QCD radiation and New Physics production at the LHC

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Outline

- Introduction: The Standard Model and the LHC
- SUSY-like signatures and their difficulties
- How to simulate QCD radiation
  - Parton showers and Matrix elements
  - Matching of jet production
- QCD radiation in New Physics processes
  - Difficulties in squark-gluino separation
  - Non-standard gluinos at the Tevatron
- Conclusions and outlook
The Standard Model and the LHC

- The Standard Model – one of the most successful theories in the history of physics
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- Describes the particle content and interactions of the microscopical world with no major discrepancies with experiment
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- The Standard Model – one of the most successful theories in the history of physics
- Describes the particle content and interactions of the microscopical world with no major discrepancies with experiment
- Yet undiscovered: The Higgs particle, breaks the Electroweak symmetry and gives mass to all particles
The Standard Model and the LHC

Problems with the Standard Model

- Quadratic quantum corrections to the mass of the Higgs particle $\rightarrow$ hierarchy problem

$$\Delta M_H^2 \sim M^2$$

- Dark matter observations in the sky

- Grand unification

$M_{Pl} \sim 10^{19}$ GeV

$\sim 100$ GeV
The Standard Model and the LHC

Solutions (to hierarchy problem)

- New weakly interacting particles and symmetries that cancel the quadratic loops

\[ H \rightarrow \tilde{t} \rightarrow t \rightarrow H + \]

\[ \sim M_{\tilde{t}}^2 - M_t^2 \]

\[ \sim 1 \text{ TeV} \quad 175 \text{ GeV} \]

- Composite Higgs (new strong interactions, Technicolor)

- Removing the hierarchy by strengthening gravity (extra spacial dimensions)
The Standard Model and the LHC

Solutions (to hierarchy problem)

- New weakly interacting particles and symmetries that cancel the quadratic loops
  $$H -\cdots- H + \sim \tilde{t} \quad \sim M_{\tilde{t}}^2 - M_t^2$$
  Most popular: SUSY
  $$\sim 1 \text{ TeV}$$
  $$175 \text{ GeV}$$

- Composite Higgs (new strong interactions, Technicolor)

- Removing the hierarchy by strengthening gravity (extra spacial dimensions)
The Standard Model and the LHC

Solutions to the hierarchy problem predict new particles which protect the Higgs mass

- Particle masses must be around $100 \text{ GeV-}1 \text{ TeV}$ – within reach for the 14 TeV LHC
- Some new particles charged under QCD – easy to produce at a hadron collider
- We are (quite) confident that something new will be discovered at the LHC!
Typical SUSY-like signatures

- At the LHC, mainly particles charged under QCD (quark and gluon partners) will be directly produced.
- Decay through "cascades" emitting quarks and leptons until reach lightest particle (dark matter).
- Signature: High-\(E\) hadron jets, leptons and missing transverse momentum.
Difficulties with SUSY-like signatures

- No visible resonances – no simple features above Standard Model backgrounds
- Complicated to measure jets and missing transverse momentum
- Difficult determining overall mass scale – only mass differences readily observable
- QCD radiation generates extra hard jets besides the decay products

Main topic of this talk
QCD radiation

Main backgrounds for SUSY-like signatures:

• W and Z production + jets
• Top quark pair production + jets
• Very high-energy pure QCD jet production

“Plus jets” = additional quarks and gluons emitted in QCD bremsstrahlung radiation from incoming or outgoing quark/gluon-lines
QCD radiation

Main backgrounds for SUSY-like signatures:

- W and Z production + jets
- Top quark pair production + jets
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\[ \text{(beam) } \bar{q} \quad \rightarrow \quad g \quad g \quad g \quad Z \quad g \quad q \text{ (beam)} \]
How to simulate QCD radiation

• Traditional method (~20 years):
  Parton showers

• Since ~10 years:
  Automatic calculation of tree-level multi-parton matrix elements

Strengths and weaknesses with both approaches!

• Since ~5 years:
  Matching of partons showers and matrix elements
Parton Showers (PS)

- Based on soft-collinear approximation
- Step-by-step subsequent QCD emissions
  - Fast, computationally cheap (1→2 splittings)
  - No limit on particle multiplicity
- Necessary for interfacing to hadronization
- Formally correct only close to collinear region
Matrix Elements (ME)

- Correct description away from the collinear region
  - diverges in the collinear region
- Includes interference and finite terms
- Necessary for calculation of high-energy jets
- Fixed particle multiplicity
- Slow, computationally heavy

Diagrams for $u \bar{d} \rightarrow e^+ \nu_e u \bar{u} g$ by MadGraph
Importance of Matrix Elements

Parton showers get multiple hard jet production from QCD radiation wrong by orders of magnitude
Matching ME and PS

Difficulties combining the two descriptions:

- Same phase space configuration can be described by both n+1-parton ME event and n-parton event + PS → Double counting
- Transition between ME and PS should be smooth
- Cross section should not be affected
- Minimize dependence on highest ME multiplicity

Solutions:

- Catani, Krauss, Kuhn, Webber [2001]
- Lönnblad [2001]
Matching ME and PS

Common approach for all matching schemes:

- Separate “hard jet” and “soft/collinear jet” regions using phase-space cutoff
- Allow ME jets to populate only “hard” region and PS emissions only “soft” region
- Modify ME description to mimick the parton shower near the cutoff
  - Reweighting of $\alpha_s$ in each emission vertex
  - Sudakov reweighting to account for no PS emissions in hard region and ensure stable cross section

Done differently in different schemes
Results of matching

log(Jet resolution scale for 1 $\rightarrow$ 2 radiated jets $\sim p_T$(2\textsuperscript{nd} jet))

**W+jets production at the Tevatron**

MadEvent+Pythia ($k_T$-jet MLM scheme)
Comparison with Tevatron Data

$p_T(W^{+/−})$ at the Tevatron

0-50 GeV

0-200 GeV
MadGraph/MadEvent

- MadGraph/MadEvent – an automatized Matrix Element and event generator
- On-demand simulation of (almost) any process in the SM or beyond (at tree level)
- Web-based or local simulation
- Interfaces to parton showers and detector simulations – full simulation chain!

Welcome to visit us at http://madgraph.hep.uiuc.edu !

Model → FeynRules → MadGraph

Detector ← Pythia ← MadEvent
MadGraph/MadEvent+Pythia

J.A. et al [arXiv:0706.2334]

• Matching schemes implemented: $k_T$ and cone jet MLM schemes, new “shower $k_T$” scheme
• Both $Q^2$- and $p_T$-ordered Pythia parton showers
• CKKW-style matching with Pythia $p_T$-showers underway (with P. Skands)
• Extensively validated, $W+\text{jets}$ compared with other generators [J.A. et al, arXiv:0706.2569]
• Allows matching in (most) SM and BSM processes
Matching in New Physics production

J.A., de Visscher, Maltoni [arXiv:0810.5350]

- We know that matching of ME+PS is vital for jet production in SM backgrounds
- But is it relevant for heavy BSM particle production?
  - Very hard jets from decays
  - Parton showers expected to be more accurate for larger masses
- Using gluino and squark production as example
- Turns out there are many cases where matching is necessary for precise description!
Double counting

- Special difficulty in SUSY matching – double counting between squark and gluino production

Example: $\tilde{q}\tilde{q}jj$
Double counting

- Special difficulty in SUSY matching – double counting between squark and gluino production

Example: $\tilde{q}\tilde{q}jj$

Double-counted with on-shell gluino prod with $\tilde{g} \rightarrow \tilde{d}_R + q$
Double counting

- Solved by keeping track of on-shell resonances in the production event files

\[
\begin{array}{cccccccccccc}
\text{event} & 6 & 0 & 0.7992762E-04 & 0.9118800E+02 & 0.7816531E-02 & 0.1300000E+00 \\
& 21 & -1 & 0 & 502 & 503 & 0.00000000000E+00 & 0.00000000000E+00 & 0.38916243784E+03 & 0.38916243784E+03 & 0.00000000000E+00 & 0.1. \\
& 1 & 1 & 0 & 501 & 501 & 0.00000000000E+00 & 0.00000000000E+00 & -0.16355197391E+04 & 0.16355197391E+04 & 0.00000000000E+00 & 0.1. \\
& 1000021 & 2 & 1 & 2 & 501 & 503 & -0.22128548022E+03 & -0.24366260777E+03 & -0.12022753376E+04 & 0.13861620323E+04 & 0.60620830799E+03 & 0.0. \\
& -1 & 1 & 3 & 3 & 503 & 0.18372150189E+02 & 0.27121771121E+02 & -0.34707630298E+02 & 0.47725399437E+02 & 0.00000000000E+00 & 0.1. \\
& 2000001 & 1 & 3 & 3 & 501 & 0 & -0.24000069821E+03 & -0.27078378488E+03 & -0.11675677073E+04 & 0.13384366329E+04 & 0.54522846200E+03 & 0.1. \\
& 20000001 & 1 & 1 & 2 & 502 & 0 & 0.22162854802E+03 & 0.24366260777E+03 & -0.44081963594E+02 & 0.63852014456E+03 & 0.54522846200E+03 & 0.1. \\
\end{array}
\]

Allows to remove double-counted events at later step

- Double-check – perform generation without resonant diagrams (gauge-inv. only in NWA!)

→ Excellent agreement
Shower parameter dependence

- Shower “tweakable”
  - Strength for fitting data (after-the-fact)
  - Weakness for predictivity
- Most important parameters used here:
  - Type of shower ($Q^2$ or $p_T$-ordered)
  - Shower starting scale
    - Factorization scale (mass of produced particle) - “wimpy”
    - Total energy of collider (14 TeV) - “power”
- Wide range of predictions from shower
Shower parameter dependence

QCD radiation for different Pythia shower params

log(Jet resolution scale for $1 \rightarrow 2$ radiated jets) (GeV)

600 GeV gluino pair production at the LHC
Shower parameter dependence

QCD radiation after matching with MG/ME

\[ \log(\text{Jet resolution scale for } 1 \to 2 \text{ radiated jets}) \ (\text{GeV}) \]

600 GeV gluino pair production at the LHC
Shower parameter dependence

QCD radiation after matching with MG/ME

Predictive → can now analyze QCD radiation
Dependence on the initial state: gg, qq

600 GeV gluino vs. squark pair production at LHC

No single shower tune for all initial states!
Can QCD rad. help determine overall mass scale? 
Possibly for particles below ~ 1 TeV!
Squark/Gluino separation

- Squark decay
  \[ \rightarrow \text{quark} + \text{weak gaugino} \]

- Gluino decay
  \[ \rightarrow \text{squark} + \text{quark} \]
  \[ \rightarrow 2 \text{quarks} + \text{weak gaugino} \]

- Differ by 1 jet – hard/soft depending on \( \Delta(\text{mass}) \)
Jet counting in gluino decay

600 GeV gluino pair production

3-body \( \tilde{g} \) decay
(squarks heavy)

\( M_{\tilde{g}} - M_q = 50 \text{ GeV} \)

\[ \sum p_T (2 \text{ hardest jets}) \quad \sum p_T (3 \text{ hardest jets}) \quad \sum p_T (4 \text{ hardest jets}) \]
Squark/Gluino separation

Scenario: squark pair production only (gluinos too heavy to be produced)

Matched production of 550 GeV squarks (data)

Unmatched production (simulation, Pythia default)

Looks like we're missing hard jet component!
Squark/Gluino separation

Scenario: squark pair production only (gluinos too heavy to be produced)

\[ \Sigma p_T(2 \text{ hardest jets}) \]
\[ \Sigma p_T(3 \text{ hardest jets}) \]
\[ \Sigma p_T(4 \text{ hardest jets}) \]

\( \tilde{q}\tilde{g} \) production, \( M_g = 700 \text{ GeV} \)

Unmatched \( \tilde{q}\tilde{q} + 25\% \tilde{q}\tilde{g} \) (fits “data”)

Easy misinterpretation: squark-gluino component
Non-standard gluinos


Many models/ideas for physics beyond the Standard Model at the LHC giving signatures with leptons, jets and missing energy

• Differences between models often subtle – difficult to distinguish in early data
• Many models (cf. SUSY) have many parameters – most unmeasurable at LHC
• Constrained versions of models introduce strong relations between observables
Non-standard gluinos

- Most common experimental approach: Exclusions in model space of minimal model (mSUGRA/mGMSB/mAMSB) with few (~4-5) parameters

- Problems:
  - Fixed relations between parameters, e.g. $m_{\tilde{g}}:m_{\tilde{W}}:m_{\tilde{B}} \sim 6:2:1$
  - Light flavor squark masses $\gtrsim$ gluino mass
  - Fixed decays and branching ratios
  - Not all possible parameter space covered
Non-standard gluinos

Non-unified/non-standard SUSY scenarios, and other models, can have $m_{\tilde{g}}:m_{\tilde{B}}$ ratio free

- A priori unclear where Tevatron is sensitive
- Need combination of $E_T + 1$-jet, 2-jet, 3-jet and multijet searches to cover whole $\tilde{g}$-$\tilde{B}$ mass plane
Non-standard gluinos

Special difficulty when decay products nearly mass-degenerate with produced particle:

- No (small) missing transverse energy in decay
Non-standard gluinos

Special difficulty when decay products nearly mass-degenerate with produced particle:

- No (small) missing transverse energy in decay
- Need recoil against jets to get $\not{E}_T$ signature
Non-standard gluinos

\[ M_g = 150 \text{ GeV} \]
\[ M_B = 40 \text{ GeV} \]

\[ M_g = 150 \text{ GeV} \]
\[ M_B = 130 \text{ GeV} \]

Tevatron, after 2-jet and missing \( E_T \) cuts
Non-standard gluinos

- Prejudice-free model scenario and improved simulation allows us to find exclusion region in $\tilde{g} - \tilde{B}$ mass plane
Conclusions and outlook

- The LHC is coming! Are we prepared?
- Signals involving jets and missing energy will (probably) be crucial for discovery of new physics
- Precision simulations necessary, both for SM backgrounds and many New Physics scenarios
- Big advances in recent years, still much to do!
  - Automatization of next-to-leading order calculations
  - Further improvement of methods for model distinction
- Exciting times are ahead!
Backup slides
Details of matching schemes

- **CKKW scheme**
  - Sudakov reweighting using analytical NLL Sudakovs
  - Analytically relatively well-understood

- **Lönnblad scheme**
  - Sudakov reweighting by using shower Sudakovs

- **MLM scheme**
  - Run shower and reject events with too hard emission
  - Can use any shower implementation
MLM matching

J.A. et al. [arXiv:0706.2569],

Use shower hardness to separate ME/PS

1. Generate multiparton event with cut on jet $k_T$
2. Cluster event and use $k_T^2$ for $\alpha_s$ scale
3. Shower event (using Pythia) starting from hard scale
4. Collect showered partons in $k_T$ jets with $k_{T\text{cut}} > k_{T\text{min}}$
5. Keep event only if each jet matched to one parton
6. For highest multiplicity sample, allow extra jets softer than $k_{T\text{min}}$

Keep

Discard unless highest multiplicity
CKKW matching

Imitate parton shower procedure for matrix elements

1. Choose a cutoff (jet resolution) scale $d_{ini}$
2. Generate multiparton event with $d_{min} = d_{ini}$ and factorization scale $d_{ini}$
3. Cluster event with $k_T$ algorithm to find “parton shower history”
4. Use $d_i \sim k_T^2$ in each vertex as scale for $\alpha_s$
5. Weight event with NLL Sudakov factor $\Delta(d_j, d_{ini})/\Delta(d_i, d_{ini})$ for each parton line between vertices $i$ and $j$ ($d_j$ can be $d_{ini}$)
6. Shower event, allowing only emissions with $k_T < d_{ini}$ (“vetoed showers”)
7. For highest multiplicity sample, use $\min(d_i)$ of event as $d_{ini}$
Boost-invariant $k_T$ measure:

\[
\begin{align*}
    d_{iB} &= p_{T,i}^2 \\
    d_{ij} &= \min(p_{T,i}^2, p_{T,j}^2) F_{ij} \\
    F_{ij} &= 2 \left\{ \cosh(\eta_i - \eta_j) - \cos(\phi_i - \phi_j) \right\}
\end{align*}
\]

- For final-state showers: Combination of NLL Sudakov factors and vetoed NLL showers guarantees independence of $d_{ini}$ to NLL order
- For initial-state showers: No proof but works ok
- Problem in practice: No NLL shower implementation! (Sherpa uses Pythia-like showers)
Shower $k_T$ scheme

- Keep/reject event based on $k_T$ of hardest shower emission (as reported by Pythia)
- Highest multiplicity treatment as in CKKW, use min dparton as cutoff
- No jet clustering
- No need of “fiducial region”, can use $k_T^{\text{match}} = d_{\text{cut}}^{\text{ME}}$
- Need similar kT definitions in ME and PS (only “new”, $p_T$-ordered showers at present)