Monte Carlo Event Generators for the LHC

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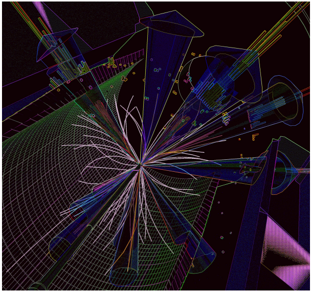
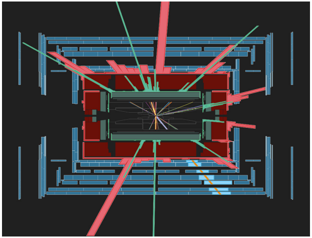
LHC Theory 2009, TRIUMF, Vancouver, April 29th, 2009

The Charge of the LHC Measurements

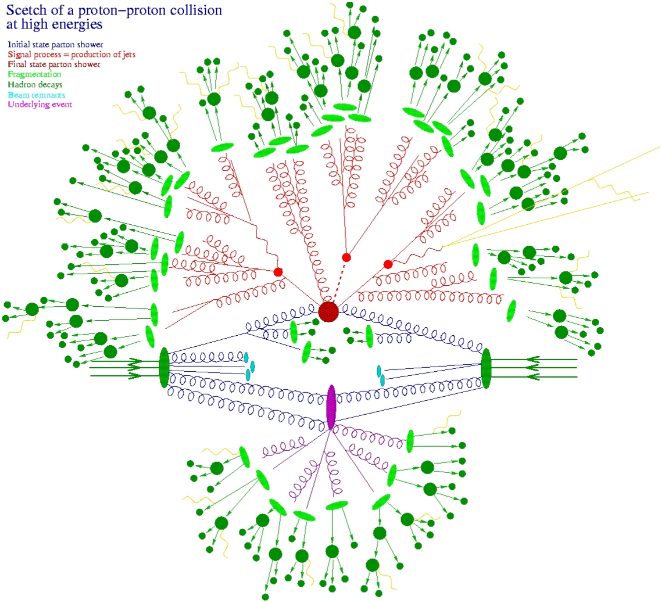
- LHC: Collisions are scheduled for October 2009 ($\sqrt{s} \lesssim 10$ TeV)





- First important task: (re)discover the Standard Model (SM)
- With higher and higher statistics:
  look for deviations of data from SM
- Extremely precise knowledge of SM distributions mandatory
- Predictions for New Physics necessary
- Usual approach: comparison Monte Carlo simulation – data

What is an event (theory)?



Definitions+Taxonomy: Monte Carlo/Event Generators

- Full or Multi-Purpose MC Generator:
  only when containing showers and hadronization
  (aka: as hadron level MC, opposite: parton level MC)
- Shower Monte Carlo: contains only showering
- Event Generator: only when generating positive weights
- Multi-Particle Event Generator: allows for at least $2 \to 6$ processes
- Generator Generator: only when arbitrary processes can be chosen by the user
- BSM MC: must (OK: should) contain at least the MSSM, Z', and one non-SUSY model
- Dedicated tools: designed for special purposes (NLO bkgd. processes, black holes, you name it)
- Best tool on the market: depends on who is giving the talk

Matrix Element Generation of (tree) amplitudes

- Computer program for $(\mathcal{L}, \{\text{incoming}\}, \{\text{outgoing}\}) \mapsto \mathcal{M}(\alpha_1, \ldots; p_1, \ldots; s_1, \ldots)$
  - $\mathcal{L}$: Lagrangian (or Feynman rules) of a model (SM, MSSM, …)
  - $\mathcal{M}(\alpha_1, \ldots; p_1, \ldots; s_1, \ldots)$: a function

$$\underbrace{\mathbf{R} \times \ldots \times \mathbf{R}}_{\text{masses, couplings, …}} \times \underbrace{V^+ \times \ldots \times V^+}_{\text{4-momenta (forward light cones)}} \times \underbrace{\mathbf{Z} \times \ldots \times \mathbf{Z}}_{\text{helicities, colors}} \to \underbrace{\mathbf{C}}_{\text{amplitude}}$$

  evaluated numerically, and linked to MC phase space integrators and generators
- early 1990s: 1st robust examples CompHEP, FeynArts, Grace, MadGraph, …

text book rules for manual calculations algorithmic ⇒ implementable in computer program

- NB: familiar trace techniques rarely used, because
  - tedious for polarized scattering
  - intermediate expressions grow quadratically with # Feynman diagrams
    - # polarization states grows with a power of the number of particles
    - # Feynman diagrams grows with a factorial of the number of particles

  ⇒ helicity amplitudes win (eventually)!
- Algorithm for generating all tree diagram topologies with n external legs
  1. generate all tree diagrams with $n-1$ external legs
  2. insert the nth line once (in propagators+external lines)
  3. adding quantum numbers from the outside in
- automated construction of efficient tree level MEs well understood

Redundancy of Feynman Diagrams

The number of tree Feynman diagrams w/ n legs grows like a factorial, e. g. in ϕ^3-theory: $F(n) = (2n-5)!! = (2n-5)\cdot(2n-7)\cdot\ldots\cdot 3\cdot 1$

n		
4		
5		
6		
7		
8		
9		
10		
11		
12		
13		
14		
15		

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n	$F(n)$
4	3
5	15
6	105
7	945
8	10 395
9	135 135
10	2 027 025
11	34 459 425
12	654 729 075
13	13 749 310 575
14	316 234 143 225
15	7 905 853 580 625

- computational costs grow beyond all reasonable limits
- gauge cancellations cause loss of precision

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n	$F(n)$	$P(n)$
4	3	3
5	15	10
6	105	25
7	945	56
8	10 395	119
9	135 135	246
10	2 027 025	501
11	34 459 425	1 012
12	654 729 075	2 035
13	13 749 310 575	4 082
14	316 234 143 225	8 177
15	7 905 853 580 625	16 368

- ☹ computational costs grow beyond all reasonable limits
- ☹ gauge cancellations cause loss of precision

Number of possible momenta in tree diagrams grows only exponentially

$$P(n) = \frac{2^n - 2}{2} - n = 2^{n-1} - n - 1$$

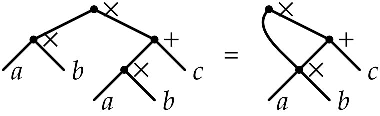
$\Rightarrow$ Feynman diagrams redundant for many external particles!

The optimal solution

Ohl/JR, 2001

⇒ Replace forest of tree diagrams by
Directed Acyclical Graph (DAG) of the algebraic expression.

$$ab(ab+c) =$$



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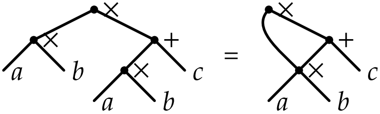
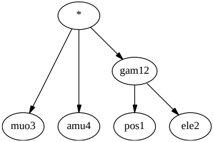


- simplest examples: $e^+e^- \to \mu^+\mu^-$, and



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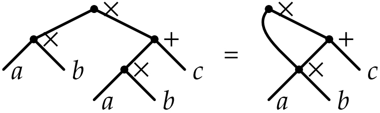
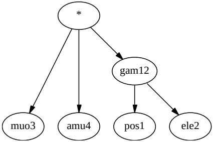
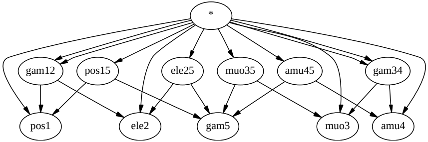


- simplest examples: $e^+e^- \to \mu^+\mu^-$, $e^+e^- \to \mu^+\mu^-\gamma$ and





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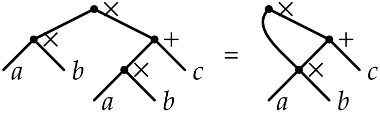
$ab(ab + c) =$ 

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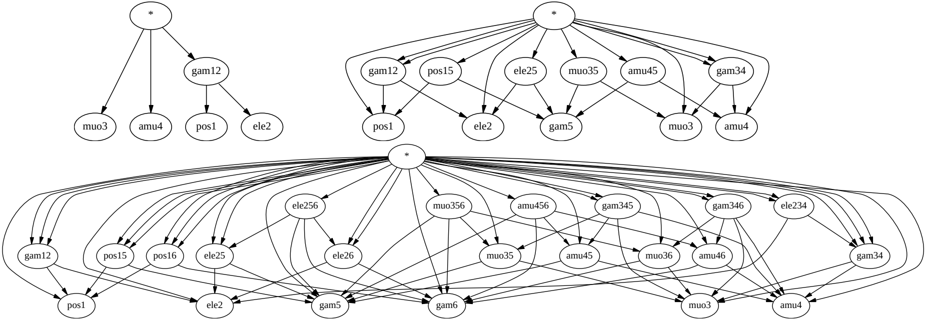


Efficient tree amplitudes – What about loops?

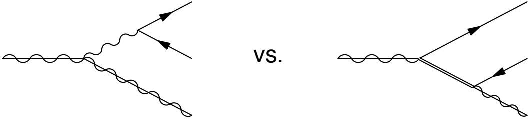
- Berends-Giele Recursion Relations [Berends, Giele]
  - manual calculations
- HELAS [Hagiwara et al.],
  - manual partial common subexpression elimination
- Madgraph [Stelzer et al.], AMEGIC++, COMIX [Krauss et al.]:
  - partial common subexpression elimination

  $\Rightarrow$ partial elimination of redundancy
- ALPHA [Caravaglios & Moretti]:
  - tree level scattering amplitude is Legendre transform of Lagragian
  - can be performed numerically, using only $P^*(n)$ independent variables
- HELAC [Papadopoulos et al.]:
  - ALPHA algorithm reformulated as recursive numerical solution of Schwinger-Dyson equ.
- O'Mega [Ohl/JR]:
  - systematic elimination of all redundancies
  - symbolic, generation of compilable code

- simple tree level algorithm $n \to n+1$ doesn't work for loop diagrams because
- most efficient, but badly documented tool for multi loop diagrams QGRAF [Nogueira, 1991]
- Approaches for loops by trees (Feynman's tree theorem) [Catani et al., JR et al.]

Phase Space Generation/Integration

- RAMBO algorithm: generates n particle momenta distributed flat in phase space (only massless particles)
- massive generalization MAMBO works badly
- Difficult task: set of 'good' integration variables different for each graph $\Rightarrow$



- Therefore: Adaptive integration using Monte Carlo sampling
  Old best tool: VEGAS [P. Lepage, 197x]
- For electroweak SM and BSM models not good enough: presence of (maybe overlapping) resonances

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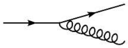
- Multi-channel adaptive phase space integration:
  - Dominant channels selected according to Feynman graph structure
  - Channel weights and channel mappings iteratively adapted
  - Highly sophisticated algorithm: VAMP (Vegas AMPlified) [T. Ohl, 1998]
- Special treatments for special situations: QCD showers/dipoles and all that...
- Final step: unweighting events ⇒ adapted grids should map integrand as close to a constant as possible

Parton Showers

- Problem: need to describe $2 \to 10 - 100$ QCD processes
- MEs may available in leading color: PS not
- QCD emission dominated by large logs: $\alpha_s^n \log^{2n} \frac{Q}{Q_o} \sim 1$:
- Generated from emissions ordered in Q: soft-/collinear

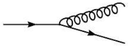
Universal DGLAP splitting kernels for collinear limit:

$$d\sigma = \sigma_0 \sum_{\text{jets}} \frac{d\theta^2}{\theta^2} \frac{\alpha_S}{2\pi} P(z) dz$$

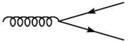


$$P_{q\to qg}(z) = C_F \frac{1+z^2}{1-z}$$

$$P_{g\to gg}(z) = C_A \frac{(1-z(1-z))^2}{z(1-z)}$$



$$P_{q\to gq}(z) = C_F \frac{1+(1-z)^2}{z}$$



$$P_{g\to qq}(z) = T_R(1-2z(1-z))$$

- Many possible evolution variables: θ, Q, $p_\perp$ $\tilde{q}$, t
  - θ: HERWIG
  - Q: PYTHIA ≤ 6.3, SHERPA
  - $p_\perp$: PYTHIA ≥ 6.4, ARIADNE, CS-SHERPA
  - $\tilde{q}$: HERWIG++

- Independent collinear emission: probabilistic picture/Sudakov factor

$$dP(\text{next emission at } t) = \frac{dt}{t} \int_{z_-}^{z^+} \frac{\alpha_s(z,t)}{2\pi} \hat{P}(z,t) dz \exp\left[- \int_{t_0}^{t} \frac{dt}{t} \int_{z_-}^{z^+} \frac{\alpha_s(z,t)}{2\pi} \hat{P}(z,t) dz \right]$$

- Soft emission: angular ordering → color coherence: important effects in
- Generally: stop shower vs. veto approach
- Lot of heuristics: hard scale, evolution parameter, available PS, integration limits, regularization, ...

- New approach: "analytic PS" (Geneva algorithm) [Bauer/Schwartz/Thaler]
  - Analytic determination of shower weights
  - allows reweighting on an event-by-event basis
  - generalization to ISR [Schmidt/JR/Kilian]

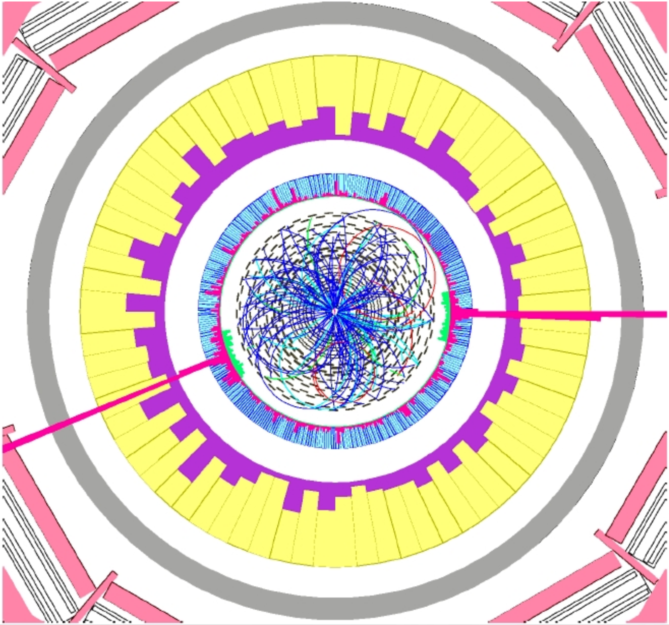
- Not mentioned: specific parton shower MCs like GENEVA, VINCIA, ARIADNE
- Not mentioned: dependence and choice of variables
- Not mentioned: non-leading color

Matrix element/parton shower matching/merging

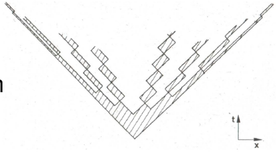
- **Problem:** Additional hard jet produced by the parton shower
  - Jets generated in regions where soft-collinear approx. invalid
  - not the whole phase space populated (dirty trick: Power Shower)
  - General rule: matrix element OK for high p_T, overshoot infrared, showers OK in the infrared, undershoot high p_T
- Solution: **Merge ME and PS**:
- Explicit corrections of $2 \to 2$+PS with $2 \to 3$ MEs (PYTHIA/HERWIG)
- Matching with LO MEs:
  - CKKW(-L): [Catani/Krauss/Kuhn/Webber, Lönnblad]
    - first hardest emission by full MEs
    - preserve shower-evolution equations (logarithmic accuracy)
    - phase-space slicing to avoid double counting $\Rightarrow$ veto shower emissions above scales
    - reweight MEs with pseudo-shower history (Sudakov factors)
  - MLM: [Mangano]
    - generate all shower history, throw away those that run into ME region
  - new CS-inspired phase-space separation criterion (SHERPA)
  - Matching allows samples of different jet multiplicity:

    $W + X|_{\text{incl.}} = W + 0j\Big|_{\text{incl.}} + W + 1j\Big|_{\text{incl.}} + W + 2j\Big|_{\text{incl.}} + \ldots$
- Matching with NLO MEs:
  - MC@NLO
  - POWHEG scheme
  - Catani-Seymour dipoles/Antennae

Higgs in disguise



Hadronization: Lund or Cluster or What?

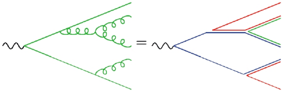


- Old models: flux tubes, independent fragmentation
- Independent fragmentation: dresses bare quarks

  "last quark", Lorentz invariance, infrared safety

- **Lund string model:** based on old string model for strong interactions
  - invented without PS in mind
  - strong physical motivation
  - universal description of data (ee fit → hadron)
  - Plethora of parameters: $\mathcal{O}(1) \sim$ per hadron

- **Cluster fragmentation model:** (uses preconfinement)
  - Parton shower orders partons in color space
  - Large N_C limit: planar graphs dominate
  - Cluster is continuum of high-mass resonances, then decays into hadrons
  - No spin info, just phase space
  - Suppression of heavier particles (esp. baryons)
  - Cluster spectrum determined by parton shower (pert. theory)



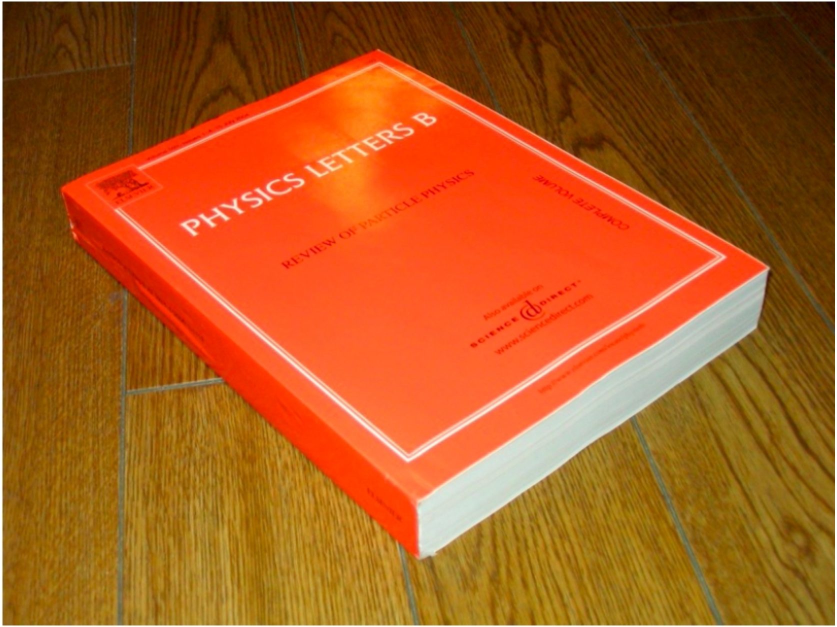
- **Summary:** All programs use either Lund or cluster (independent fragmentation only for inclusive cross sections)

Hadronic decays

$$B^{*0} \to \gamma B^0$$
$$\hookrightarrow \bar{B}^0$$
$$\hookrightarrow e^- \bar{\nu}_e D^{*+}$$
$$\hookrightarrow \pi^+ D^0$$
$$\hookrightarrow K^- \rho^+$$
$$\hookrightarrow \pi^+ \pi^0$$
$$\hookrightarrow e^+ e^- \gamma$$

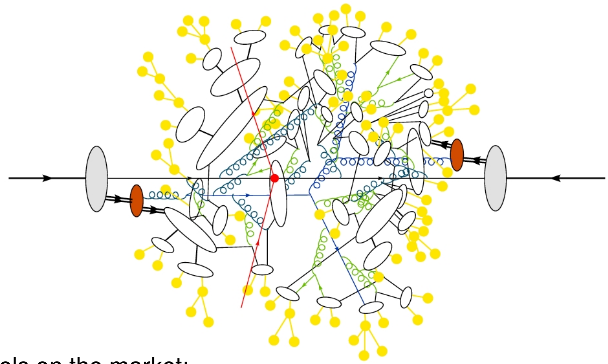
- radiative EM decay
- weak mixing
- weak decay
- strong decay
- weak decay, ρ mass smeared
- ρ^+ polarized, angular correlations
- Dalitz decay, m_{ee} peaked

100s of particles, 1000s of decay modes, form factors, PDG unitarity violation, ...


PHYSICS LETTERS B
REVIEW OF PARTICLE PHYSICS
COMPLETE VOLUME
Also available on
SCIENCE DIRECT
www.sciencedirect.com

Underlying Event (aka Multiple Interactions, UE/MI)

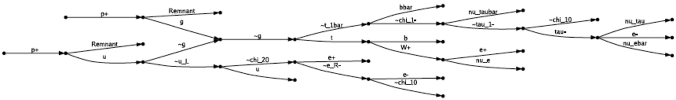
- Various definitions:
  - everything that is not of interest
  - multiple parton interactions (MPI) from same bunch
  - beam remnants: soft interactions and ISR



- Many models on the market:
  - Eikonal approximation of optimal theorem
  - Adding more than one hard interaction
  - Lots of dirty details: what to do about ....???
- Still best reference: PYTHIA manual !!!

HERWIG++

- Acronym: **H**adron **E**mission **R**eactions **W**ith **I**nterfering **G**luons
- Authors/location: Durham/Manchester/Karlsruhe S. Gieseke, P. Richardson, M. Seymour, P. Marchesini + postdocs/PhDs
- Current version 2.3.1 `http://projects.hepforge.org/herwig`
- Reference arXiv:0803.0883
- Prog. language: `C++` (new adaptation of older `FORTRAN 77` program)
- contains parton shower (angular ordered), POWHEG matching
- contains hadronization (cluster fragmentation model)
- contains multiple interactions/UE (`JIMMY`)
- No arbitrary processes: hardcoded library for SM processes (built: BSM chains)
- BSM: MSSM/UED/RS, only as decay chains with spin correlations
- No multi-leg matrix elements: cascade set-up, but including spin density matrices



- Interface to other (ME) generators

PYTHIA (6 vs. 8)

- Acronym: none (wise and mighty seer from the ancient times)
- Authors/location: Lund/Fermilab T. Sjöstrand, S. Mrenna, P. Skands
- Current version: 6.4 + 8.1.20 `http://projects.hepforge.org/pythia6` and `http://home.thep.lu.se/~torbjorn/pythia.html`
- Reference: arXiv:hep-ph/0603175 and arXiv:0710.3820 [hep-ph]
- Prog. Language: FORTRAN 77 (PYTHIA 6) C++ (PYTHIA 8)
- parton shower (virt. $\to p_\perp$ ordered, dipole shower [v8])
- Hadronization (Lund string model)
- No arbitrary processes: fixed process library
- BSM: in v6 a bit everything, not yet in v8
- Remarks:
  - Most (fine???-) tuned tool of the world
  - based on the JETSET jet simulator
  - no automatized ME/PS matching yet

SHERPA

- Acronym: **S**imulation of **H**igh-**E**nergy **R**eactions with **PA**rticles
- Authors/location: Durham/SLAC/Heidelberg F. Krauss, S. Schumann, T. Gleisberg et al.
- Current version 1.1.3 `http://projects.hepforge.org/sherpa`
- Prog. language: C++ (1st program in community!)
- Reference arXiv:0811.4622 [hep-ph]
- Several parton showers ($p_\perp$ ordered, Catani-Seymour)
- Hadronization package (cluster fragmentation)
- Multiple Interactions: several independent approaches
- Arbitrary processes: a generator generator
- BSM: MSSM, UED, RS
- Remarks:
  - First program to implement CKKW matching
  - Very serious work towards inclusion of NLO MEs

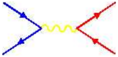
ALPGEN

- Acronym: **ALP**HA **Gen**erator
- Authors/location: CERN M. Mangano, M. Moretti, F. Piccinini, R. Pittau
- Current version 2.13 `http://mlm.home.cern.ch/mlm/alpgen`
- Reference arXiv: hep-ph/0206293
- Prog. language: `FORTRAN 77` (partially `FORTRAN 95`)
- no parton shower
- no hadronization
- no arbitrary processes: library of fixed processes
- no BSM
- Remarks:
  - first to implement MLM ME/PS matching
  - Take care: no complete jet processes: not more than 3 quark pairs!
  - very fast and efficient ME (plus importance sampling over subprocesses) compensate weaker PS generator

CompHep/CalcHep

- Acronym: **COMP**utations/**CALC**ulations in **H**igh-**E**nergy **P**hysics
- Authors/location: Moscow/Southampton E. Boos, S. Sherstnev, S. Pukhov, A. Belyaev et al.
- Current version 4.5.0 `http://comphep.sinp.msu.ru`
- Reference arXiv: hep-ph/0403113
- Prog. language: `FORTRAN 77`
- no parton shower
- no hadronization
- Arbitrary processes: a generator generator
- BSM: MSSM, Little Higgs, UED, Moose Models, own Feynman rules generator (LANHEP)
- Remarks:
  - very easy BSM model file syntax
  - uses trace technology: limited to $2 \to 3 - 4$
  - has to use `FORM` to simplify

MadEvent



- Acronym: **MA**trix element and **D**iagrams for **EVENT** generation
- Authors/location: Illinois/Louvain/SLAC T. Stelzer/F. Maltoni/J. Alwall/R. Frederix et al.
- Current version 4 `http://madgraph.hep.uiuc.edu`
- Reference arXiv: 0706.2334 [hep-ph]
- Prog. language: `FORTRAN 77`
- no parton shower
- no hadronization
- Arbitrary processes: a generator generator (Madgraph)
- BSM: MSSM, 2HDM
- Remarks:
  - based on the HELAS library
  - Webinterface for easy (theory) usage
  - ME/PS matching implemented
  - MadDipole aiming at inclusion of NLO calculations
  - Many tools/interfaces for e.g. analyses

PHEGAS

- Acronym: **PH**as**E** space **G**ener**A**tor for **S**imulations
- Authors/location: Athens/Wuppertal C. Papadopoulos, M. Worek, A. Cafarella
- Current version 1.1.0 `http://helac-phegas.web.cern.ch/helac-phegas`
- Prog. language: `FORTRAN 95`
- Reference arXiv: hep-ph/0007335
- no parton shower
- no hadronization
- Arbitrary processes: a generator generator (HELAC)
- No BSM
- Remarks:
  - Contains very fast and efficient matrix elements (in a numerical form)
  - MLM matching scheme implemented
  - MC over helicities and colors

WHIZARD

- Acronym: **W**, **HI**ggs, **Z**, **A**nd **R**espective **D**ecays (deprecated)
- Authors/location: Freiburg/Siegen/Würzburg W. Kilian, T. Ohl, JR + PhDs
- Current version: 1.93 (2.0.0 α) `http://projects.hepforge.org/whizard` and `http://whizard.event-generator.org`
- Reference arXiv: 0708.4233 [hep-ph]
- Languages: `O'Caml` and `FORTRAN 95` (`FORTRAN 2003` in v2.0.0)
- parton shower ($p_\perp$ ordered) and analytic (v2.0.0α)
- no hadronization
- underlying event: preliminary version for v2.0.0α
- Arbitrary processes: a generator generator (O'Mega)
- BSM: cf. next page
- 2.0 features: ME/PS matching, cascades, new versatile user interface and syntax, WHIZARD as a shared library

WHIZARD – Overview over BSM Models

Very high level of Complexity:

- $e^+e^- \to t\bar{t}H \to b\bar{b}b\bar{b}jj\ell\nu$ (110,000 diagrams)
- $e^+e^- \to ZHH \to ZWWWW \to bb + 8j$ (12,000,000 diagrams)
- $pp \to \ell\ell + nj, n = 0, 1, 2, 3, 4, \ldots$ (2,100,000 diagrams with 4 jets + flavors)
- $pp \to \tilde{\chi}^0_1\tilde{\chi}^0_1 bbbb$ (32,000 diagrams, 22 color flows, $\sim 10,000$ PS channels)
- $pp \to VVjj \to jj\ell\ell\nu\nu$ incl. anomalous TGC/QGC
- Test case $gg \to 9g$ (224,000,000 diagrams, matched by PHEGAS)

MODEL TYPE	with CKM matrix	trivial CKM
QED with e, μ, τ, γ	–	QED
QCD with d, u, s, c, b, t, g	–	QCD
Standard Model	SM_CKM	SM
SM with anomalous couplings	SM_ac_CKM	SM_ac
SM with K matrix	—	SM_KM
MSSM	MSSM_CKM	MSSM
MSSM with gravitinos	—	MSSM_Grav
NMSSM	—	NMSSM
extended SUSY models	—	PSSSM
Littlest Higgs	—	Littlest
Littlest Higgs with ungauged $U(1)$	—	Littlest_Eta
Littlest Higgs with T parity	—	Littlest_Tpar
Simplest Little Higgs (anomaly-free)	—	Simplest
Simplest Little Higgs (universal)	—	Simplest_univ
UED	—	UED
SUSY Xdim. (inoff.)	—	SED
Noncommutative SM (inoff.)	—	NCSM
SM with Z'	—	Zprime
SM with gravitino and photino	—	GravTest
Augmentable SM template	—	Template

easy to implement new models

Dedicated NLO Tools

- A lot of tools on the market: just a sketchy overview here
- MCFM (**M**onte **C**arlo for **F**e**M**tobarn processes)
  - K. Ellis, J. Campbell (Fermilab/Glasgow), `http://mcfm.fnal.gov`, `FORTRAN 77` v5.4, no publ.
  - parton-level NLO tool for W, Z, H and jets at hadron colliders (can be linked to hadronic tools)
  - important: contains spin correlations for decays
- MC@NLO
  - S. Frixione, B. Webber (Cambridge), `http://www.hep.phy.cam.ac.uk/theory/webber/MCatNLO`, v3.4, `FORTRAN 77` arXiv: hep-ph/0204244
  - needs `HERWIG` for parton shower
  - contains a working prescription for matching NLO calculations and parton showers ("MC@NLO scheme")
  - does not contain decays of particles/spin correlations only partially
- VBFNLO (parton-level NLO MC for vector boson fusion)
  - D. Zeppenfeld + 16 people (Karlsruhe et al.), `http://www-itp.particle.uni-karlsruhe.de/~vbfnloweb`, v2.0.2, `FORTRAN 77` arXiv:0811.4559 [hep-ph]
  - based on the HELAS library
  - includes strong NLO corrections, all decays with full spin correlations
- MANY, MANY, MANY more!!!

Programming languages: FORTRAN vs. C++

- Traditional line of reasoning:
  - Monte Carlos are programs for numerical number crunching
  - FORTRAN 77 is suited best for number crunching
  - All old MCs written in FORTRAN 77
- Modern viewpoint:
  - Big software environments need modularity and object-orientedness
  - With C++ there is a FREE compiler to do so
  - ⇒ switch all newer programs to C++
  - Note: FORTRAN 95 had a bad and tedious start
- Post-modern viewpoint:
  - FORTRAN 2003 is as sophisticated in MOD and OO as C++

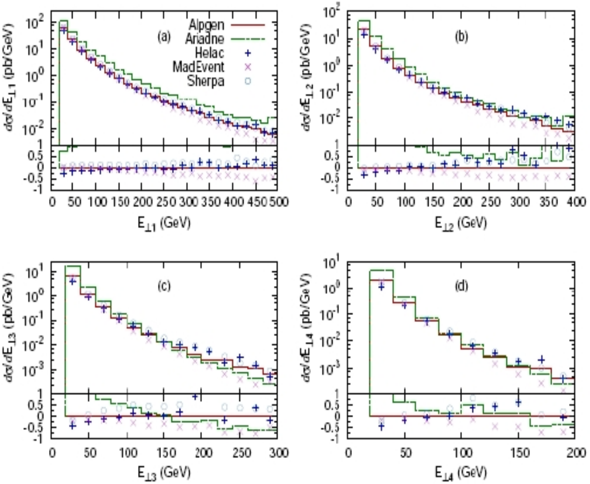
```
# Derived type enhancements: parameterized derived types, improved
  control of accessibility, improved structure constructors, and finalizers.
# Object oriented programming support: type extension and inheritance, polymorphism, dynamic type allocation,
  and type-bound procedures.
# Data manipulation enhancements: allocatable components (incorporating TR 15581), deferred type parameters,
  VOLATILE attribute, explicit type specification in array constructors and allocate statements, pointer enhancements,
  extended initialization expressions, and enhanced intrinsic procedures.
# Input/output enhancements: asynchronous transfer, stream access, user specified transfer operations for derived types,
  user specified control of rounding during format conversions, named constants for preconnected units,
  the FLUSH statement, regularization of keywords, and access to error messages.
# Procedure pointers.
# Support for IEEE floating-point arithmetic and floating point exception handling (incorporating TR 15580).
# Interoperability with the C programming language.
```

  - There are free compilers for this (gfortran and g95)
  - FORTRAN 2003 is still ideally suited for number crunching

Language of choice depends on taste/bias of authors, usually not performance

Jet Physics in the SM – The Role of Merging

- Inclusive p_T spectra of 4 jets [Alwall et al., '08]



ALPGEN – MLM matching with angular-ordered HERWIG shower

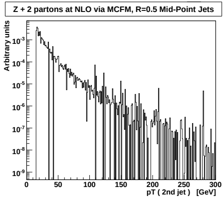
ARIADNE – MadGraph MEs, p_T-ordered dipole PS, CKKW-L matching, PYTHIA hadronization

PHEGAS – PYTHIA mass-ordered PS with MLM matching

MadEvent – PYTHIA mass-ordered PS with MLM matching

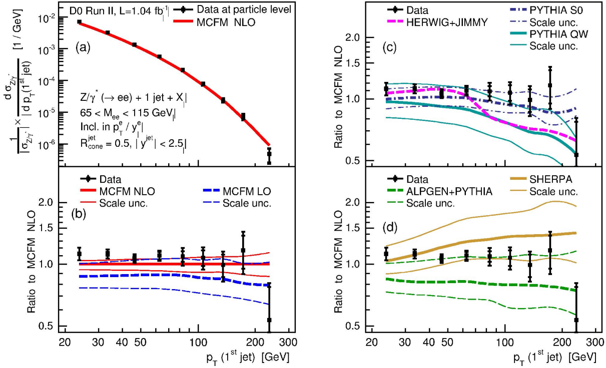
SHERPA – mass-ordered PS with CKKW matching, PYTHIA hadronization

Jets at Tevatron



- **Goal:** Compare different MC predictions for Z+Jets/W+Jets with Tevatron data
- Test tools and methods for LHC
- Use MCFM vs. SHERPA/ALPGEN/PYTHIA

[H. Nilsen for D0, 09]



- MCFM describes jet shapes, PYTHIA/HERWIG fail, ALPGEN/SHERPA describe the shapes, but having large scale errors

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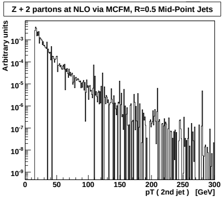

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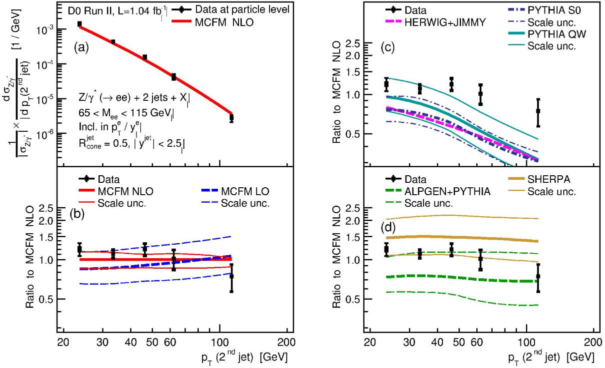

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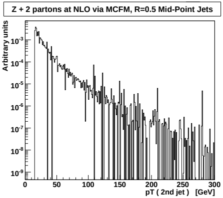

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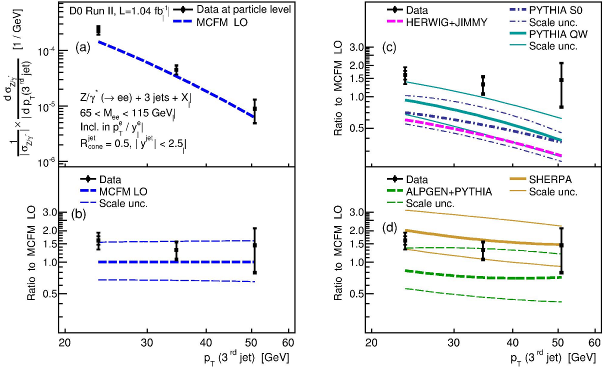

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Jet Physics in BSM

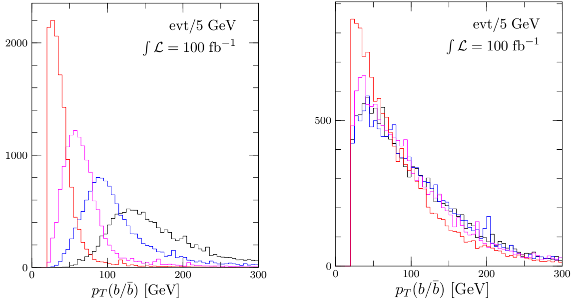
$g \to b\bar{b}$-splitting, b-ISR as combinatorial background

[Hagiwara/Kilian/Krauss/Plehn/Rainwater/JR/Schumann, 06]

$pp \to \tilde{\chi}^0_1 \tilde{\chi}^0_1 b\bar{b}b\bar{b}$:	32112 diagrams, 22 color flows, $\sim$ 4000 PS channels

$\sigma(pp \to b\bar{b}\tilde{\chi}^0_1\tilde{\chi}^0_1) = 1177$ fb $\longrightarrow$ $\sigma(pp \to b\bar{b}b\bar{b}\tilde{\chi}^0_1\tilde{\chi}^0_1) = 130.7$ fb

Forward discrimination of ISR and decay jets difficult:



Only the most forward jet considerably softer

Jet Physics in BSM

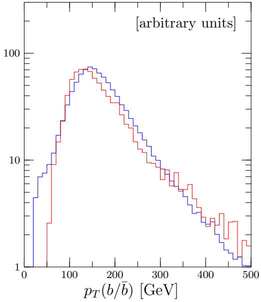
$g \to b\bar{b}$-splitting, b-ISR as combinatorial background

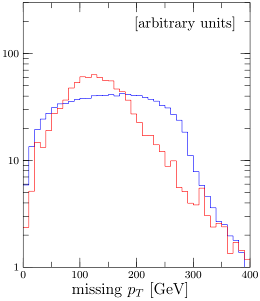
[Hagiwara/Kilian/Krauss/Plehn/Rainwater/JR/Schumann, 06]

$pp \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 b\bar{b}b\bar{b}$:	32112 diagrams, 22 color flows, $\sim$ 4000 PS channels

$\sigma(pp \to b\bar{b}\tilde{\chi}_1^0\tilde{\chi}_1^0) = 1177\,\text{fb} \quad \longrightarrow \quad \sigma(pp \to b\bar{b}b\bar{b}\tilde{\chi}_1^0\tilde{\chi}_1^0) = 130.7\,\text{fb}$

Only marginal differences in $p_{T,b}$, PDF: Maximum at lower value



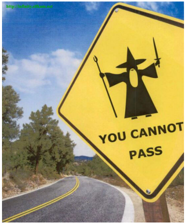


shifted to lower $\not{p}_T$: light particles balance out event

The Phantom Menace – Debugging new models

- E.g. MSSM
- 5318 couplings (with Goldstone/4-point)
- negative neutralino matrices: explicit factor of i
- Definitions of mixing angles, phases, signs $(A, \mu, \dots)$ (⇒SLHA)
- Recommended usage: SUSY Les Houches Accord (SLHA)
- In the future: easier (or maybe only less tough) `FeynRules` [N. Christensen, C. Duhr]

What about tests?
Have we checked?



- Unitarity Checks $2 \to 2, 2 \to 3$
- Ward-/Slavnov-Taylor identities for gauge symmetries and SUSY
- Compare different programs!

Comparison of Automated Tools for Perturbative Interactions in SuperSymmetry

cf. `http://whizard.event-generator.org/susy_comparison.html`

$\tau^+\tau^- \to X$

Process	status	Madgraph/Helas 0.5 TeV	Madgraph/Helas 2 TeV	Whizard/O'Mega 0.5 TeV	Whizard/O'Mega 2 TeV	Sherpa/A'Megic 0.5 TeV	Sherpa/A'Megic 2 TeV
$\tilde\tau_1\tilde\tau_1^*$	●	257.57(7)	79.63(4)	257.32(1)	79.636(4)	257.30(1)	79.638(4)
$\tilde\tau_2\tilde\tau_2^*$	●	46.55(1)	66.86(2)	46.368(2)	66.862(3)	46.372(2)	66.862(3)
$\tilde\tau_1\tilde\tau_2^*$	●	95.50(3)	19.00(1)	94.637(3)	19.0015(8)	94.645(5)	19.000(1)
$\tilde\nu_\tau\tilde\nu_\tau^*$	●	502.26(7)	272.01(8)	502.27(2)	272.01(1)	502.30(3)	272.01(1)
$\tilde\chi_1^0\tilde\chi_1^0$	●	249.94(2)	26.431(1)	249.954(9)	26.431(1)	249.96(1)	26.431(1)
$\tilde\chi_1^0\tilde\chi_2^0$	●	69.967(3)	9.8940(3)	69.969(2)	9.8940(4)	69.968(3)	9.8937(5)
$\tilde\chi_1^0\tilde\chi_3^0$	●	17.0387(3)	0.7913(1)	17.0394(1)	0.79136(2)	17.040(1)	0.79137(5)
$\tilde\chi_1^0\tilde\chi_4^0$	●	7.01378(4)	1.50743(3)	7.01414(6)	1.5075(5)	7.0141(4)	1.50740(8)
$\tilde\chi_2^0\tilde\chi_2^0$	●	82.351(7)	18.887(1)	82.353(3)	18.8879(9)	82.357(4)	18.8896(1)
$\tilde\chi_2^0\tilde\chi_3^0$	●	—	1.7588(1)	—	1.75884(5)	—	1.7588(1)
$\tilde\chi_2^0\tilde\chi_4^0$	●	—	2.96384(7)	—	2.9640(1)	—	2.9639(1)
$\tilde\chi_3^0\tilde\chi_3^0$	●	—	0.046995(4)	—	0.0469966(9)	—	0.046999(2)
$\tilde\chi_3^0\tilde\chi_4^0$	●	—	8.5852(4)	—	8.55857(3)	—	8.5856(4)
$\tilde\chi_4^0\tilde\chi_4^0$	●	—	0.26438(2)	—	0.264389(5)	—	0.26437(1)
$\tilde\chi_1^+\tilde\chi_1^-$	●	185.09(3)	45.15(1)	185.093(6)	45.147(2)	185.10(1)	45.151(2)
$\tilde\chi_2^+\tilde\chi_2^-$	●	—	26.515(1)	—	26.5162(6)	—	26.515(1)
$\tilde\chi_1^+\tilde\chi_2^-$	●	—	4.2127(4)	—	4.21267(9)	—	4.2125(2)
h^0h^0	●	0.3533827(3)	0.0001242(2)	0.35339(2)	0.00012422(3)	0.35340(2)	0.000124218(6)
h^0H^0	●	—	0.005167(4)	—	0.0051669(3)	—	0.0051671(3)
H^0H^0	●	—	0.07931(3)	—	0.079301(6)	—	0.079311(4)
A^0A^0	●	—	0.07975(3)	—	0.079758(6)	—	0.079744(4)
Zh^0	●	59.591(3)	3.1803(8)	59.589(3)	3.1802(1)	59.602(3)	3.1829(2)
ZH^0	●	2.8316(3)	4.671(5)	2.83169(9)	4.6706(3)	2.8318(1)	4.6706(2)
ZA^0	●	2.9915(4)	4.682(5)	2.99162(9)	4.6821(3)	2.9917(2)	4.6817(2)
A^0h^0	●	—	0.005143(4)	—	0.0051434(3)	—	0.0051440(3)
A^0H^0	●	—	1.4880(2)	—	1.48793(9)	—	1.48802(8)
H^+H^-	●	—	5.2344(6)	—	5.2344(2)	—	5.2345(3)

Comparison for the NMSSM

$\tau^+\tau^- \to X$					
Process	status	Madevent 0.5 TeV	Madevent 2 TeV	WHIZARD 0.5 TeV	WHIZARD 2 TeV
$\tilde\tau_1\tilde\tau_1^*$	●	xxx.xx(xx)	xx.xx(xx)	100.34(12)	57.67(57)
$\tilde\tau_2\tilde\tau_2^*$	●	xx.xx(x)	xx.xx(x)	40.17(4)	54.92(7)
$\tilde\tau_1\tilde\tau_2^*$	●	xxx.xx(xx)	xx.xx(x)	104.16(11)	65.47(9)
$\tilde\nu_\tau\tilde\nu_\tau^*$	●	xxx.x(x)	xxx.x(x)	641.6(7)	317.4(4)
$\tilde\chi_1^0\tilde\chi_1^0$	●	xxx.xx(xx)	xx.xx(x)	212.60(12)	25.97(2)
$\tilde\chi_1^0\tilde\chi_2^0$	●	xx.xx(x)	x.xxx(x)	28.15(2)	3.653(4)
$\tilde\chi_1^0\tilde\chi_3^0$	●	xx.xx(x)	x.xxx(x)	55.29(3)	7.100(8)
$\tilde\chi_1^0\tilde\chi_4^0$	●	—	x.xxxx(x)	—	0.5657(6)
$\tilde\chi_1^0\tilde\chi_5^0$	●	—	x.xxxx(x)	—	0.2478(2)
$\tilde\chi_2^0\tilde\chi_2^0$	●	x.xxx(x)	x.xxxx(x)	4.470(3)	0.5581(6)
$\tilde\chi_2^0\tilde\chi_3^0$	●	xx.xx(x)	x.xxx(x)	37.42(3)	5.358(6)
$\tilde\chi_2^0\tilde\chi_4^0$	●	—	x.xxxx(x)	—	0.4205(3)
$\tilde\chi_2^0\tilde\chi_5^0$	●	—	x.xxxx(x)	—	0.3307(3)
$\tilde\chi_3^0\tilde\chi_3^0$	●	—	xx.xx(x)	—	17.93(2)
$\tilde\chi_3^0\tilde\chi_4^0$	●	—	x.xxx(x)	—	1.099(1)
$\tilde\chi_3^0\tilde\chi_5^0$	●	—	x.xxxx(x)	—	0.4325(3)
$\tilde\chi_4^0\tilde\chi_4^0$	●	—	x.xxxxxx(x)	—	0.010181(5)
$\tilde\chi_4^0\tilde\chi_5^0$	●	—	xx.xxx(x)	—	10.524(9)
$\tilde\chi_5^0\tilde\chi_5^0$	●	—	x.xxxxx(x)	—	0.01639(2)
$\tilde\chi_1^+\tilde\chi_1^-$	●	xxx.x(x)	xx.xx(x)	322.8(3)	48.36(6)
$\tilde\chi_2^+\tilde\chi_2^-$	●	—	xx.xx(x)	—	27.08(2)
$\tilde\chi_1^+\tilde\chi_2^-$	●	—	x.xxx(x)	—	1.786(1)
$H_1^0H_1^0$	●	x.xxxxxx(x)	x.xxxxxx(x)	0.004001(5)	0.001089(2)
$H_1^0H_2^0$	●	x.xxxx(x)	x.xxxxxxx(x)	0.2386(3)	0.0006198(9)
$H_1^0H_3^0$	●	—	x.xxxxxx(x)	—	0.00581438(6)
$H_2^0H_2^0$	●	x.xxxx(x)	x.xxxxxx(x)	0.1130(1)	0.004243(6)
$H_2^0H_3^0$	●	—	x.xxxx(x)	—	0.1530(2)
ZH_1^0	●	xx.xx(x)	x.xxx(x)	53.57(8)	3.054(5)
$A_1^0A_1^0$	●	x.xxxxx(x)	x.xxxxxxx(x)	0.04173(6)	0.0002356(3)
$A_1^0A_2^0$	●	—	x.xxxxxxxxx(x)	—	0.000001268(3)

BSM Example: Resonances in VV scattering

Alboteanu/Kilian/JR, 0806.4145

Model-independent description for LHC, respect weak isospin ($\rho \approx 0$):

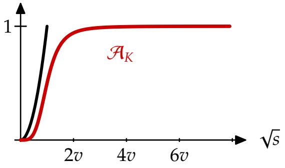
	$J = 0$	$J = 1$	$J = 2$
$I = 0$	σ^0 (Higgs ?)	ω^0 (γ'/Z' ?)	a^0 (Graviton ?)
$I = 1$	$\pi^\pm, \pi^0$ (2HDM ?)	$\rho^\pm, \rho^0$ (W'/Z' ?)	$t^\pm, t^0$
$I = 2$	$\phi^{\pm\pm}, \phi^\pm, \phi^0$ (Higgs triplet ?)	—	$f^{\pm\pm}, f^\pm, f^0$

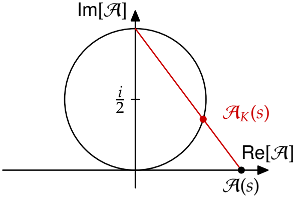
LHC access limited: 1. resonance correct, guarantee unitarity

K-Matrix unitarization

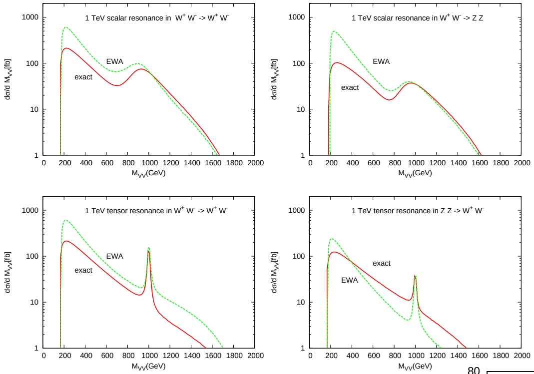
$$\mathcal{A}_K(s) = \mathcal{A}(s)/(1 - i\mathcal{A}(s))$$

- Low-energy theorem (LET): $\frac{s}{v^2}$
- K-matrix ampl.: $|\mathcal{A}(s)|^2 \overset{s\to\infty}{\longrightarrow} 1$
- Poles $\pm iv$: M_0, Γ large



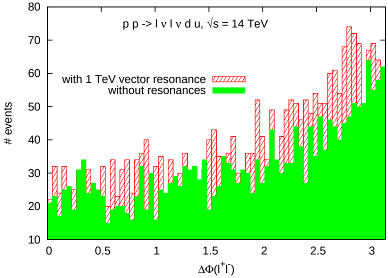


- Unitarization in each spin-isospin eigen-channel
- breaks crossing invariance
- Explicit “time arrow” in WHIZARD



- Effective W approx. vs. WHIZARD full matrix elements
- Shapes/normalization of distributions heavily affected
- EWA: Sideband subtraction completely screwed up!

- Example: 850 GeV vector resonance
- coupling $g_\rho = 1$
- Discriminator: angular correlations
- Ongoing ATLAS study



Summary & Outlook

- LHC demands for full analyses with spin corr., bkgd., hadronic environment

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☹ There is no perfect Monte Carlo for LHC!

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☹ There probably never will be!?

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☺ We can profit from the embarassment of riches!

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- ☹ There is no perfect Monte Carlo for LHC!
- ☹ There probably never will be!?
- ☺ We can profit from the embarassment of riches!
- Use tools which are suited to your specific problem. (Never switch off your brain!)

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- There probably never will be!?
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  - Parton showers, Matching
  - Underlying Event, Tuning
  - Automatization, NLO development
  - BSM: implementations and validations

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There probably never will be!?

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  - Parton showers, Matching
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- Topics left out
  - Event formats and interfacing
  - MHV amplitudes and twistors
  - computer aided/fully automated one/multi loop calculations
  - dipole subtraction MadDipole,Sherpa,WHIZARD
  - NLO matching (anything automated public???)
  - Detector simulation/Fast simulation

Monte Carlos: Battle of legs vs. loops

Monte Carlos: Battle of legs vs. loops