The Monte-Carlo Event Generator WHIZARD

Wolfgang Kilian

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Tsinghua University, September 2014

Monte Carlo programs for High-Energy Colliders

LHC, **ILC**, future projects:

The interesting processes contain 4, 6, or more final-state particles in the elementary hard scattering: electroweak, Higgs, new physics

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This is all covered by universal event generators: WHIZARD

WHIZARD in a Nutshell

WHIZARD for Colliders

- pp: Tevatron $\Rightarrow$ LHC, FCC, ...
- e^+e^-: LEP and TESLA/NLC $\Rightarrow$ ILC, CEPC, CLIC, ...
- ep, $\gamma\gamma$, ...

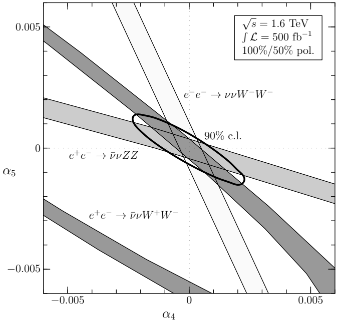
Key Parts of WHIZARD:

1. O'Mega: Automatic tree matrix elements for arbitrary elementary processes, supports SM and many BSM extensions
2. Phase-space parameterization module
3. VAMP: Generic adaptive integration and (unweighted) event generation
4. Intrinsic support or external interfaces for:

   Models and Feynman rules, beam properties, cascade decays, shower, hadronization, analysis, event file formats, etc., etc.
5. Free-format steering language SINDARIN

2. Some History

Vector-Boson Scattering at high energies,
E. Boos, H.-J. He, WK, A. Pukhov, C.-P. Yuan, P.M. Zerwas, Phys.Rev. D57 (1998)



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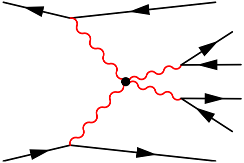

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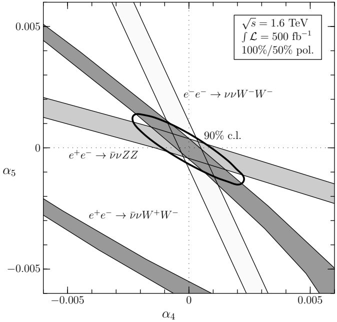

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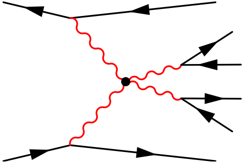

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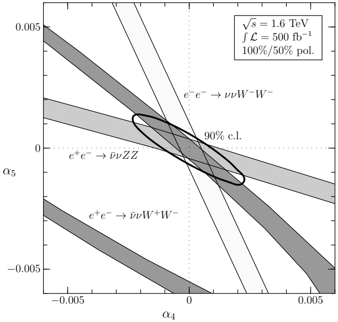

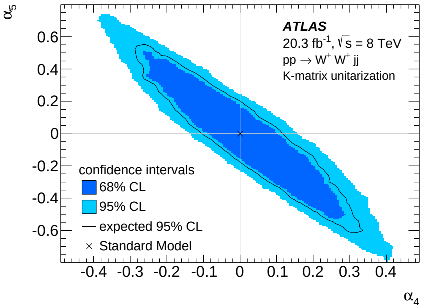

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ATLAS collaboration, arXiv:1405.6241

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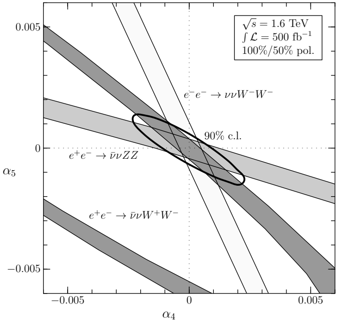

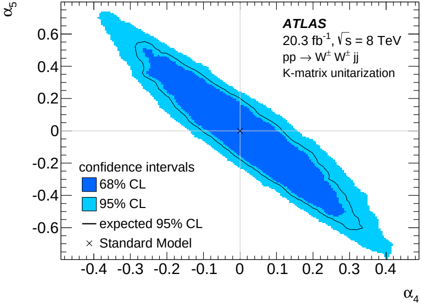

Discovery of Vector-Boson Scattering

ATLAS collaboration, arXiv:1405.6241 — simulation using WHIZARD

Milestones

1.0 1999: Generic MC generator for electroweak multi-particle processes at TESLA (W, Higgs, Z) [WK, LC-TOOL-2001-039]

1.97 Final v1: LHC physics, full Standard Model, detailed beam properties, new-physics models including MSSM, various event formats

$\Rightarrow$ Linear Collider event samples at SLAC

$\Rightarrow$ Base for most TESLA and ILC studies

2.0 2010: Major rewriting, increased flexibility in program structure and in user interface [WK, T. Ohl, J. Reuter, Eur.Phys.J.C71 (2011) 1742]

2.2 Current production version:

- FeynRules support
- Internal density-matrix formalism $\Rightarrow$ cascade decays
- QCD shower + matching
- OpenMP parallelization
- SINDARIN language for input and workflow

3. Amplitudes

Amplitudes

The amplitude generator for WHIZARD is called OMega

[M. Moretti, T. Ohl, J. Reuter, hep-ph/0102195]

(integrated into WHIZARD since version 2).

Some Benchmarks:

- $e^+e^- \to t\bar{t}H \to b\bar{b}b\bar{b}jj\ell\nu$ (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)
- $pp \to \tilde{\chi}_1^0\tilde{\chi}_1^0 bbbb$ (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)

$\Rightarrow$ Complete tree-level amplitudes without approximations

O'Mega: Optimal matrix elements

Ohl/Reuter, 2001

Ω

- [.·.] Replace forest of tree diagrams by
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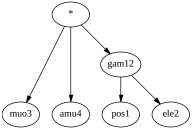

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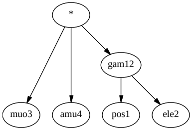

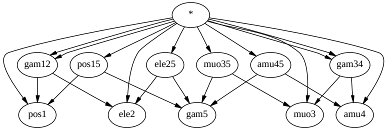

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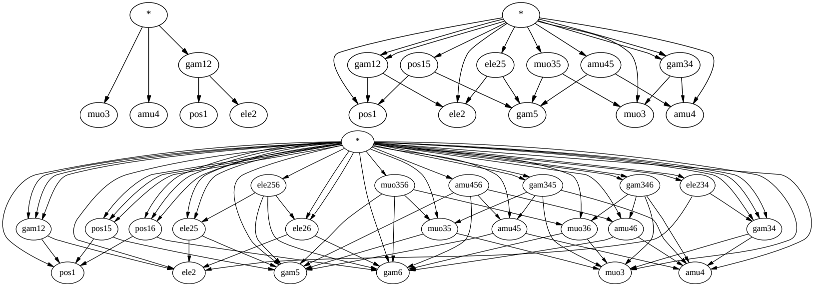

Hard matrix elements: particle types

Possible particle types

- Spin 0 particles
- Spin 1/2 fermions (Majorana and Dirac)
  Fermi statistics for both fermion-number conserving and violating cases
- Spin 1 particles
  - massive and massless
  - Unitarity and Feynman gauge
  - arbitrary R_ξ gauges
- Spin 3/2 particles (Majorana only, gravitinos)
- Spin 2 particles (massless and massive, gravitons)
- Dynamic particles vs. pure insertions
- Unphysical particles for Ward- and Slavnov-Taylor identities

Hard matrix elements: restrictions

OMega does not use an expansion in terms of Feynman graphs. All possible Feynman graphs are implicitly included, but a selection of Feynman graphs is not possible.

```
process nnh = "e+", "e-" => nue, nuebar, H
```

Instead, one may restrict the intermediate states, if meaningful:

```
process nnh = "e+", "e-" => nue, nuebar, H { $restrictions = "3+4 ~ Z" }
```

WHIZARD – Overview over BSM Models

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 gauge couplings	SM_ac_CKM	SM_ac
SM with anomalous top couplings	SMtop_CKM	SMtop
SM with WW resonances and unitarization	—	SSC
MSSM	MSSM_CKM	MSSM
MSSM with gravitinos	—	MSSM_Grav
NMSSM	NMSSM_CKM	NMSSM
extended SUSY models	—	PS/E/SSM
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
3-site model	—	Threeshl
UED	—	UED
SM with Z'	—	Zprime
SM with gravitino and photino	—	GravTest
Augmentable SM template	—	Template

Automatic tools for adding a new model: FeynRules and SARAH.

4. Phase Space

Phase-space integration is the most difficult part of the algorithm, because:

- the integrand (amplitude squared) varies over orders of magnitude
- we integrate over > 10 dimensions
- the peak structure is not aligned to any dimension, because many pole structures interfere
- suitable mappings can only be found if the peak structures align
- the algorithm must yield a good accuracy (for the total cross section)

$$\text{statistical error} = \frac{\Delta\sigma}{\sigma} = \frac{\text{accuracy}}{\sqrt{N}}$$

and good rejection efficiency (for simulating unweighted events)

$$\text{efficiency} = \frac{\text{average integrand}}{\text{maximum integrand}}$$

Phase Space in WHIZARD

WHIZARD's phase-space handling consists of three parts

1. Choice of parameterization of phase space (**Wood**):
   - Find the pole structures (channels) that dominate the matrix element
2. VEGAS discretization and adaptive grid improvement (**VAMP**)
   [T. Ohl, Comput. Phys. Commun. **120**, 13 (1999)]
   - Each channel is assigned its own VEGAS grid
3. Combine all channels using the standard multi-channel formula, and iteratively adapt the weights of the channels.

Multichannel MC integration

Choose functions $g_i(q)$ and weights w_i:

$$\int dq\,|A(q)|^2 = \int dq\,\frac{\sum_i w_i g_i(q)}{\sum_j w_j g_j(q)}\,|A(q)|^2 = \sum_i w_i \int dq\,\frac{g_i(q)}{g(q)}\,|A(q)|^2$$

In WHIZARD, the g_i are the Jacobians of the individual mappings,

$$g_i(y^{(i)}) = \frac{1}{\left|\frac{dq}{dx^{(i)}}\right|} \times \prod_k \frac{1}{\left|\frac{dx_k^{(i)}}{dy_k^{(i)}}\right|}$$

First factor: analytically known and numerically evaluated.

Second factor: given by bin widths of VAMP grids

The weights w_i are iteratively adapted, simultaneously with the bin widths.

By choosing the combination of both methods, we get

- ⇒ dominant contributions with their singularities are regularized
- ⇒ the residual variation is tamed by VAMP grid adaption. This can also lessen the impact of subdominant peaks.
- ⇒ Adapting both grids and weights simultaneously, we can achieve both an accurate Monte-Carlo integration

$$\frac{\Delta\sigma}{\sigma} \approx \frac{0.1\ldots 10}{\sqrt{N}}$$

and a reasonable reweighting efficiency

$$\epsilon =\approx 0.1\ldots 10\,\%$$

5. Beams

Usage

Input in SINDARIN command language

Hadron collider example

```
sqrts = 14 TeV
$pdf_builtin_name = "CTEQ6L"
...
beams = p, p => pdf_builtin
```

Lepton collider example

```
sqrts = 500 GeV
...
beams = "e+", "e-" => circe2 => isr
```

PDF (hadron colliders)

For PDF evaluation:

Standard package LHAPDF

must be linked to WHIZARD at compile time. Then, all LHAPDF structure functions that the user has downloaded, are available.

Alternative, for the impatient:

Built-in interface and data for a few commonly used structure functions (CTEQ6 etc.)

can be used anytime, no download necessary.

Beamstrahlung in WHIZARD

Classical interaction of the Coulomb fields of the two colliding beams, results in a statistical distribution of energy loss for the colliding particles.

1. Circe1: [T. Ohl, Comput. Phys. Commun. **101**, 269 (1997)]
   - Output of GuineaPig runs parameterized by smooth functions
   - Usable either as structure functions or as generator
   - In WHIZARD: analogous to PDF

   Caveat: Only fixed number of hard-coded parameter sets (ILC)

2. Circe2:
   - Output of GuineaPig/CAIN runs parameterized by histograms
   - Usable as generator
   - In WHIZARD: exchangable with Circe1

   Caveat: Requires histogram-data file for given parameter set

3. Beam-events file:
   - Output of GuineaPig/CAIN runs used directly
   - Usable as pseudo-generator
   - In WHIZARD: also analogous

   Caveat: Beam-event file has finite number of events

Initial-State Radiation

Photon radiation from incoming charged particles
enhanced by powers of $\log \frac{s}{m^2}$

$$f(x) \approx \epsilon(1-x)^{-1+\epsilon} \qquad \text{with} \qquad \epsilon = \frac{\alpha}{\pi} Q^2 \log \frac{s}{m^2}$$

$\Rightarrow$ important for electrons/positrons, less so for protons

WHIZARD implementation: result of all-order soft resummation and third-order explicit (parameterized) calculation

[M. Skrzypek and S. Jadach, Z. Phys. C **49**, 577 (1991).]

Simulation for e^+e^- Colliders

- beamstrahlung + ISR
- Parameter sets in collaboration with ILC and CLIC groups
- Example $e^+e^- \to b\bar{b}$:

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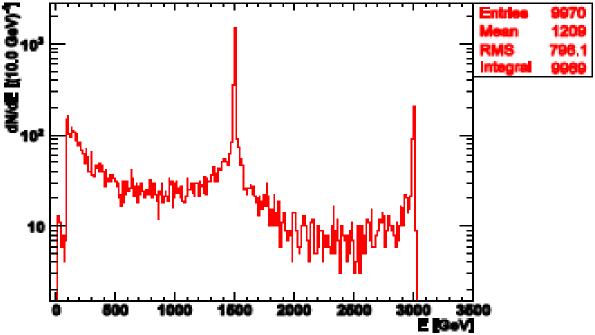

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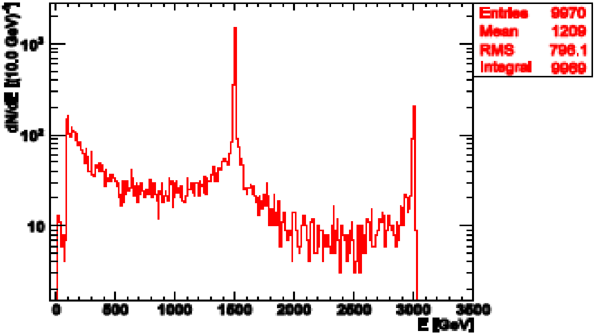


Luminosity spectrum picks up the Z resonance!

6. QCD

QCD Effects

Color in final state: several options

1. Partonic event files with color correlation, to be handled by external shower/hadronization (PYTHIA 6, PYTHIA 8, HERWIG)
2. Internally linked PYTHIA 6 via Les Houches Interface (for color correlation) ⇒ automatic generation of showered/hadronized event files
3. WHIZARD's own internal shower (analytic shower) and internal PYTHIA hadronization
4. internal shower with external hadronization

Extra radiation: avoid double-counting

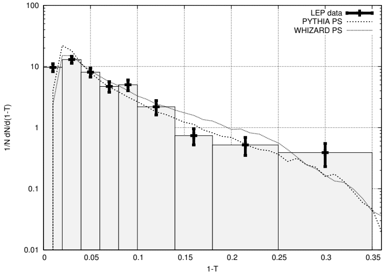
- Matrix element for extra radiation + MLM matching scheme

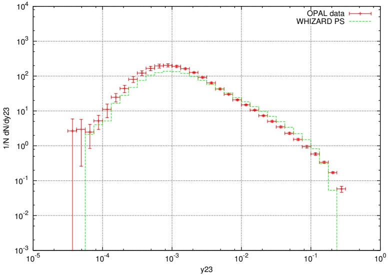
Analytic Parton Shower

[WK, J. Reuter, S. Schmidt, D. Wiesler, JHEP **1204**, 013 (2012)]

- Analytic Parton Shower:
  - no shower veto: shower history is exactly known
  - allows reweighting and maybe more reliable error estimate

- validated against PYTHIA shower (tuning: assistance welcome!)





- matching with hard matrix elements

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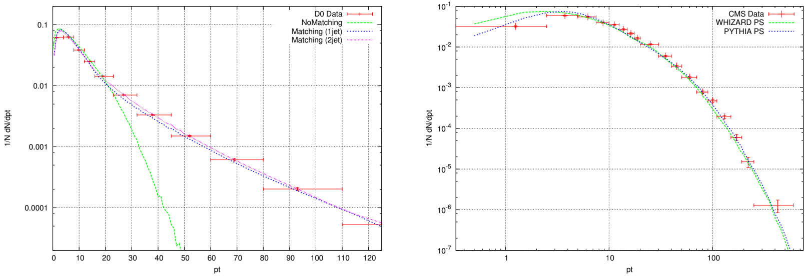


- matching with hard matrix elements

QCD NLO

A NLO module for WHIZARD is currently in development; first snapshot: tutorial at iSTEP/PKU

- Real radiation: automatically generated with OMega matrix elements
- Virtual (loop) amplitude: external program (GoSam)
- IR/collinear subtraction: FKS scheme
- NLO-radiation combination: POWHEG algorithm

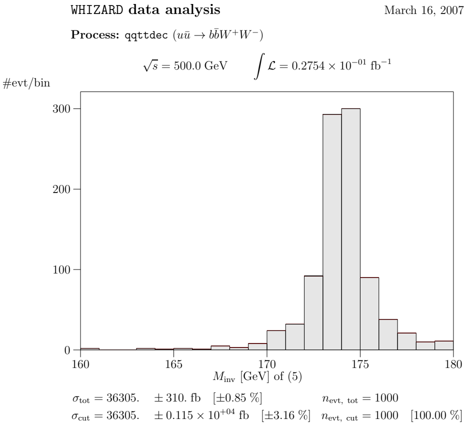
All algorithms are intended to be exchangeable, so multiple methods should eventually be implemented.

7. Features and Applications

More physics aspects/features of WHIZARD 2

- SINDARIN
  (Scripting INtegration, Data Analysis, Results display and INterfaces)
  - steering: process definition, parameters, models, beam structure, scans/loops, conditionals, I/O, file formats, ...
  - expressions: for cuts, scales, weights
  - analysis: observables, plots, histograms
- Decay cascades including full spin correlations
- Event-dependent scales in PDFs and running α_s
- Event-file reanalysis (matrix-element reweighting)
- Anomalous couplings, resonances and unitarity in vector-boson scattering

WHIZARD histograms



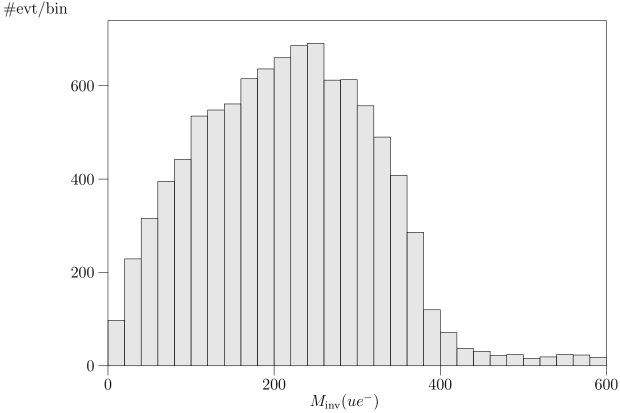
Syntax in WHIZARD 2.x

```
$title = "Jet Energy in $pp\to \ell\bar\nu j$"
$x_label = "$E$/GeV"
histogram e_jet (0 GeV, 80 GeV, 2 GeV)
analysis = record pt_lepton (eval Pt [extract index 1 [sort by Pt [lepton]]]);
           record pt_jet (eval Pt [extract index 1 [sort by Pt [jet]]]);
           record e_lepton (eval E [extract index 1 [sort by Pt [lepton]]]);
           record e_jet (eval E [extract index 1 [sort by Pt [jet]]])
```

Example: LHC SUSY cascade decays

$$p + p \to \tilde{u} + \tilde{u}^* \to \bar{\tilde{u}}_1 + u + \tilde{e}^+_{12} + e^-$$

- **Full process:**



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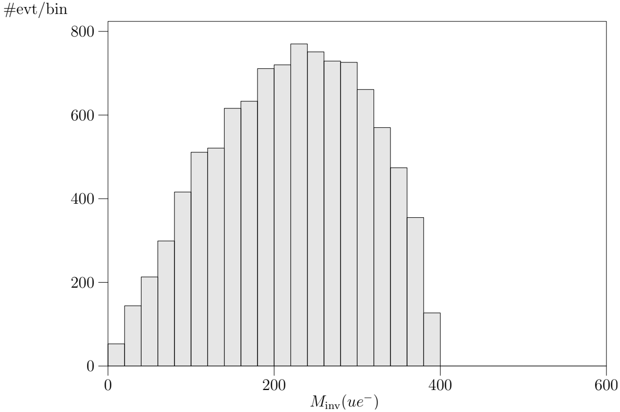
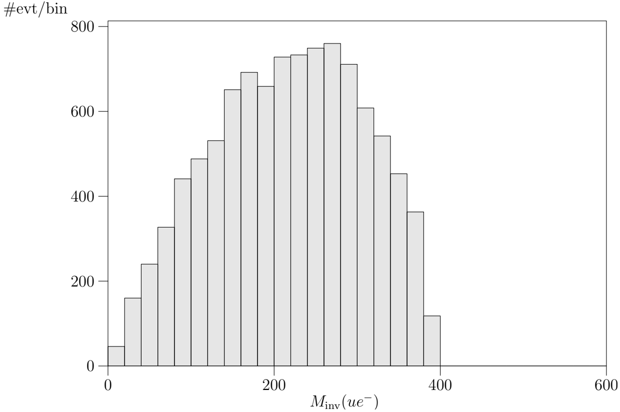
- **Factorized process w/ full spin correlations:**



Example: LHC SUSY cascade decays

$$p + p \to \tilde{u} + \tilde{u}^* \to \bar{\tilde{u}}_1 + u + \tilde{e}^+_{12} + e^-$$

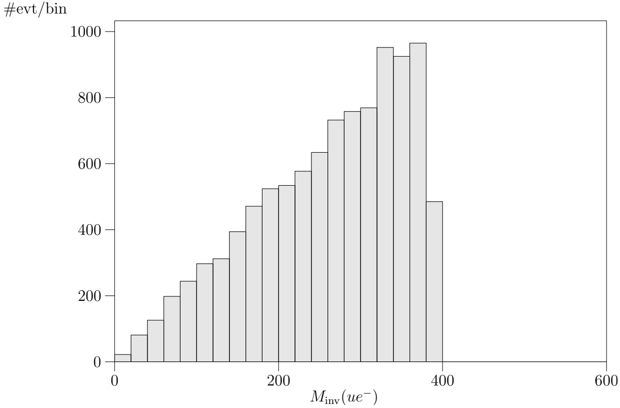
- **Factorized process w/ classical spin correlations:**



Example: LHC SUSY cascade decays

$$p + p \to \tilde{u} + \tilde{u}^* \to \bar{\tilde{u}}_1 + u + \tilde{e}^+_{12} + e^-$$

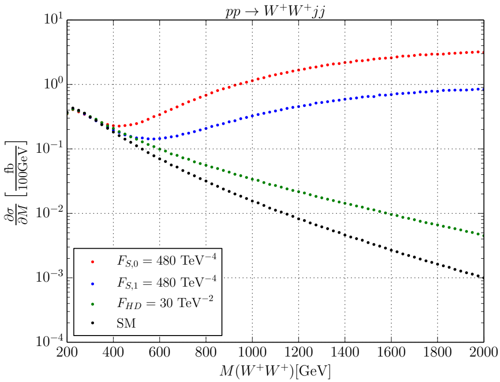
- **Factorized process w/ no spin correlations:**



Extrapolation of Anomalous Vector-Boson Scattering

Process $pp \to W^+W^+jj$

[W. Kilian, T. Ohl, J. Reuter, M. Sekulla, arXiv:1408.6207 [hep-ph]]



naively calculated: violates unitarity limits

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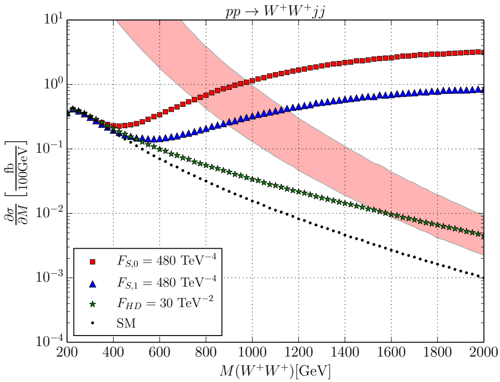

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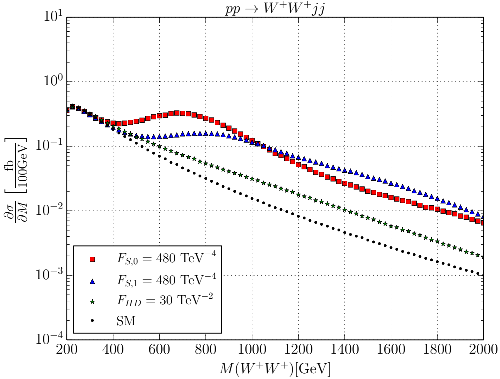
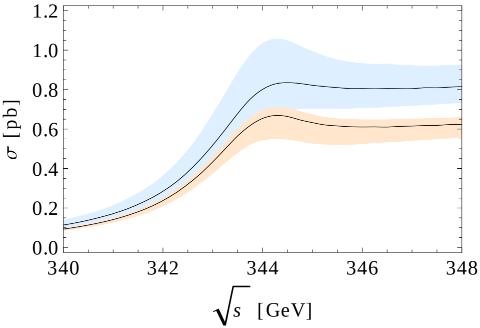


unitary (direct T matrix scheme): well-behaved

Resummation of Gluon Exchange at $t\bar{t}$ threshold

Process $e^+e^- \to b\bar{b}W^+W^-$ with WHIZARD [not yet published]



Shown: Leading-log and Next-to-leading-log resummed cross section

[not yet in public version]

8. Conclusions

WHIZARD Summary

Project Coordinators

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- Thorsten Ohl (University of Würzburg)
- Jürgen Reuter (DESY)

Coauthors (currently)

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Second WHIZARD Forum

Castle of Würzburg, March 16–18, 2015