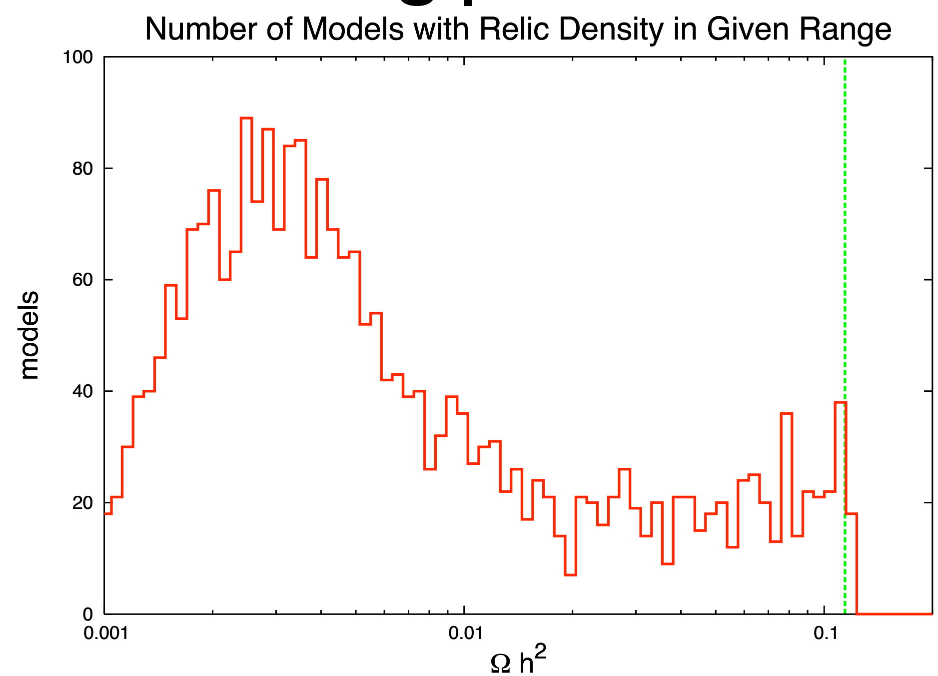
- N.B. Different scales

Relic LSP density

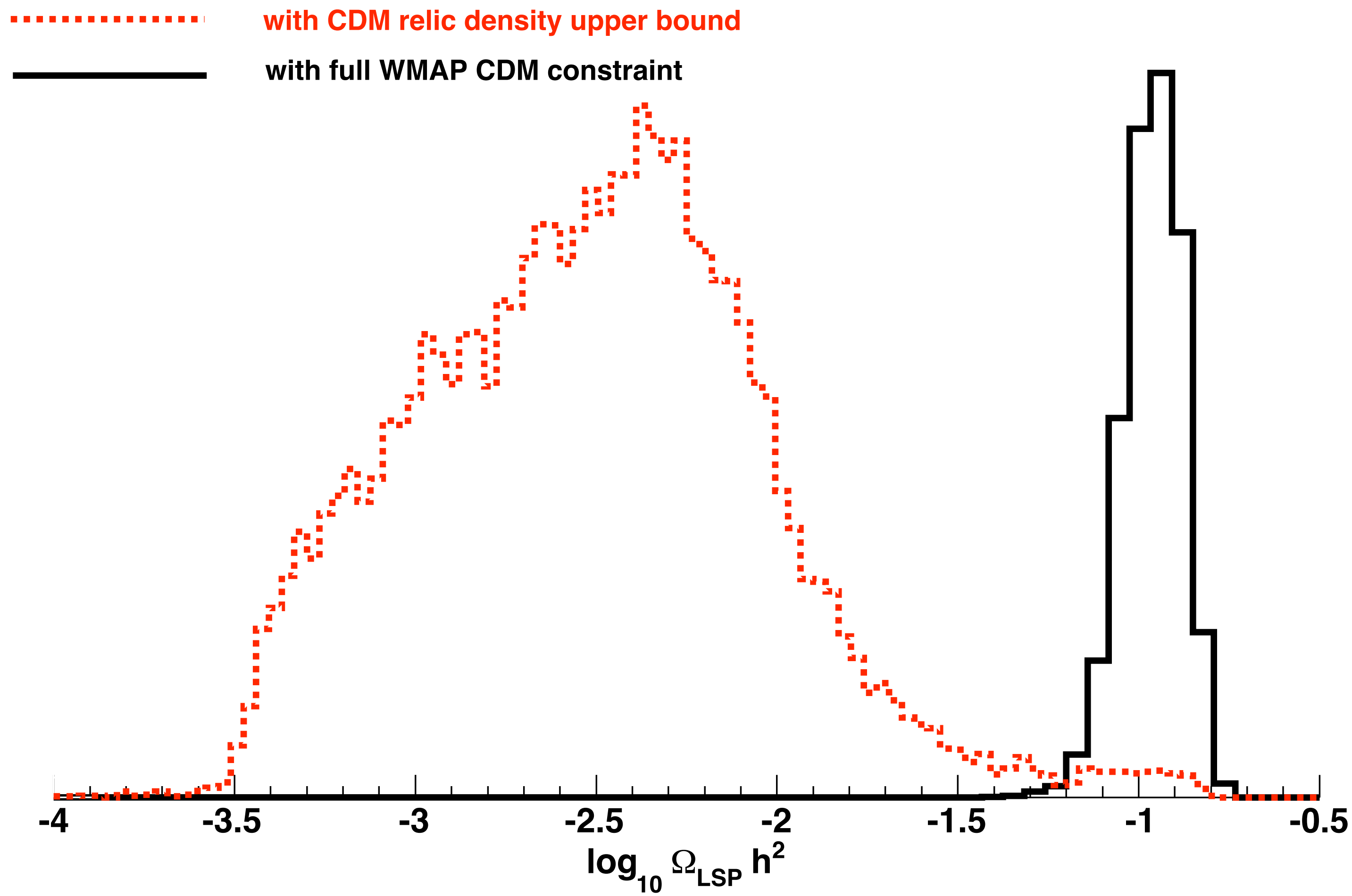
Flat prior



Log prior



- In most models LSP only a small fraction of dark matter!



- Similar result from AbdusSalam et al. if they relax WMAP constraint

Conclusions

- Many powerful new techniques and tools
  - NLO wish-list will soon be completed
  - MCs matched to NLO and multijets
  - Fast, IR-safe, practical jet algorithms
  - Powerful parameter space searches
- Why the sudden surge in progress?
  - LHC attracts clever young people to phenomenology!