Tools for SUSY

(and BSM in general)

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What do we want?

What do we want?

What do we want?

Write the Lagrangian down

What do we want?

Write the Lagrangian down

Press "Enter"

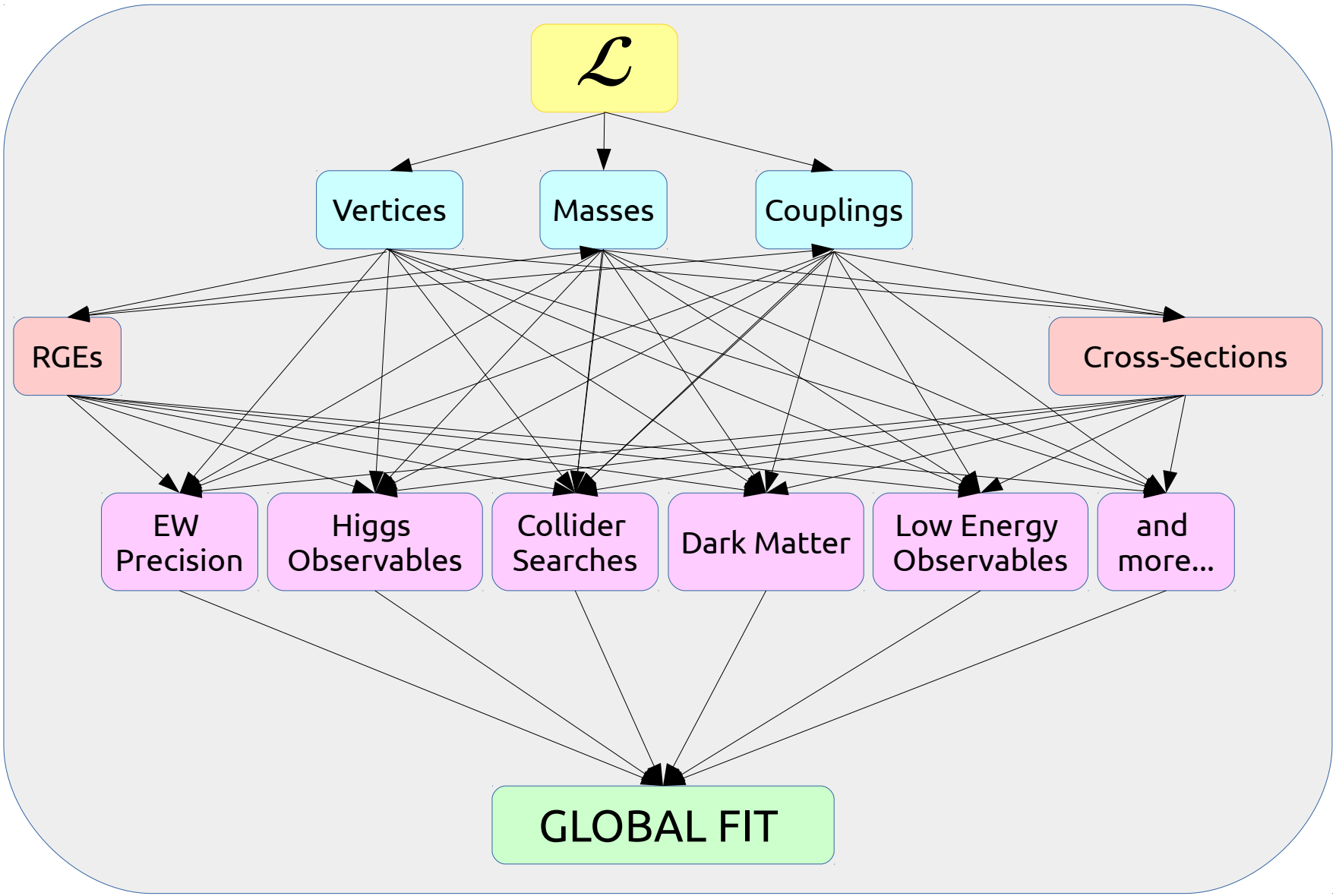
What do we want?

Write the Lagrangian down

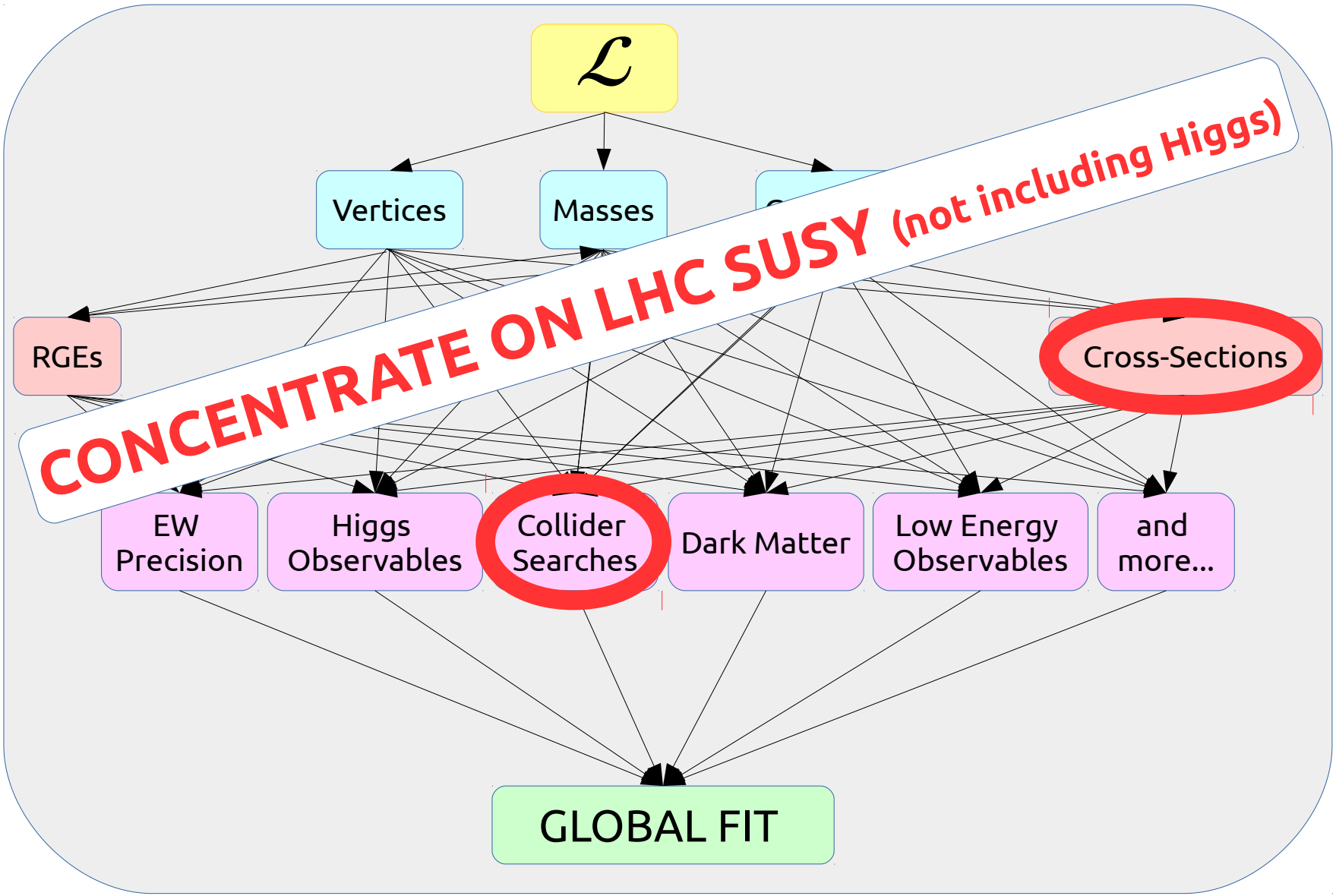
Press "Enter"

Computer fits the model parameters to all relevant observables

Overview


$\mathcal{L}$
Vertices
Masses
Couplings
RGEs
Cross-Sections
EW Precision
Higgs Observables
Collider Searches
Dark Matter
Low Energy Observables
and more...
GLOBAL FIT

Overview


$\mathcal{L}$
Vertices
Masses
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Cross-Sections
CONCENTRATE ON LHC SUSY (not including Higgs)
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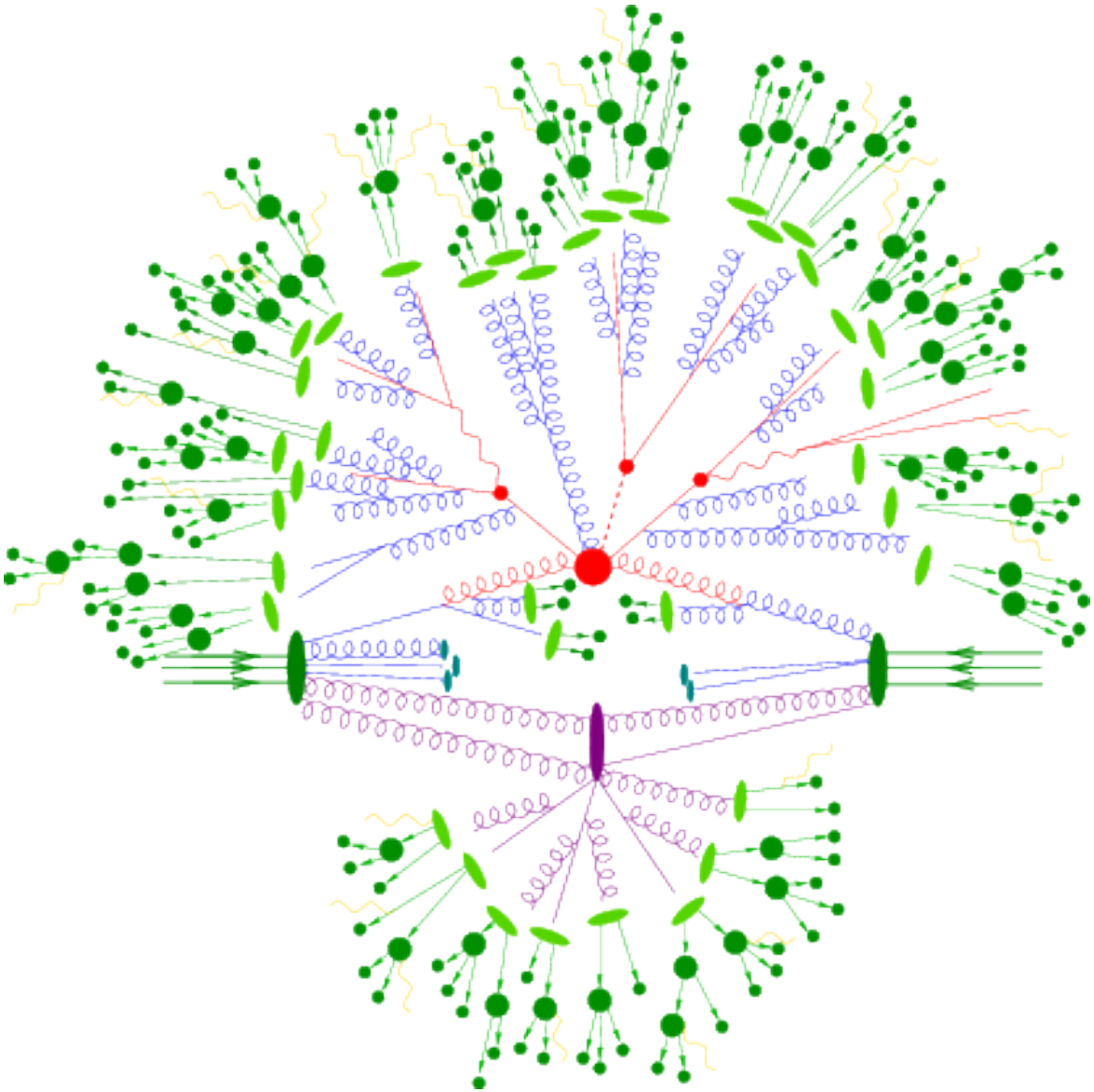
and more...
GLOBAL FIT

Monte Carlo Generation



Sherpa

Monte Carlo generation

BSM now standard in many tools

- Built in and via UFO (FeynRules) interface
- For bulk (e.g. mSUGRA) regions of parameter space results are very similar

Current 'defaults'

- MadGraph (Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Stelzer + many more...)
- Pythia (6 or 8) (Sjöstrand, Ask, Desai, Ilten, Mrenna, Prestel, Skands + many more...)
- Herwig (Richardson, Webber, Gieseke, Grellscheid, Platzer, Seymour + many more...)
- Sherpa (Krauss, Gleisberg, Höche, Schumann, Schönherr, Siegert, Winter + many more...)
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Important differences if we look more closely

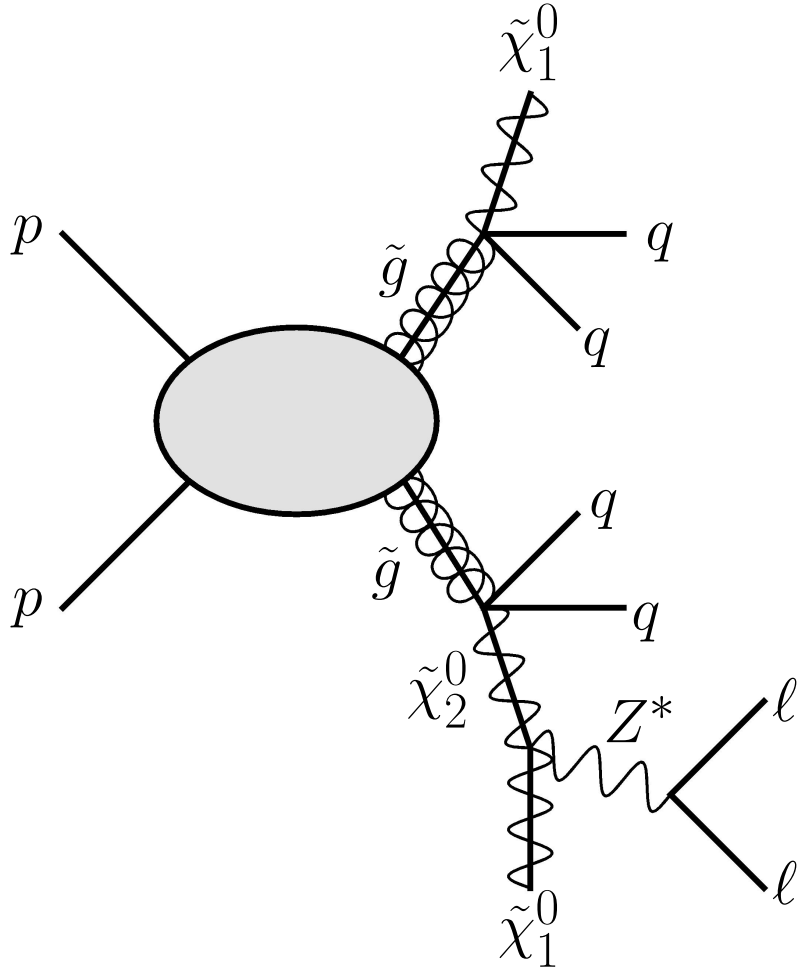
Spin correlations

ME evaluation

- BSM often involves decay chains
- In principle 2→n can be calculated (MadGraph, Sherpa, Whizzard)
  - Computation time is a killer

Factorise

- Use narrow width approximation to factorise
- All spin information lost
  - 'Standard' MG5+Pythia6 decays according to phase space



Spin correlations

Algorithm

- E.g. massive vector

$$\begin{aligned}\mathcal{M} \sim & \quad j_1^\mu \left(g_{\mu\nu} - \frac{p_\mu p_\nu}{p^2} \right) j_2^\nu \\ = & \quad \sum_\lambda \underbrace{j_1^\mu \varepsilon_\mu^*(\lambda)}_{\mathcal{M}_{\text{prod}}(\lambda)} \underbrace{\varepsilon_\nu(\lambda) j_2^\nu}_{\mathcal{M}_{\text{dec}}(\lambda)}\end{aligned}$$

Implementation

- Herwig $\rightarrow$ original

  (Richardson; 2001)

- Sherpa $\rightarrow$ recent addition

  (Höche, Kuttimalai, Schumann, Siegert; 2014)

- MadSpin $\rightarrow$ SM focus

  (Artoisenet, Frederix, Mattelaer, Rietkerk: 2012)

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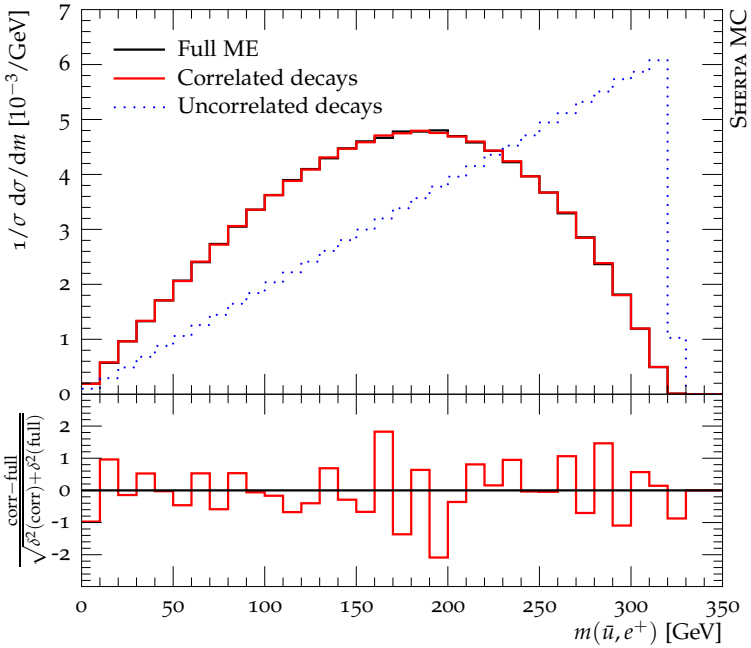

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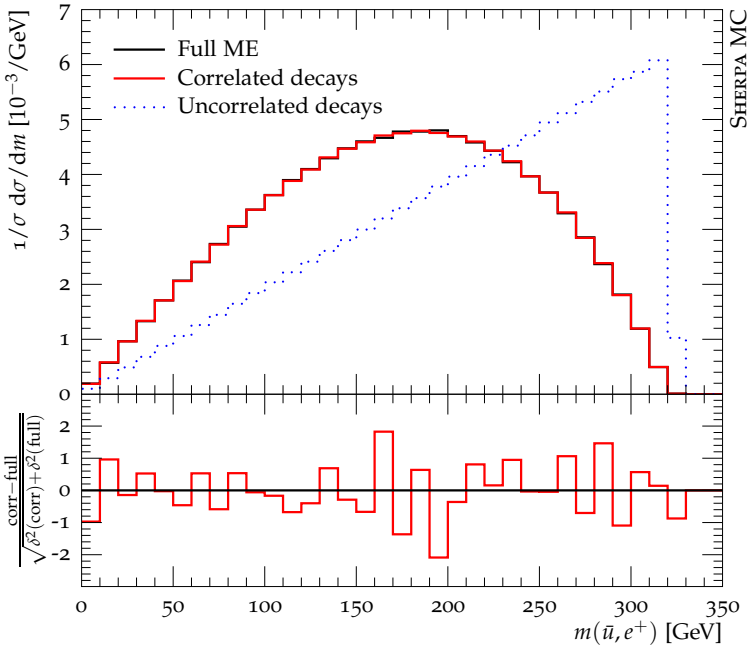

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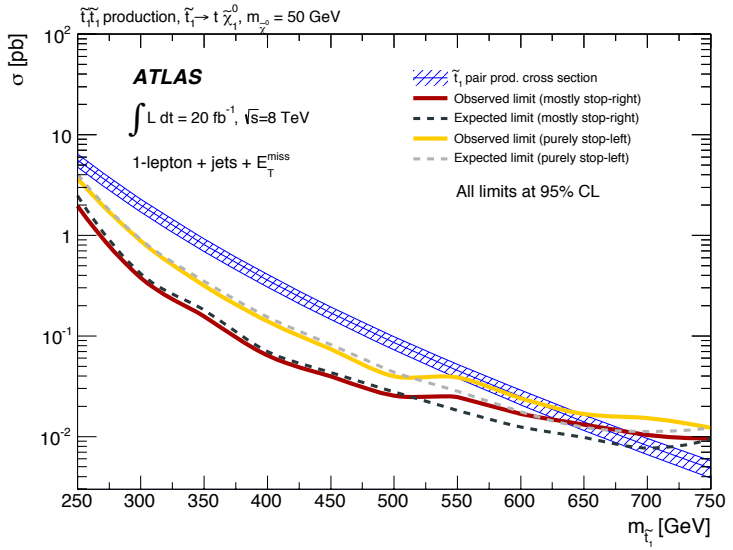
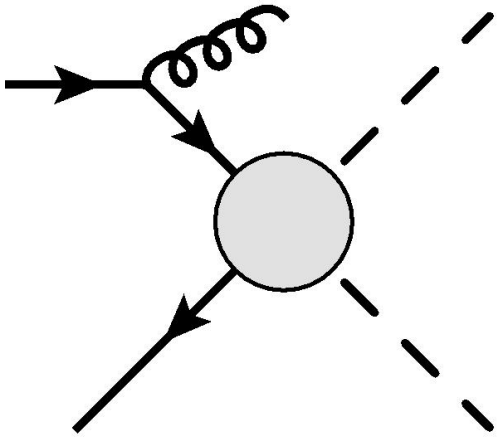


Initial state radiation

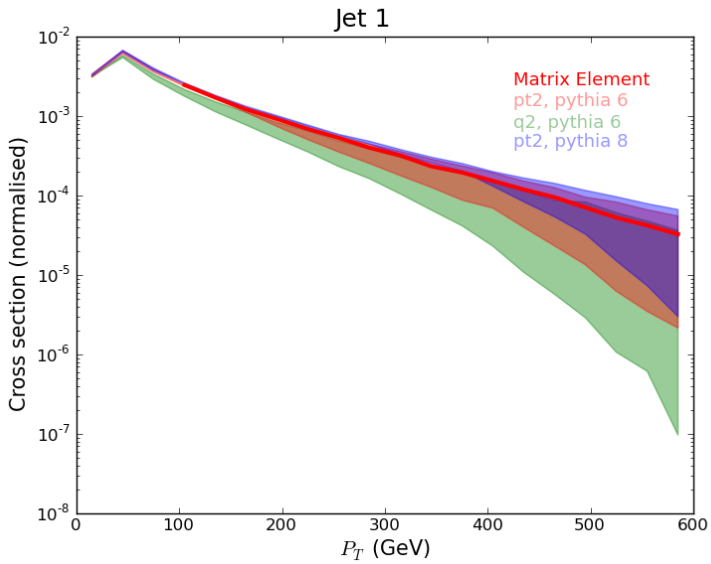
ISR LHC searches

- EFT dark matter, natural stops, direct neutralinos, compressed spectra, invisible Higgs decays...



ISR prediction

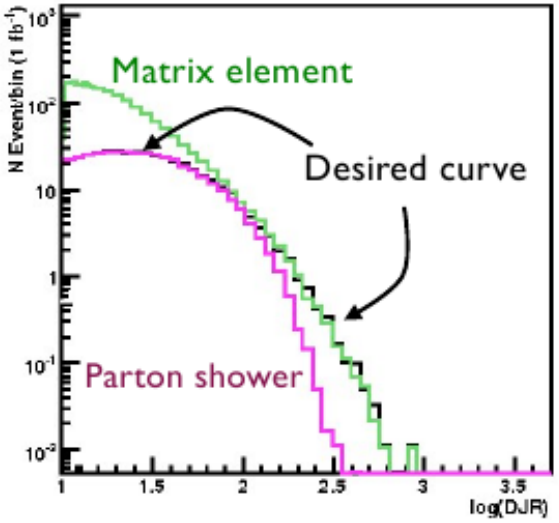
- Parton showers give widely differing results
- Matrix element calculation required
- Careful to avoid double counting
- MLM (Mangano, Moretti, Piccinini, Treccani; 2006)
- CKKW (Catani, Krauss, Kuhn, Webber; 2001)



Initial state radiation

Matching algorithm

- ME diverges in soft/collinear limit
- PS resums logs
- Veto hard PS radiation
- Produce fully inclusive sample



Maltoni

BSM Implementations

- MG5+P6 - Original BSM (MLM)

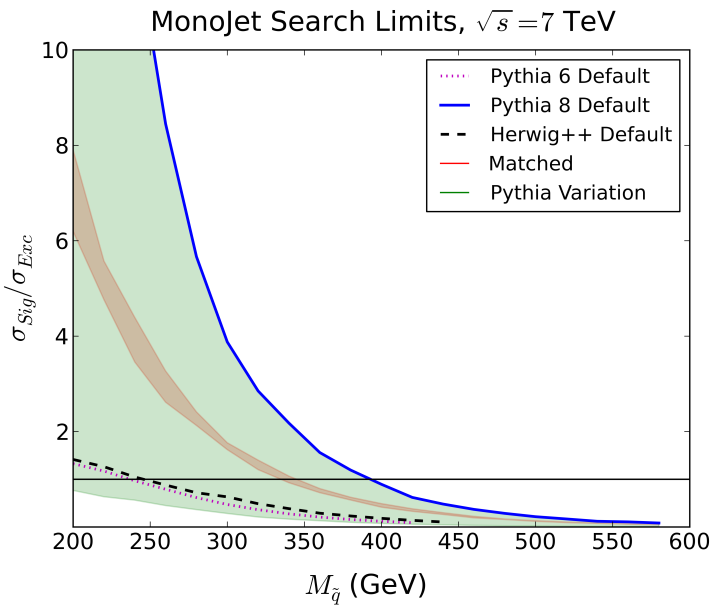
  (Alwall, de Visscher, Maltoni; 2008)

- Pythia 8 - Need to calculate ME elsewhere (CKKW-L)

  (Lönnblad, Prestel; 2012)

- Sherpa - Uncoloured (CKKW)

  (Höche, Kuttimalai, Schumann, Siegert; 2014)



SUSY (BSM) @ NLO

SM @ NLO (QCD)

- Event generation in SM@NLO now standard
- MadGraph5_aMC@NLO fully automated
- Many processes available in Sherpa and Herwig

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BSM Auto-NLO is here!

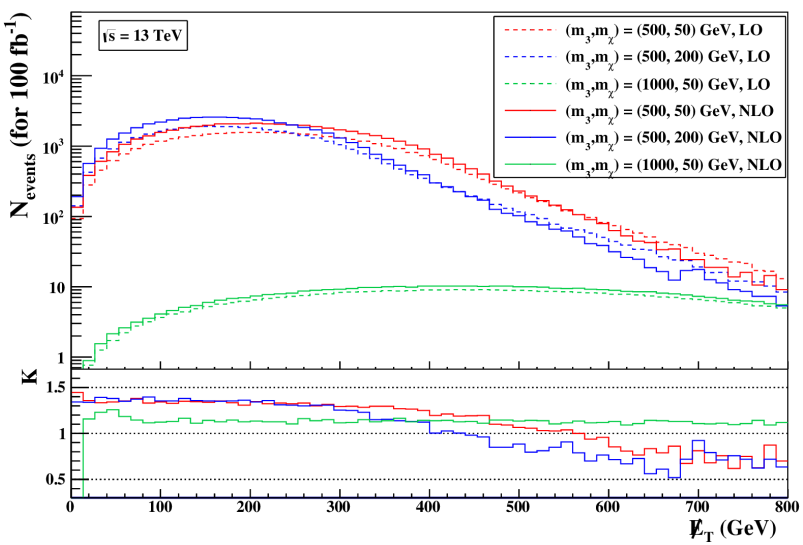
Implemented in MadGraph5_aMC@NLO

- NLOCT (Degrande; 2014)
- Automatic extraction and calculation of UV-counterterms and R_2 from tree level Lagrangian
  - OPP (Ossola, Papadopoulos, Pittau; 2007)
  - MadLoop (Hirschi, Frederix, Frixione, Garzelli, Maltoni; 2011)
  - FeynRules (Alloul, Christensen, Degrande, Duhr, Fuks; 2013)
  - FeynArts (Hahn; 2001)
- In principle works with any renormalisable Lagrangian

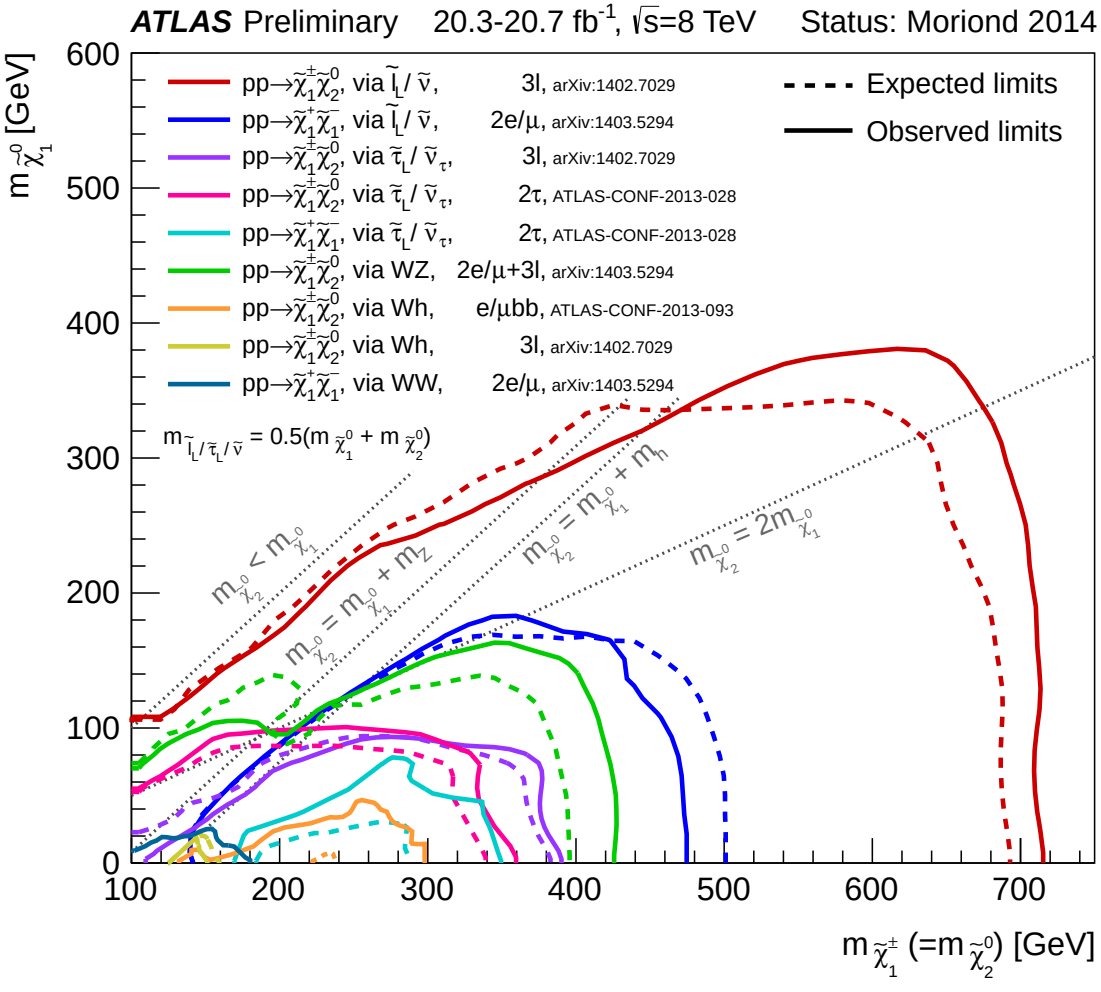
SUSY (BSM) @ NLO

Validated models

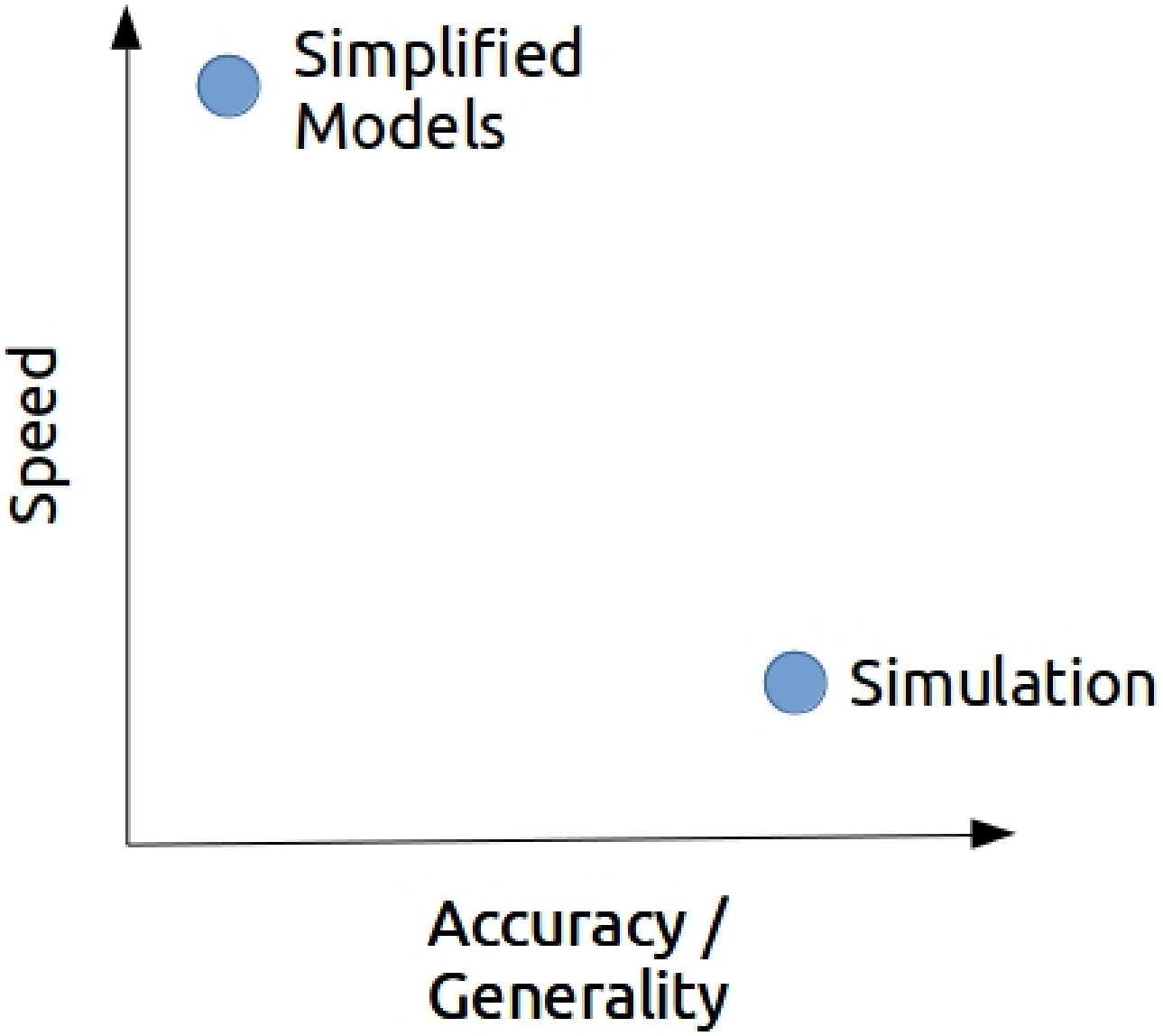
- Simplified DM models (Mawatari)
- Effective Higgs couplings (Demartin, Maltoni, Mawatari, Page, Zaro; 2013, 2014)
- Sgluon (Degrande, Fuks, Hirschi, Proudom, Shao; 2014)
- Stop (Degrande, Fuks, Hirschi, Proudom, Shao; 2014)
- THDM (Degrande; 2014)
- Full MSSM and NMSSM (including *ggH*) in development



LHC Interpretation



Current approaches



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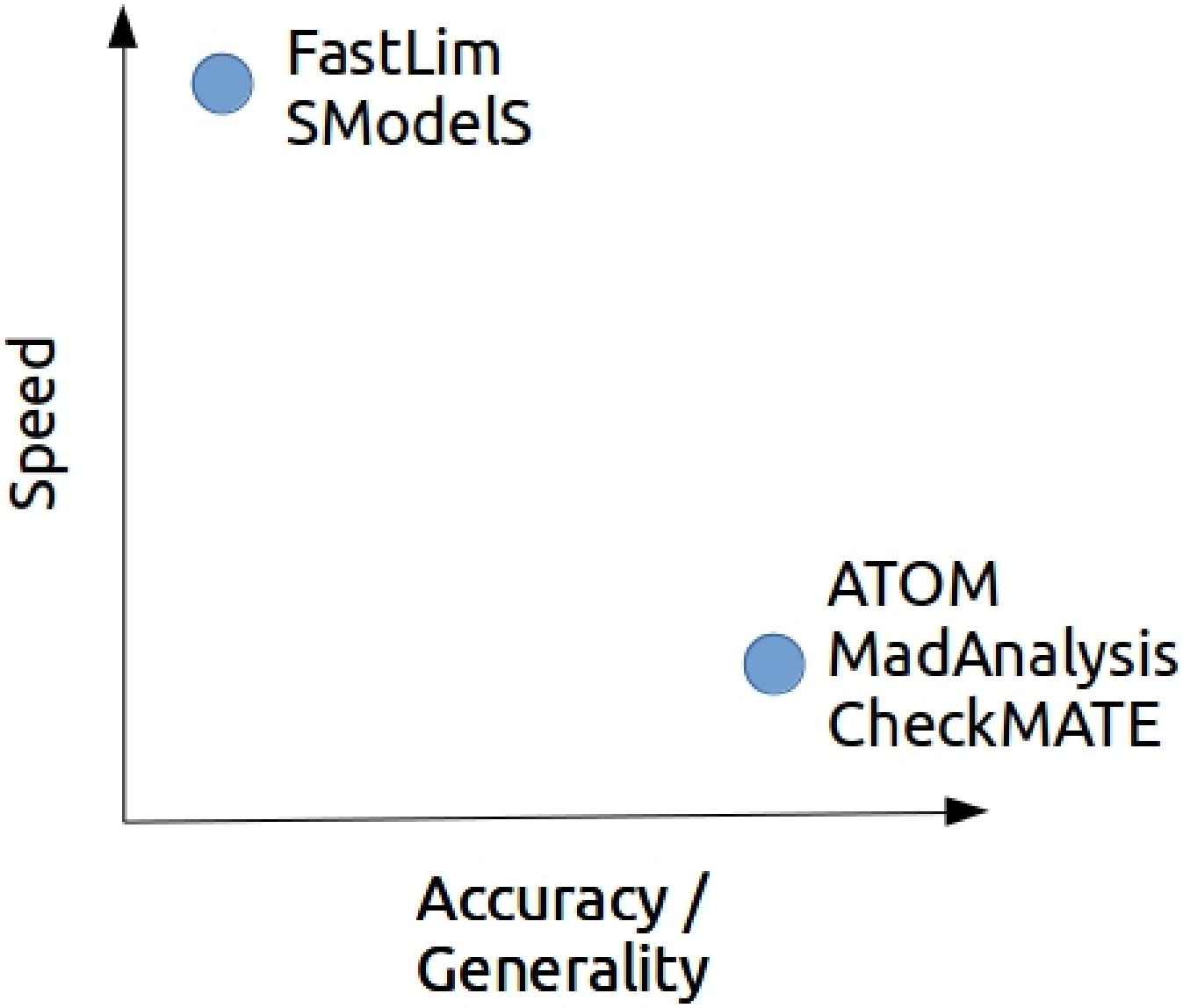
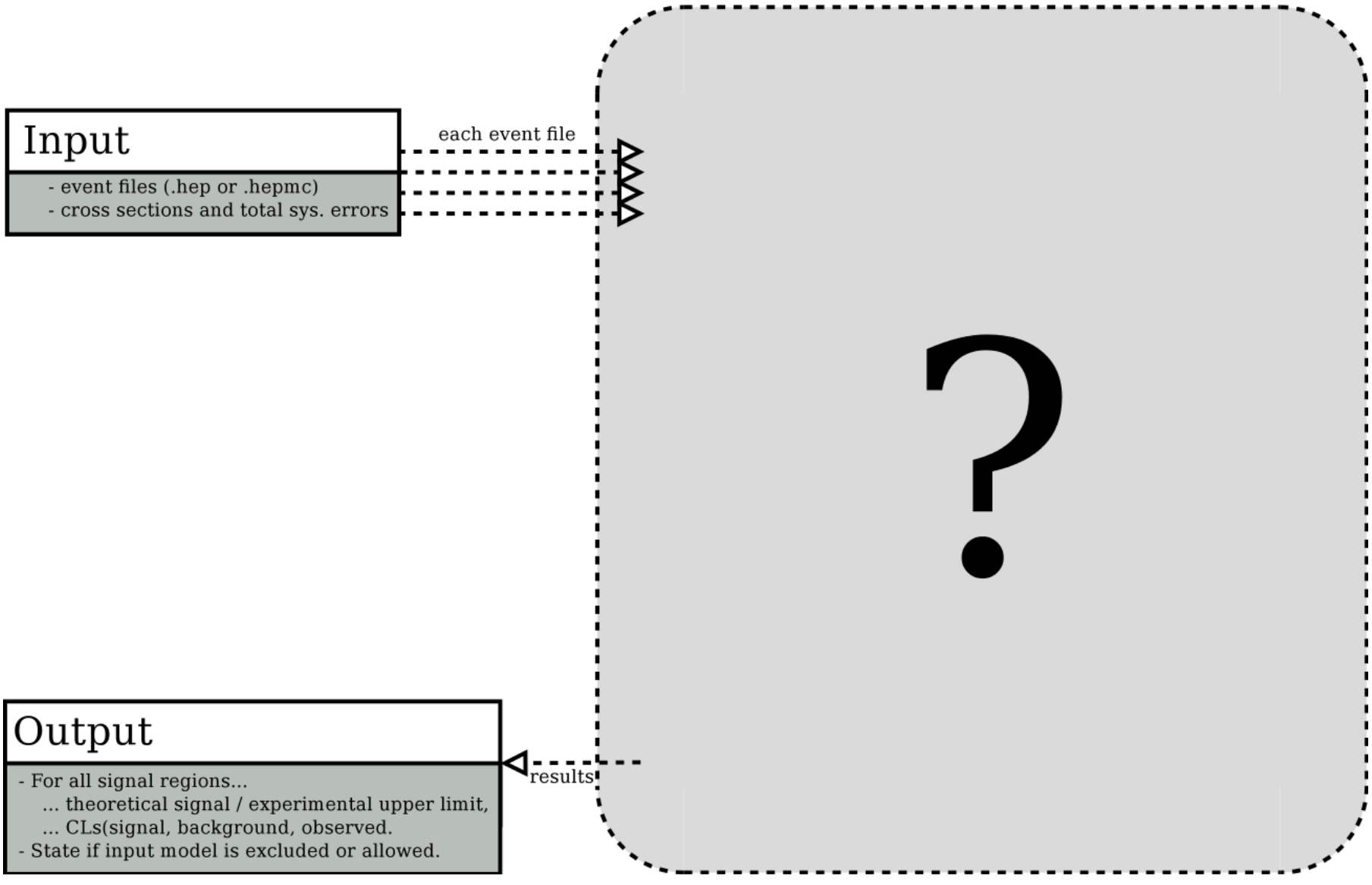


Simulation Program Flow



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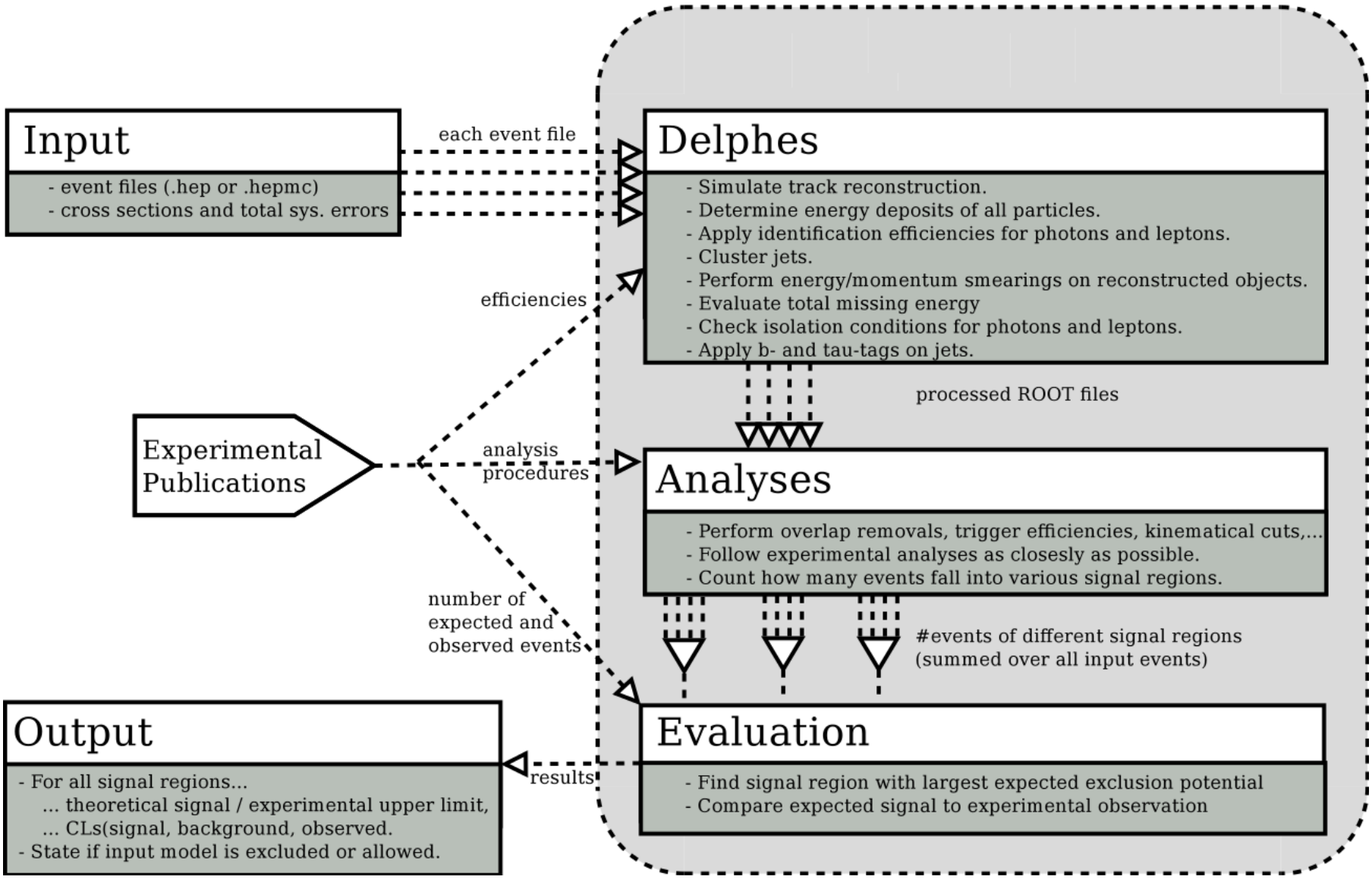


Available tools

MadAnalysis5 (Bein, Chalons, Conte, Dumont, Fuks, Kulkarni, Kraml, Schmitt, Sengupta, Wymant)

- 7 validated analyses (+ 18 unvalidated)
- Based on Delphes3 (de Favereau, Delaere, Demin, Giammanco, Lemaître, Mertens, Selvaggi)
- Soon cross-compatible with CheckMATE

CheckMATE (Desai, Drees, Dreiner, Kim, Rolbiecki, Schmeier, JT)

- 19 validated analyses (+ 20 unvalidated)
- Also based on Delphes3
- CheckMATE 2 soon public (SLHA input, MG5+Pythia8 built in, 2x faster, designed for cluster)

ATOM (Kim, Papucci, Sakurai, Weiler)

- Not yet public (available if you ask nicely)
- $\sim$ 15 analyses
- Based on Rivet (Buckley, Butterworth, Lonnblad, Grellscheid, Hoeth, Monk, Schulz, Siegert)

Investigating excesses

Example – CMS dilepton edge

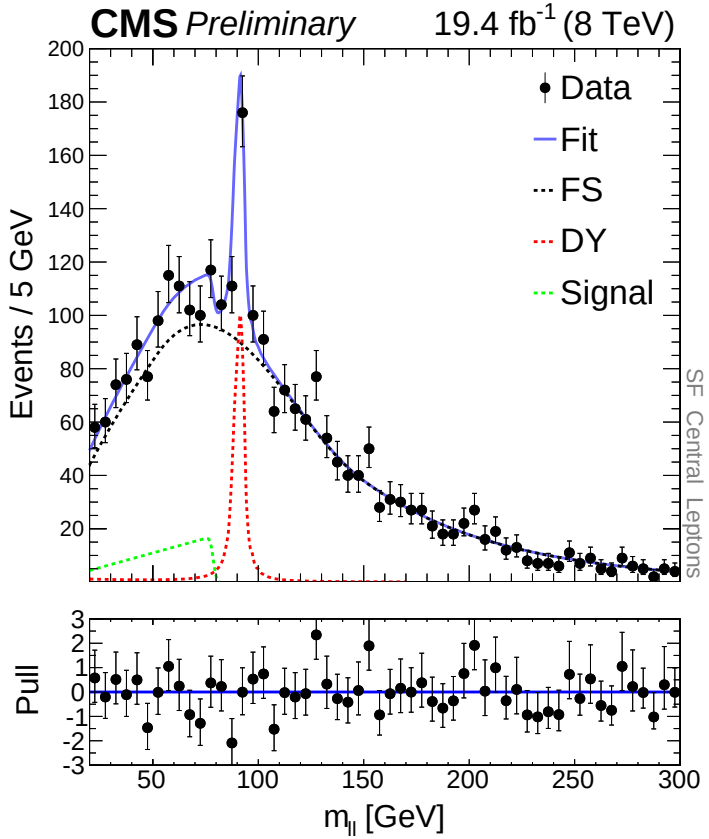
- $\sim 2.6\sigma$ excess

Gluino Model

- Neutralinos produced in decay
- Off-shell Z $\rightarrow$ di-leptons

Other Models

- Squarks, sbottoms, stops
- Sleptons in chain



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- Neutralinos produced in decay
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- Other ideas $\rightarrow$ Squarks, sbottoms, stops, sleptons in decay

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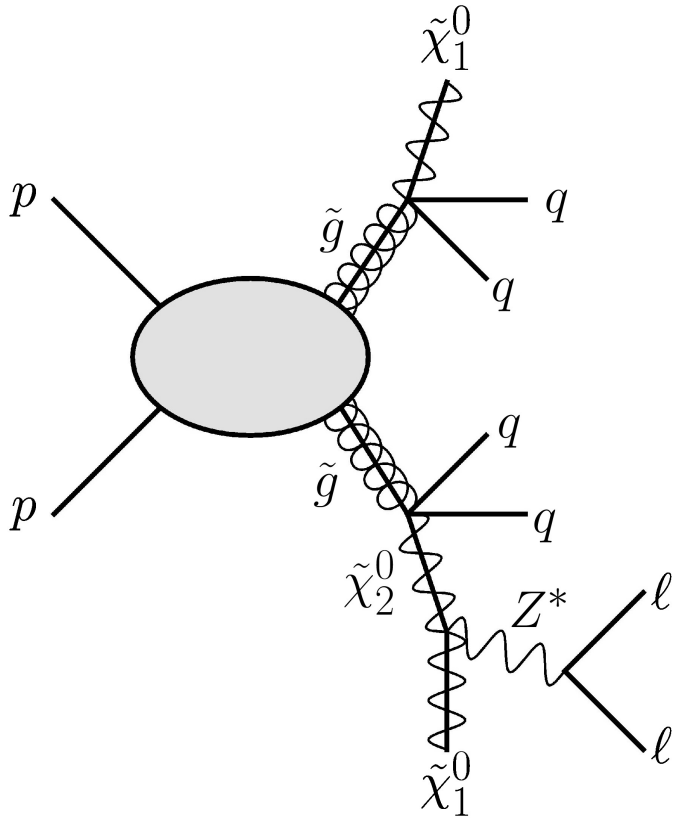
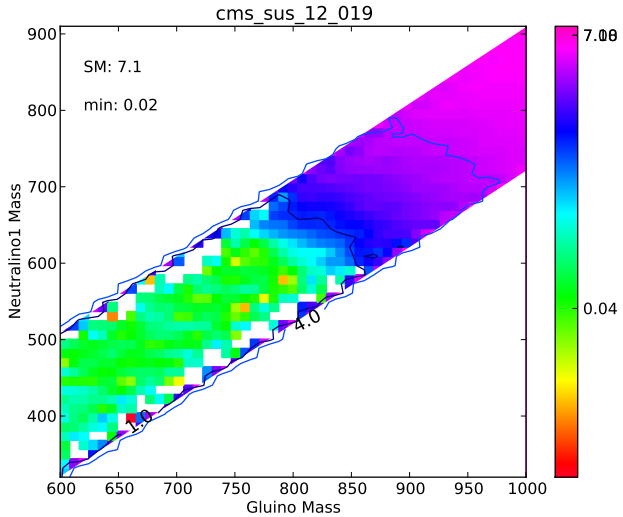


SUSY Fit

Dilepton fit

- Tune di-leptonic branching ratio to match edge
- Find solution for wide range of masses



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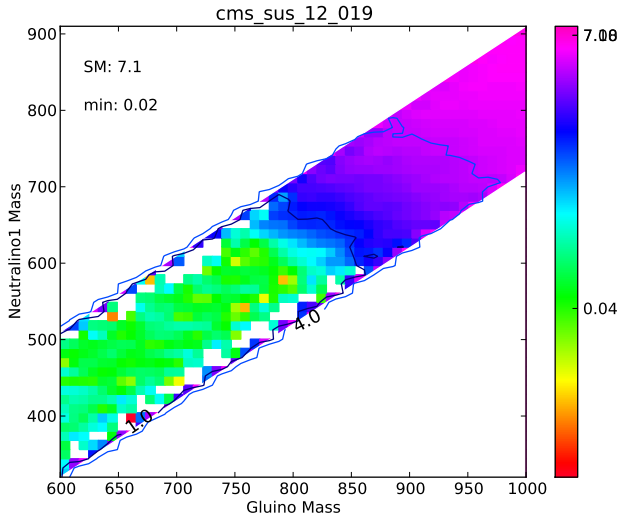
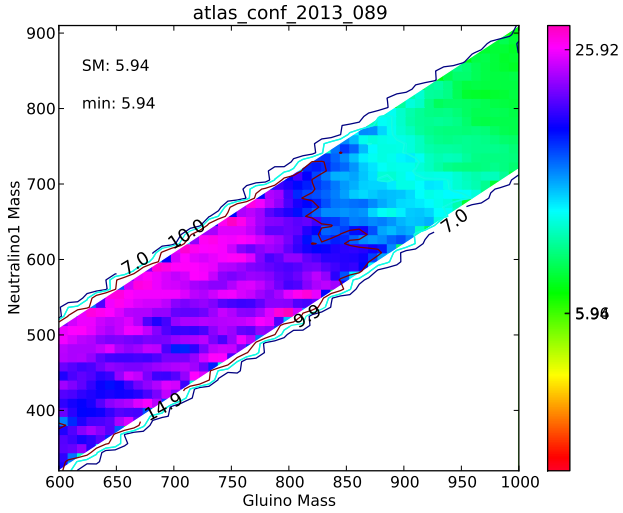


Other SUSY searches

- Must check other SUSY searches
- Gluino solution ruled out at over 3-σ by ATLAS 2 lepton search (atlas_conf_2013_089)



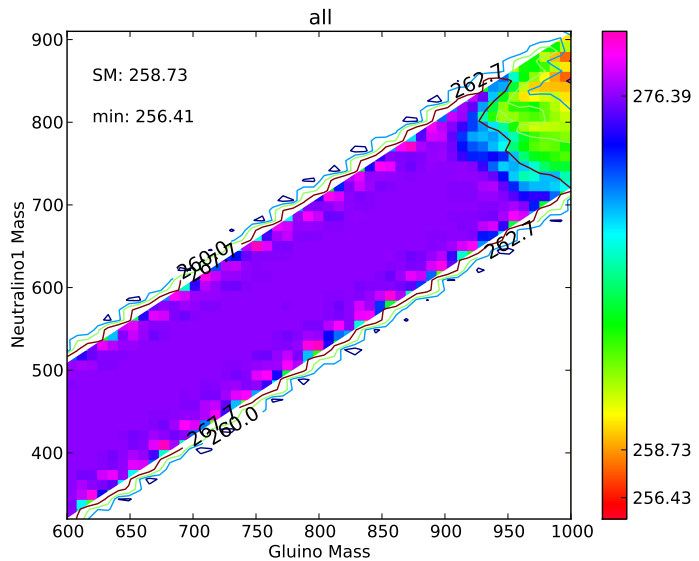
Global Fit

No good SUSY solution
(Grothaus, Liew, Sakurai; 2015)

(Kim, Rolbiecki, JT; 2015)

- Fit gives point with no visible edge
- Same is true for Squarks, Sbottoms, Stops
  - Slepton mediated decays are even worse
- ATLAS $\rightarrow$ nothing below Z (1503.03290) ...but 3.0 σ on–Z
  (Liew, Mariotti, Mawatari, Sakurai, Vereecken; 2015)
  (Cahill-Rowley, Hewett, Ismail, Rizzo; 2015)
  (Cao, Shang, Yang, Zhang; 2015)
  (Collins, Dror, Farina; 2015)

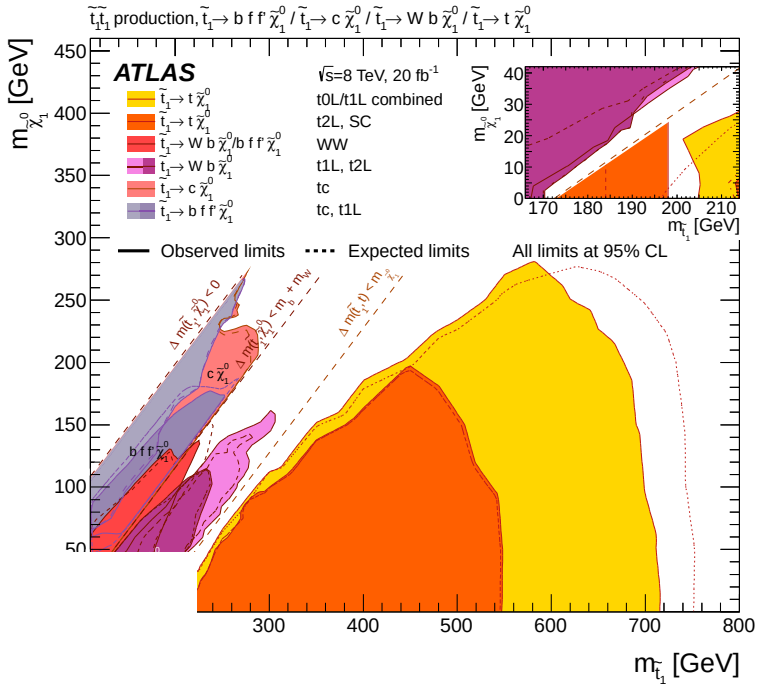
  ...

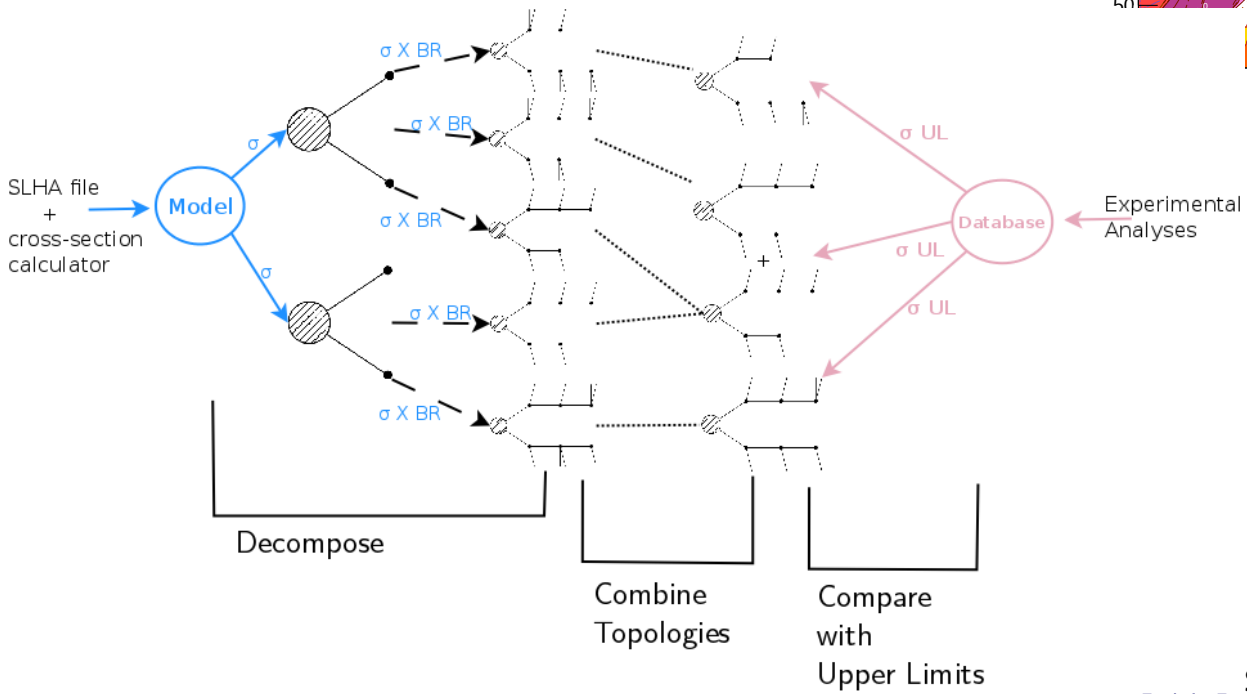


Simplified Model Tools

Simplified Models

- Set limits on specific topology instead
- Assume 100% branching ratio
- Easily rescaled to model





Simplified Model Tools

Available Tools

- FastLim (10 analyses) (Papucci, Sakurai, Weiler, Zeune; 2014)
- SModelS (26 analyses) (Kraml, Kulkarni, Laa, Lessa, Magerl, Magerl et al; 2014)
- XQCAT (5 analyses) (Barducci, Belyaev, Buchkremer, Cacciapaglia, Deandrea et al; 2014)

Advantages

- Fast! (few seconds per point)
- Use actual experimental results

Disadvantages

- Based around a particular model (usually MSSM)
- Limits conservative (sometimes very)
  - More than 1-step decays difficult
  - Limited coverage of asymmetric decays
- Probably difficult to apply to fitting a signal

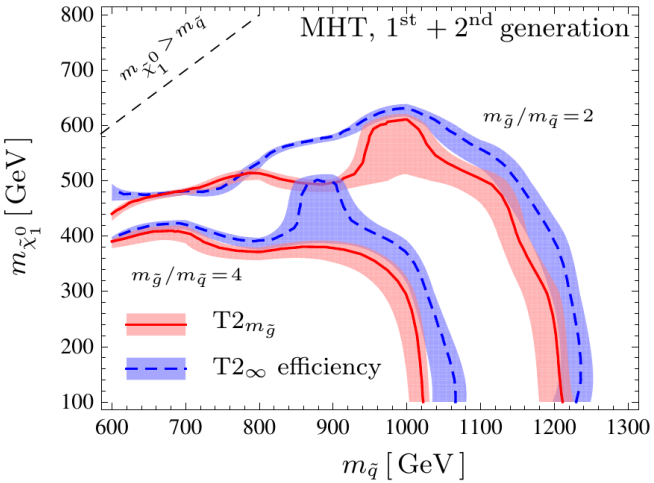
Setting Limits

How far can we push simplified models?

Squark production

- Gluino mass changes kinematics
- Limits look reasonable

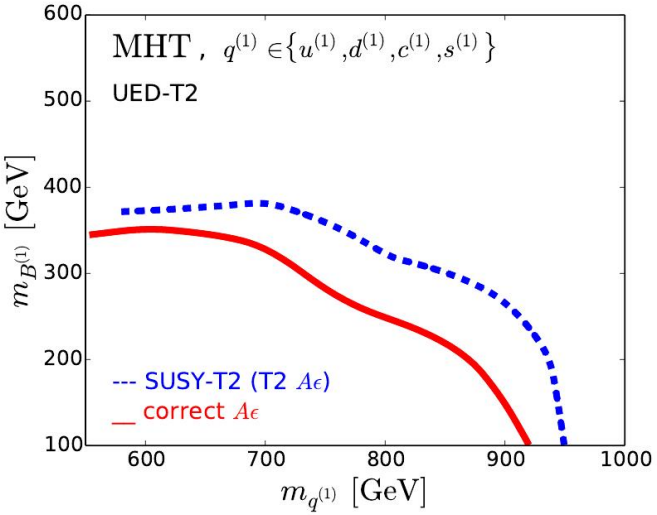
(Edelhäuser, Heisig, Krämer, Oymanns, Sonneveld; 2014)



UED Example

- Spin changes kinematics

(Edelhäuser, Krämer, Sonneveld; 2014)



A plea to experimentalists

LHC papers have improved markedly

- Cutflows now standard
- Setup documentation far better
- Simplified models adopted widely
- HEPDATA delivery (but not conf notes...)

...but

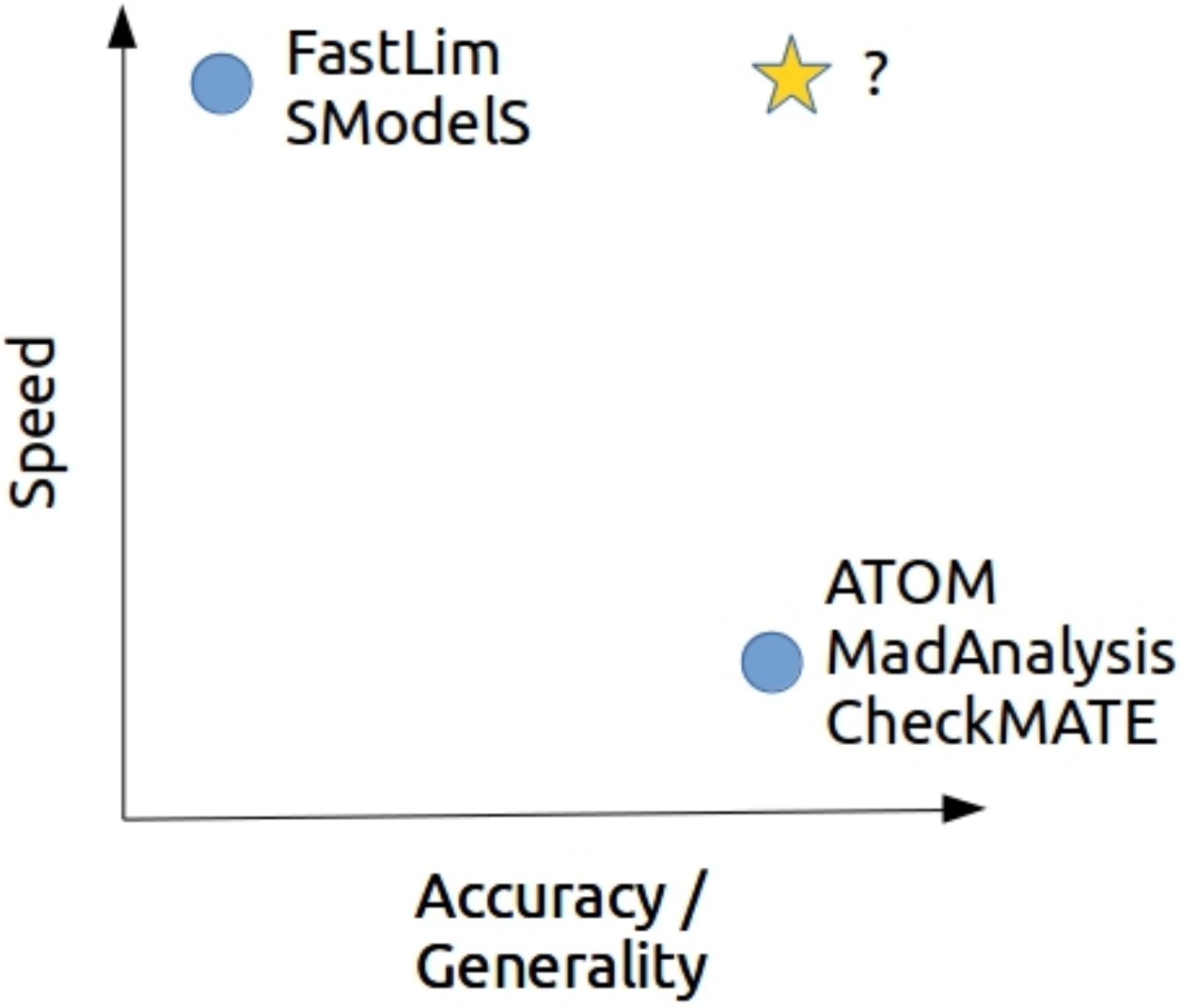
- Final state objects often badly documented
- Error breakdown often missing
- Please keep analyses (exclusively) binned (or likelihood tool)

Please read

- Searches for New Physics: Les Houches Recommendations for the Presentation of LHC Results

(Kraml, Allanach, Mangano, Prosper, Sekmen et al; 2012)

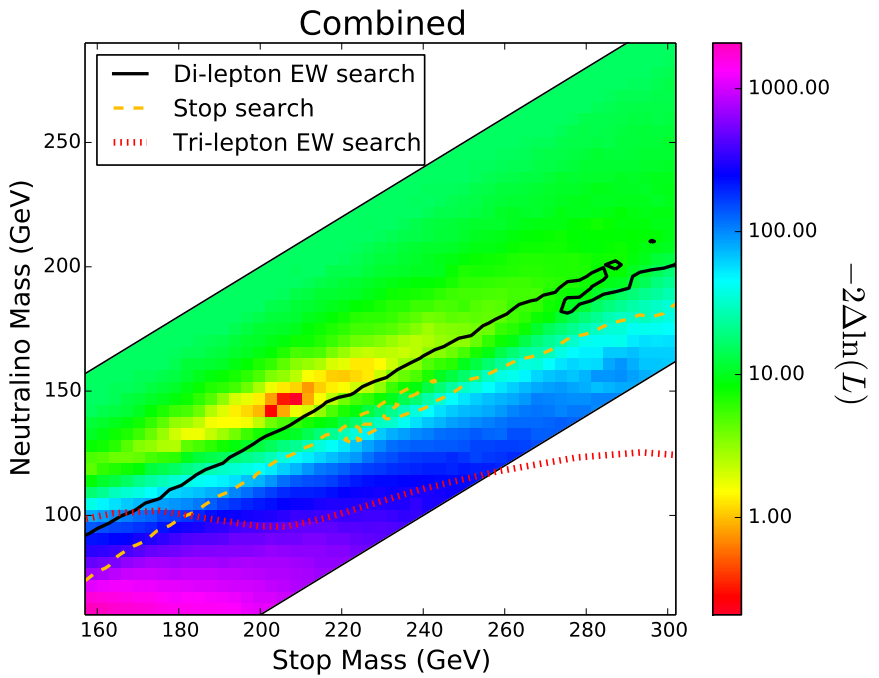
Can we do better?



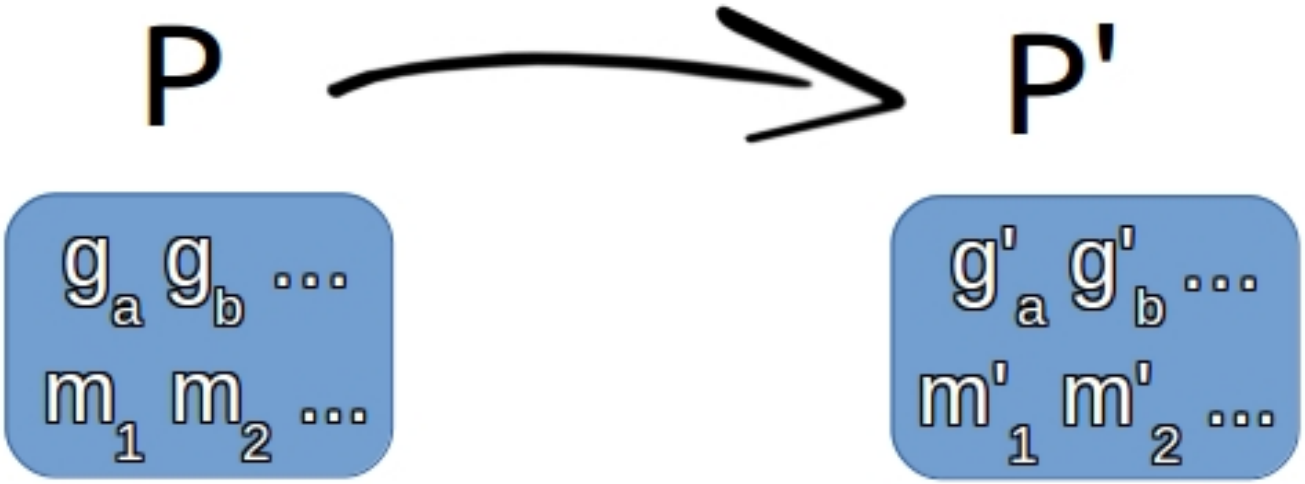
LHC inverse problem

Models with MET are difficult

- Want to perform fit with many free parameters
- Signal regions may have very low acceptance
- 2d scans already have CPU as limiting factor



Parameter scans



Moving from $P \rightarrow P'$, need:

- Final state cross-sections
- Distributions

Aim

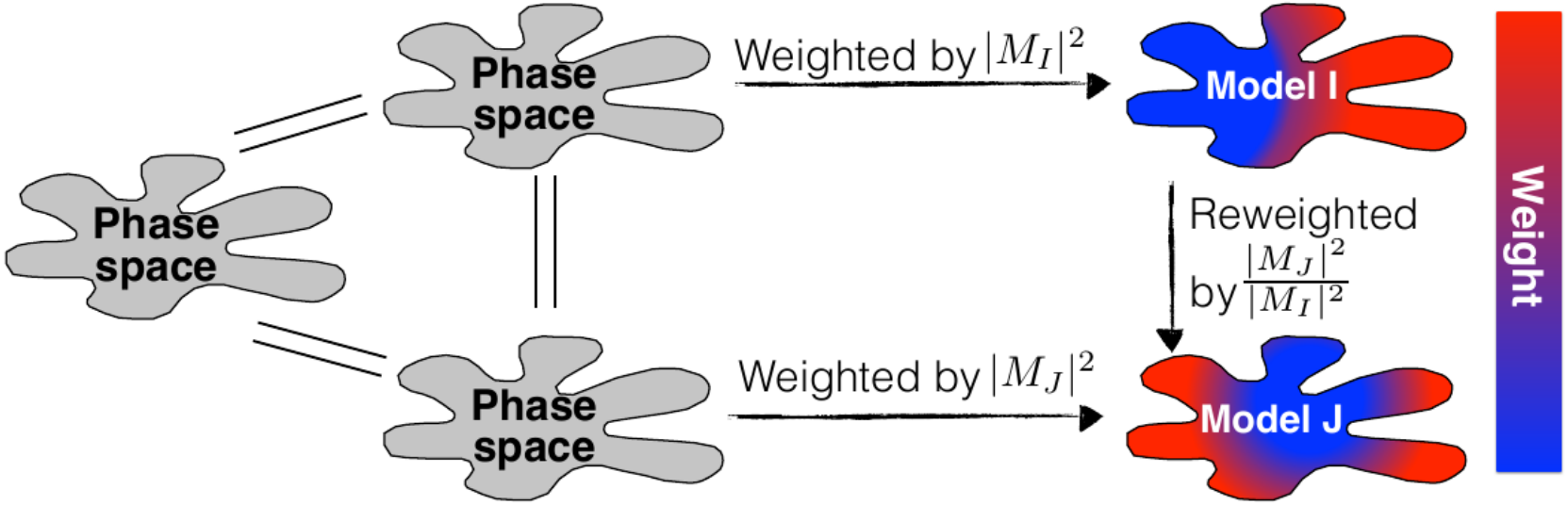
- Per point evaluation $\rightarrow \mathcal{O}(secs)$
- Accuracy $\rightarrow$ 10% on acceptance
- Arbitrary BSM models
- Arbitrary Monte-Carlo generators

Parameter scans

Matrix element method for arbitrary BSM scans

(Gainer, Lykken, Matchev, Mrenna, Park; 2014)

- Central idea $\rightarrow$ Re-use events via re-weighting
  - Experiments generate large samples of unweighted events for arbitrary topologies
  - Full parton shower and detector simulation performed
  - BSM events by reweighting ME at same phase space point



Parameter scans

Two key practical issues

- Requires experiments to do more work
  - In addition far more detailed detector information can be derived
- Only allows changes in couplings and spins
  - Crucially masses must be the same

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- Requires experiments to do more work
  - In addition far more detailed detector information can be derived
- Only allows changes in couplings and spins
  - Crucially masses must be the same

Our idea

- Optimise for speed
  - No matrix element evaluation
  - Re-use parton shower
  - Re-use detector sim
  - Re-use jet algorithm
- Allow masses to vary
- Keep spins the same
- Model and Monte-Carlo agnostic

Couplings

First order effects

- Total Cross-Section
- Branching Ratio

Second order effects $\rightarrow$ ignore

- Kinematical Distributions
- Requires
  - Interference terms small
  - Narrow width approximation satisfied

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Solution

- Simply reweight events $\rightarrow$ Total normalisation guaranteed
- Generally, acceptances only weakly depend on coupling structures

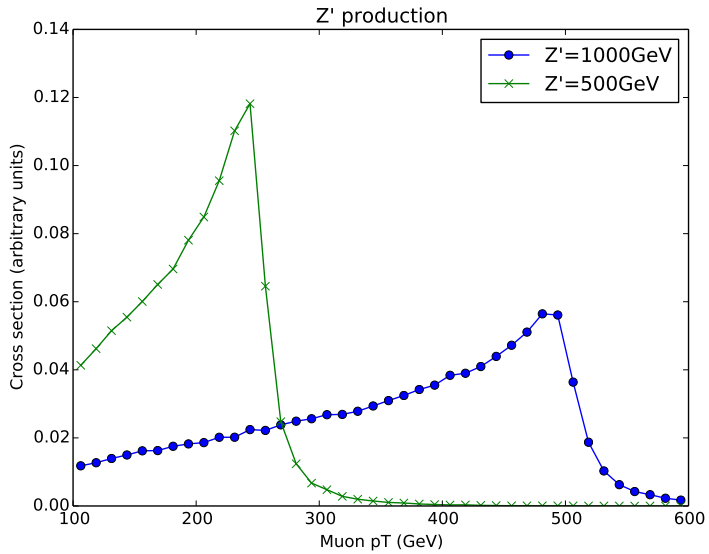
Masses

Easy part

- Total Cross-Section $\rightarrow$ Reweight
- Branching Ratios $\rightarrow$ Reweight

More difficult

- Kinematical Distributions
  - Clearly not a sub-leading effect for mass changes



Idea

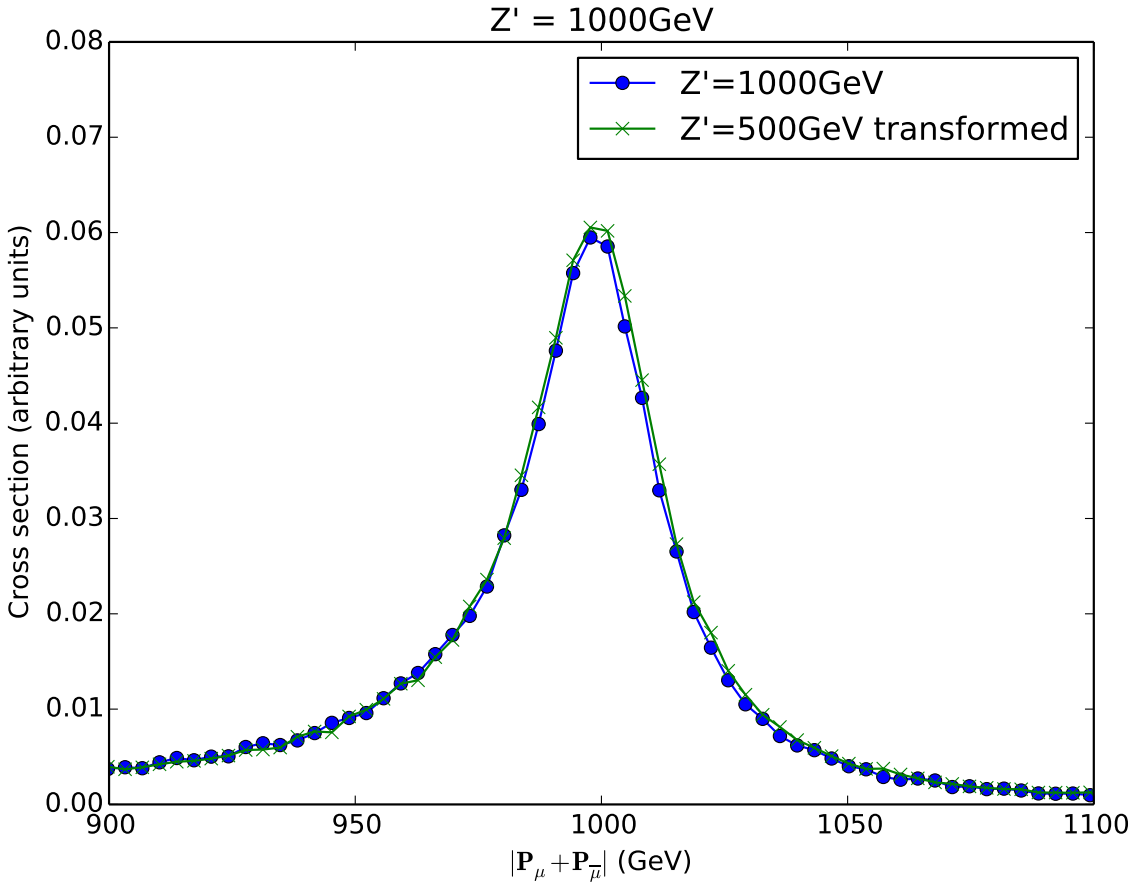
Guiding principle

- Production: $\vec{p} \to \vec{p}, m \to m'$
  - Ensures we sample full phase space
  - 'Off-shellness' constant
- Decays: Rest frame angles conserved
  - All kinematics specified by momentum conservation
- Final state particles: Matched to hard event
  - Kinematics determined by hard partons
  - Smeared in proportion to original event particles

Reweighting

- $1/s$: Leading cross-section behaviour
- PDFs: Leading LHC angular distribution behaviour
- α_s: If QCD production (and ISR)

Z' example

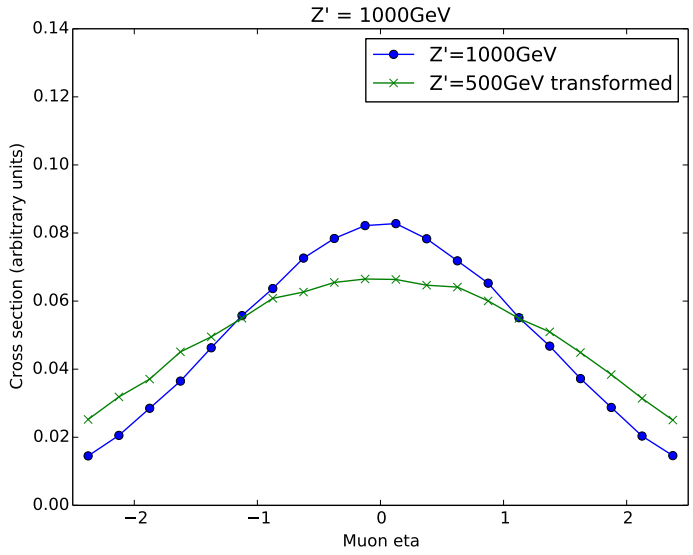


By definition, invariant mass is reproduced

Z' example

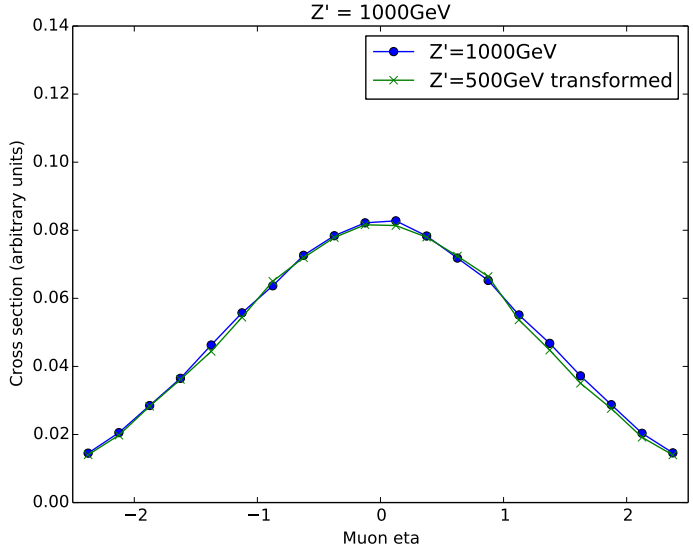
Without PDF reweighting

- At higher $\sqrt{s}$ production becomes more central

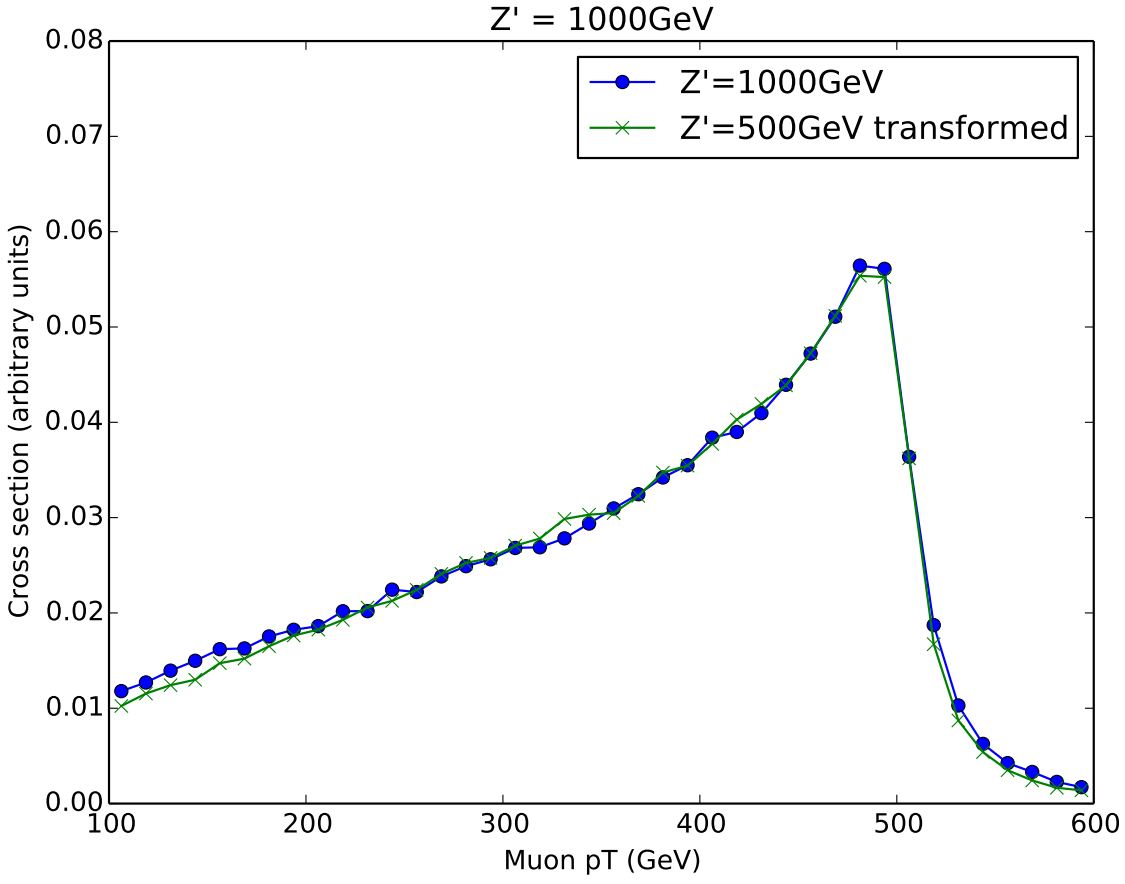


With PDF reweighting

- PDF reweighting corrects production angles



Z' example



Other distributions also reproduced

Future plans

Seems to work for Z'

- Now playing with top model $\rightarrow$ multi-stage decays
- Apply to SUSY and recalculate exclusions
- Completely testable for any parameter point

Generalise

- Algorithm should work automatically with any BSM model
- Any choice of Monte-Carlo event generator
- User simply supplies FeynRules model and parameter ranges
- Offer matrix element evaluation as an option

Optimise

- Currently $\rightarrow \sim$ 5 secs for 100,000 events

Summary

Amazing range of BSM tools now available

- Automatic Langrangian fitting to observables is (almost) a reality

Event generation

- Spin correlations should not be forgotten
- Matrix element matching now standard
- Auto-NLO showing great progress

LHC Interpretation

- Simulations reproduce experiments very closely
- Simplified models allows for rapid testings of models

New ideas still needed for speed and accuracy

What I ignore (I'm sorry...)

Lagrangian/Superpotential interpretation

- SARAH (Staub, Ohl, Porod, Speckner, Dreiner, Nickel, Vicente, Goodsell)
- FeynRules (Christensen, Duhr, Fuks, Degrande, Grellscheid, Mattelaer, Reiter, Alloul, D'Hondt, De Causmaecker, De Traubenberg, de Aquino, Deutschmann, Garcia-Cely, Mawatari, Oexl, Takaesu)
- Susyno (Fonseca)

Spectrum Generation/RGE's

- SPheno (Staub, Porod)
- SoftSUSY (Allanach, Athron, Bednyakov, Bernhardt, Grellscheid, Hanussek, Kom, Ruiz de Austri, Slavich, Tunstall, Voigt, Williams)
- Suspect (Djouadi, Kneur, Moultaka, Ughetto, Zerwas)
- ISAJET/ISASUGRA (Paige, Protopopescu, Baer, Tata)
- FlexibleSUSY (Athron, Park, Stöckinger, Voigt)
- SuSeFLAV (Chowdhury, Garani, Vempati)

What I ignored (I'm sorry...)

Decay widths

- SUSY-HIT (Djouadi, Kalinowski, Mambrini, Mühlleitner, Spira)

Higgs

- HiggsBounds/HiggsSignals (Bechtle, Brein, Heinemeyer, Stål, Stefaniak, Weiglein, Williams)
- FeynHiggs (Heinemeyer, Thomas Hahn, Heidi Rzehak, Georg Weiglein, Wolfgang Hollik)
- Lilith (Bernon, Dumont)
- SusHi (Harlander, Liebler, Mantler)
- 2HDMC (Eriksson, Rathsman, Stål)

Dark Matter

- micrOMEGAs (BÃ©langer, Boudjema, Pukhov, Semenov)
- DM@NLO (Herrmann, Klasen, Kovarik, Harz, Le Boulc'h, Meinecke, Steppeler)
- DarkSUSY (Gondolo, Edsjö, Ullio, Bergström, Schelke, Baltz, Bringmann, Duda)

What I ignored (I'm sorry...)

Cross-Sections @ NLO

- Prospino (Beenakker, Höpker, Klasen, Krämer, Plehn, Spira, Zerwas)
- NLL-FAST (Beenakker, Brensing-Thewes, Borschensky, Krämer, Kulesza, Motyka, Laenen, Niessen)
- MadGolem (Goncalves Netto, Lopez-Val, Mawatari, Plehn, Wigmore)
- Resummino (Bozzi, Fuks, Klasen, Lamprea, Rothering, Debove)
- MadGraph5_aMC@NLO (Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Shao, Stelzer, Torrielli, Zaro, de Visscher, Vittoria Garzelli, Pittau, Degrande, Fuks, Proudom, Shoa)
- GoSam (Cullen, Deurzen, Greiner, Heinrich, Luisoni, Mirabella, Peraro, Schlenk, von Soden-Fraunhofen)

What I ignored (I'm sorry...)

Global Fitting (mostly private)

- GAMBIT (Athron, Balazs, Bringmann, Buckley, Chrzaszcz, Conrad, Cornell, Dal, Edsjö, Farmer, Hsu, Jackson, Krislock, Kvellestad, Mahmoudi, Martinez, Pato, Putze, Raklev, Rogan, Saavedra, Savage, Scott, Serra, Weniger, White)
- Mastercode (Bagnaschi, Buchmüller, Cavanaugh, Citron, De Roeck, Dolan, Ellis, Flächer, Heinemeyer, Isidori, Marrouche, Santos, Olive, Sakurai, de Vries, Weiglein)
- Fittino (Bechtle, Desch, Sarrazin, Uhlenbrock, Wienemann, Dreiner, Stefaniak, Hamer, Krämer, Porod, O'Leary, Prudent, Bringmann, Hensel, Nguyen)
- SFitter (Lafaye, Plehn, Rauch, Zerwas, López-Val, Klute)
- Lots of 'unbranded' fits as well...