♕ Checkmating theories at the LHC ♕

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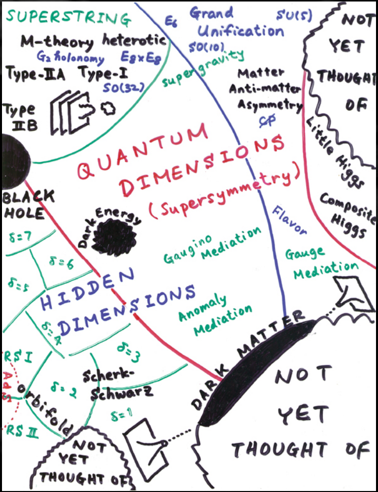
http://checkmate.hepforge.org RWTH Aachen University

♔ Testing theories

- ♙ Theorists have been busy for the past ∼40 years
  - ♖ Massive number of models invented
- ♘ LHC collaborations cannot possibly cover all of this space

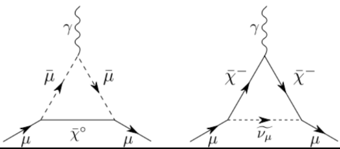


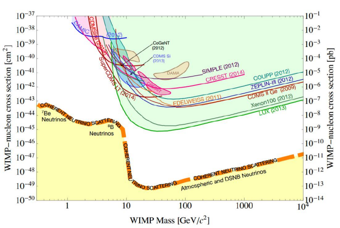
H. Murayama

♔ Testing theories

Experimental probes

- ♙ Electroweak precision
- ♖ Higgs observables
- ♘ Collider searches
- ♗ Dark Matter
- ♕ Flavour physics
- ♔ and many more...





Huge amount of work for any theorist!

Experimental probes

- ♙ Electroweak precision
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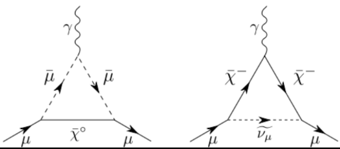
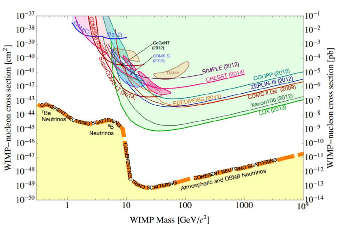




Huge amount of work for any theorist! → Automate!

♔ What do we want?

♔ What do we want?

Write the Lagrangian down

♔ What do we want?

Write the Lagrangian down

Press "Enter"

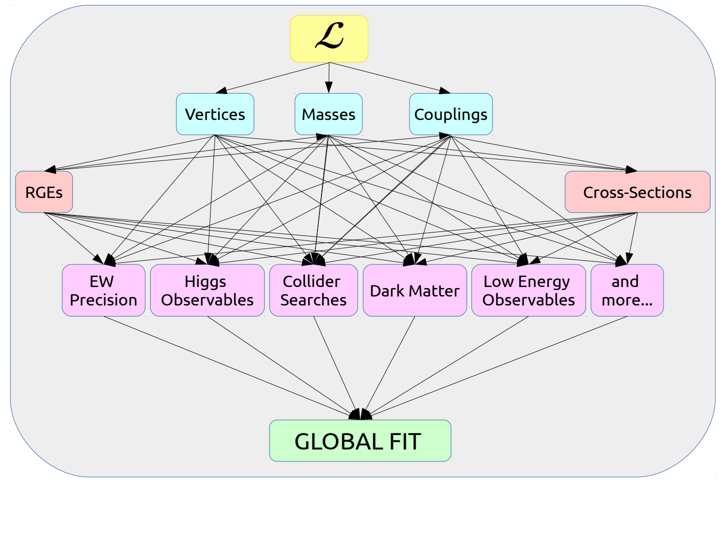
♔ What do we want?

Write the Lagrangian down

Press "Enter"

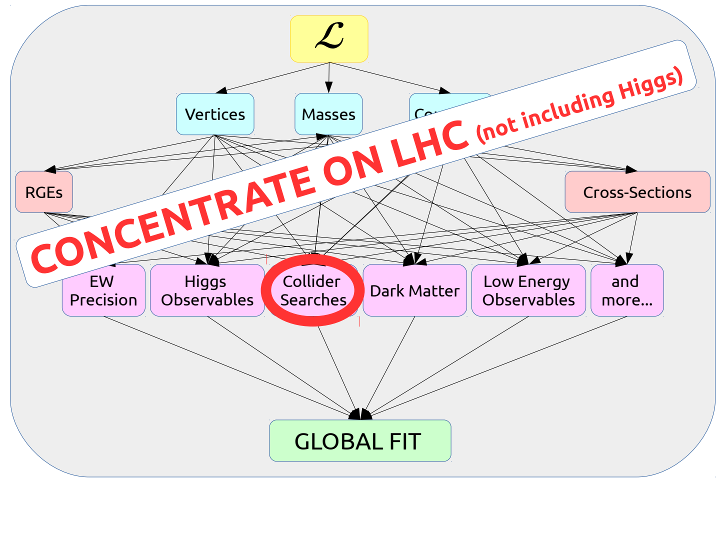
Computer fits the model parameters to all relevant observables

♔ 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
RGEs
Cross-Sections
EW Precision
Higgs Observables
Collider Searches
Dark Matter
Low Energy Observables
and more...
GLOBAL FIT
CONCENTRATE ON LHC (not including Higgs)

General Structure

Enter Lagrangian into SARAH/FeynRules (or use pre-existing model)

♔ General Structure

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Calculate matrix element with MadGraph

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CheckMATE runs on events and returns answer

General Structure

Enter Lagrangian into SARAH/FeynRules (or use pre-existing model)

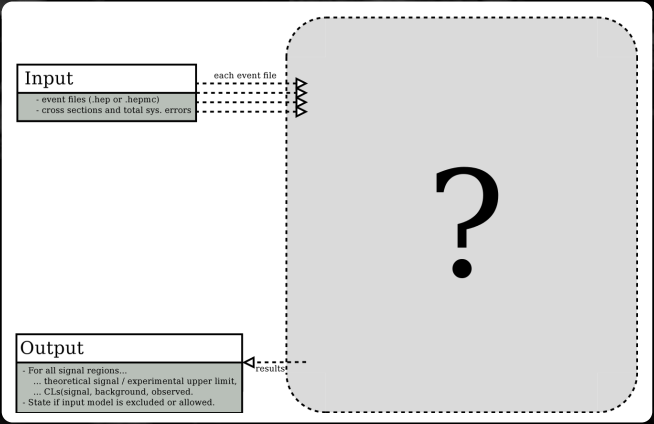
CheckMATE 2

Calculate matrix element with MadGraph

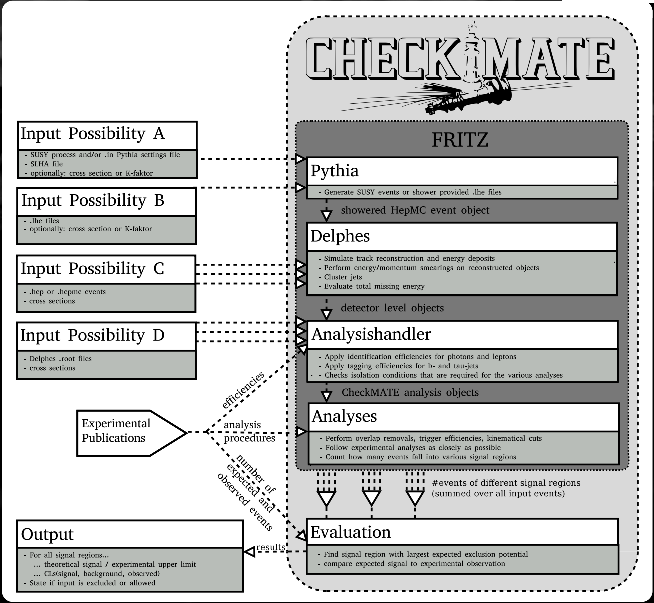
Shower and hadronise events with Pythia

CheckMATE runs on events and returns answer

♔ Simulation Program Flow



Simulation Program Flow



Available Analyses

8 TeV Analyses

```
###############################################################################
#Name                     NSR  Description                                      Lumi
atlas_1308_1841           13   ATLAS, 0 lepton + >= 7 jets + etmiss             20.3
atlas_1308_2631           6    ATLAS, 0 leptons + 2 b-jets + etmiss             20.1
atlas_1402_7029           20   ATLAS, 3 leptons + etmiss (chargino+neutralino)  20.3
atlas_1403_4853           12   ATLAS, 2 leptons + etmiss (direct stop)          20.3
atlas_1403_5294           13   ATLAS, 2 leptons + etmiss, (SUSY electroweak)    20.3
atlas_1403_5294_CR        4    ATLAS, 2 leptons + etmiss CR, (SUSY electroweak) 20.3
atlas_1404_2500           5    ATLAS, Same sign dilepton or 3l                  20.3
atlas_1405_7875           15   ATLAS, 0 lepton + 2-6 jets + missingET           20.3
atlas_1407_0583           27   ATLAS, 1 lepton + (b-)jets + etmiss (stop)       20.3
atlas_1407_0600           9    ATLAS, 3 b-jets + 0-1 lepton + etmiss            20.1
atlas_1407_0608           3    ATLAS, Monojet or charm jet (stop)               20.3
atlas_1411_1559           1    ATLAS, monophoton plus MET                       20.3
atlas_1502_01518          9    ATLAS, Monojet plus missing energy               20.3
atlas_1503_03290          1    ATLAS, 2 leptons + jets + missingET              20.3
atlas_conf_2012_104       2    ATLAS, 1 lepton + >= 4 jets + etmiss             5.8
atlas_conf_2012_147       4    ATLAS, Monojet + etmiss                          10.0
atlas_conf_2013_021       4    ATLAS, WZ standard model (3 leptons + etmiss)    13.0
atlas_conf_2013_024       3    ATLAS, 0 leptons + 6 (2 b-)jets + etmiss         20.5
atlas_conf_2013_031       2    ATLAS, Higgs spin measurement (WW)               20.7
atlas_conf_2013_036       5    ATLAS, 4 leptons + etmiss                        20.7
atlas_conf_2013_049       9    ATLAS, 2 leptons + etmiss                        20.3
atlas_conf_2013_061       9    ATLAS, 0-1 leptons + >= 3 b-jets + etmiss        20.1
atlas_conf_2013_062       19   ATLAS, 1-2 leptons + 3-6 jets + etmiss           20.1
atlas_conf_2013_089       12   ATLAS, 2 leptons (razor)                         20.3
atlas_conf_2014_014       1    ATLAS, 2 leptons + b-jets (stop)                 20.3
atlas_conf_2014_033       3    ATLAS, WW standard model measurement             20.3
atlas_conf_2014_056       1    ATLAS, ttbar spin correlation measurement        20.3
atlas_conf_2015_004       1    ATLAS, invisible Higgs decay in VBF              20.3
###############################################################################
```

Available Analyses

8 TeV continued

```
################################################################################
#Name                      NSR  Description                                         Lumi
atlas_1403_5222            5    ATLAS, stop production with Z boson and b-jets      20.3
atlas_1506_08616           12   ATLAS, di-lepton and 2b-jets+lepton at 8 TeV        20.0
cms_1303_2985              59   CMS, alpha_T + b-jets                               11.7
cms_1301_4698_WW           1    CMS, WW standard model measurement                  3.5
cms_1405_7570              57   CMS, Various chargino and neutralino                19.5
cms_1408_3583              7    CMS, monojet + MET                                  19.7
cms_1502_06031             6    CMS, 2 leptons, jets, missingET (only on-Z)         19.4
cms_1504_03198             1    CMS, 1 lep, >=3 j, >=1 b-j, etmiss (DM +2top)       19.7
cms_smp_12_006             4    CMS, WZ standard model (3 leptons + etmiss)         19.6
cms_sus_13_016             1    CMS, OS lep 3+ b-tags                               19.5
cms_sus_12_019             4    CMS, 2 leptons, >= 2 jets + etmiss (dilep edge)     19.4
################################################################################
```

7 TeV Analyses

```
##################################################################################
#Name                         NSR  Description                                       Lumi
atlas_1210_2979               1    ATLAS, WW measurement with 2 leptons              4.6
cms_1306_1126_WW              1    CMS, WW standard model measurement                4.9
##################################################################################
```

♔ Available Analyses

13 TeV Analyses

#Name	NSR	Description	Lumi
atlas_1602_09058	4	ATLAS, 2 ss leptons or 3 leptons	3.2
atlas_1604_07773	13	ATLAS, monojet	3.2
atlas_1604_01306	1	ATLAS, photon + MET search at 13 TeV	3.2
atlas_1605_03814	7	ATLAS, 2-6 jets + Etmiss	3.2
atlas_1605_04285	7	ATLAS, 1 lepton + jets + Etmiss	3.3
atlas_1605_09318	8	ATLAS, >= 3 b-jets + 0-1 lepton + Etmiss	3.3
atlas_1606_03903	3	ATLAS, 1-lepton + jets + etmiss (stop)	3.2
atlas_conf_2015_082	1	ATLAS, leptonic Z + jets + Etmiss	3.2
atlas_conf_2016_013	10	ATLAS, 4 top quark (1 lepton + jets, VLQ search)	3.2
atlas_conf_2016_050	5	ATLAS, 1-lepton + jets + etmiss (stop)	13.3
atlas_conf_2016_076	6	ATLAS, 2 leptons + jets + etmiss	13.3

14 TeV (High-Lumi) Analyses

#Name	NSR	Description	Lumi
atlas_phys_pub_2013_011	4	ATLAS, hadronic and leptonic stop search	3000.0
atlas_phys_2014_010_300	10	ATLAS, 2-6 jets + met	300.0
atlas_phys_2014_010_sq_hl	10	ATLAS, 2-6 jets + met	3000.0
atlas_2014_010_hl_3l	1	ATLAS, 3 leptons + etmiss (char+neut)	3000.0
checkmate_dilepton_hl	9	custom slepton/chargino dilepton search	3000.0
atl_phys_pub_2014_010_sbottom	6	0 leptons + 2 b-jets + Etmiss	300.0

♔ Analyses

Good coverage of E^T_{miss} and SUSY

- Over 50 analyses implemented (including 11 at 13 TeV)
- Over 300 individual signal regions
- New analyses being added all the time

CheckMATE 2

- MadGraph and Pythia now integrated
  - Code improvements → 2X faster on single core
  - Hugely improved cluster performance → easy scans
- Combination of analyses now possible
- High-lumi analyses now included
- Beta version now available for download
  - Manual will be public soon

♔ Analysis Manager

What if you want a different analysis?

- Ask us first!
  - We are often working on many analyses that are not yet public

AnalysisManager (arXiv:1503.01123)

- Automatised tool for adding analyses
  - All possible final states types
  - Library of kinematical variables
  - Statistics automatically calculated
- User is only required to implement set of cuts in C++
  - Many CheckMATE analyses have now been coded by external users
- Also perfect for prototyping new analyses

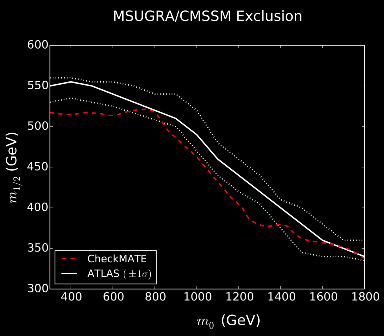
♔ Validation Example

atlas_conf_2013_047 (0 leptons + 2-6 jets + $\not\!\!E_T$, 8 TeV, 20.3 fb^{-1})

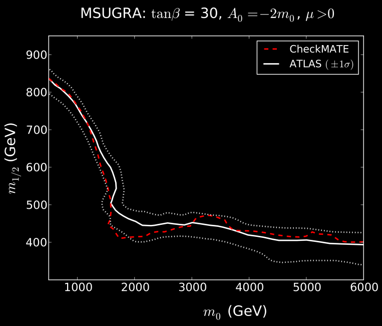
Process	$\tilde{q}\tilde{q}$ direct			
Point	$m(\tilde{q}) = 450$ GeV $m(\tilde{\chi}_1^0) = 400$ GeV		$m(\tilde{q}) = 662$ GeV $m(\tilde{\chi}_1^0) = 287$ GeV	
Signal Region	A-medium		C-medium	
Source	ATLAS	CheckMATE	ATLAS	CheckMATE
Generated events	20000	50000	5000	50000
In	100	100	100	100
Jet Cleaning *	99.7	-	99.6	-
0-lepton *	89.9	-	98.2	-
$E_T^{miss} > 160$ GeV *	15	-	80.7	-
$p_T(j_1) > 130$ GeV	12.9	12.9	80.0	79.3
$p_T(j_2) > 130$ GeV	9.0	8.4	75.6	75.3
$p_T(j_3) >$ 0-60 GeV	9.0	8.4	35.3	35.6
$p_T(j_4) >$ 0-60 GeV	9.0	8.4	11.5	11.3
$\Delta\phi(j_i > 40, E_T^{miss}) > 0.4$	7.0	6.8	10.1	9.9
$\Delta\phi(j_i > 40\text{ GeV}, E_T^{miss}) > 0 - 0.2$	7.0	6.8	9.3	9.2
$E_T^{miss}/\sqrt{H_T} > 0 - 15$	2.6	1.8	9.3	9.2
$E_T^{miss}/m_{eff}(N_j) > 0.15 - 0.4$	2.6	1.8	7.2	6.8
$m_{eff}(\text{incl.}) > 1 - 2.2$ TeV	0.1 ± 0.02	0.08 ± 0.01	3.0 ± 0.2	3.1 ± 0.1

♔ Validation Example

ATLAS, 1 ℓ + $\not{E}_T$



ATLAS, 0 ℓ + 2–6 jets + $\not{E}_T$



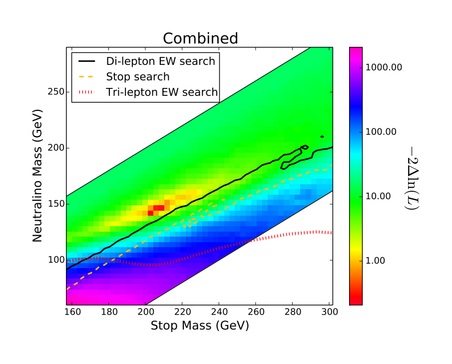
Overall Statement

- ♙ Generally good agreement, sometimes more conservative
- ♖ All validation notes on website (now with MC cards)

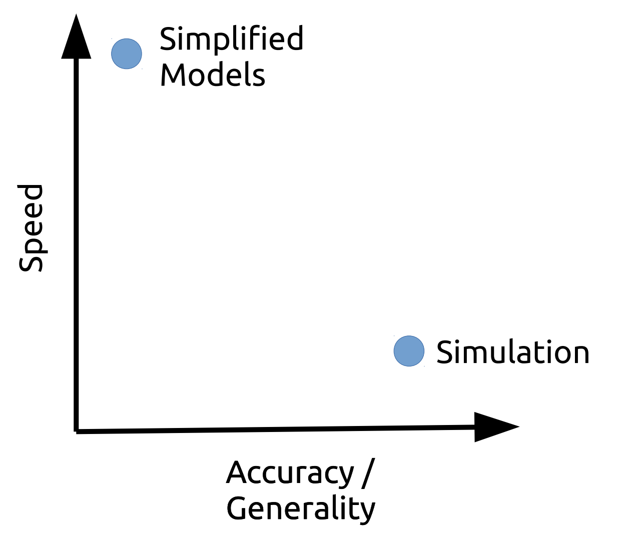
♔ Where next?

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



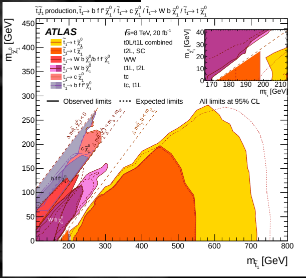
♔ Simplified Models

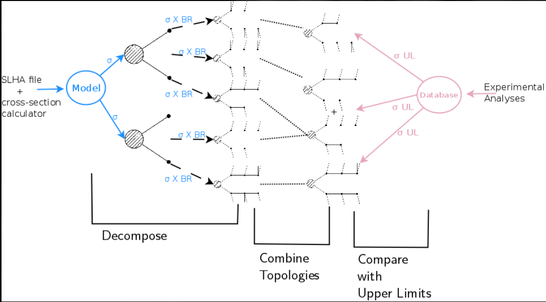


♔ Simplified Model Tools

Simplified Models

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





SModelS

♔ Simplified Model Tools

Available Tools

- ♙ FastLim (10 analyses) (Papucci, Sakurai, Weiler, Zeune; 2014)
- ♘ SModelS (46 analyses) (Kraml, Kulkarni, Laa, Lessa, Magerl, Waltenberger et al; 2014)
- ♗ XQCAT (5 analyses) (Barducci, Belyaev, Buchkremer, Cacciapaglia, Deandrea et al; 2014)

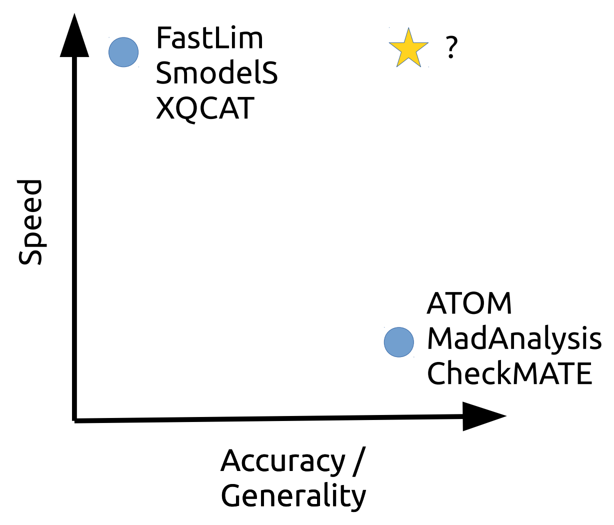
Advantages

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

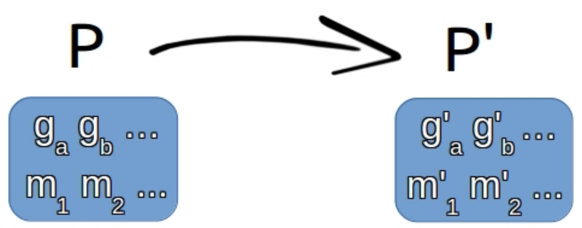
Disadvantages

- ♗ 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

Can we do better?



♔ Parameter scans (with F. Poncza)



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

- ♙ Final state cross-sections (including branching ratios)
- ♖ Distributions

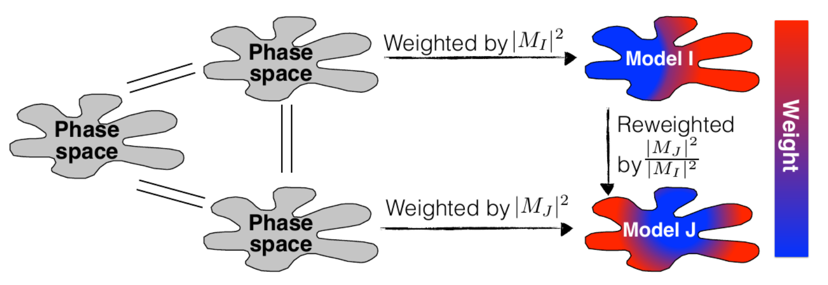
Aim

- ♘ Per point evaluation $\to \mathcal{O}(secs)$
- ♗ Accuracy → 10% on acceptance
- ♕ Arbitrary BSM models

Matrix element method for arbitrary BSM scans

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

- Central idea → 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

Key practical issues

- ♘ Only allows changes in couplings and spins
  - ♗ Crucially masses must be the same

♔ Parameter scans

Key practical issues

- 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 agnostic

♔ Couplings

First order effects

- ♙ Total Cross-Sections
- ♖ Branching Ratios

Second order effects → ignore

- ♙ Kinematical Distributions
- ♖ Requires
  - ♘ Interference terms small
  - ♗ Narrow width approximation satisfied

Couplings

First order effects

- Total Cross-Sections
- Branching Ratios

Second order effects → ignore

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

Solution

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

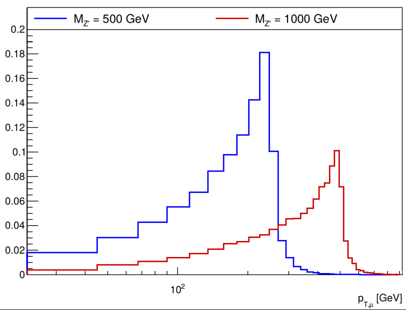
♔ Masses

Easy part

- Total Cross-Section → Reweight
- Branching Ratios → Reweight

More difficult

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



♔ Idea

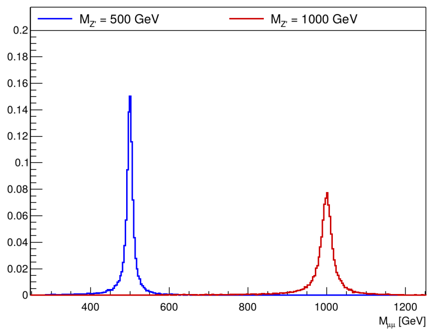
Guiding principle

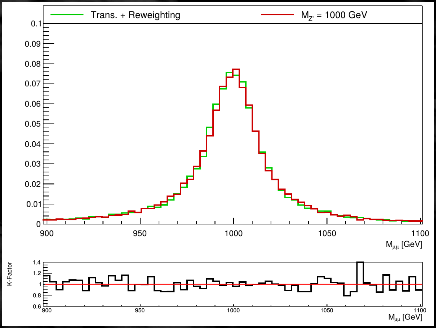
- Production: $\vec{p} \to \vec{p}$, $m \to m'$
  - Ensures we sample full phase space
  - 'Off-shellness' constant
- Decays: Rest frame angles conserved
  - All kinematics specified by momentum conservation
- Final state particles: Matched to hard event
  - Kinematics determined by hard partons
  -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





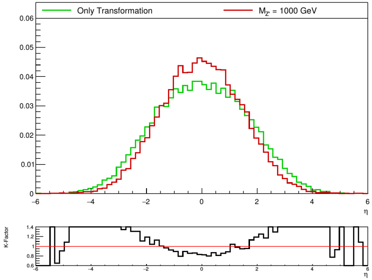
Z' toy model

- $pp \to Z' \to \mu^+\mu^-$
- Transform $m_{Z'} = 500$ GeV events to $m_{Z'} = 1$ TeV
- Breit-Wigner is reproduced

♔ Z' example

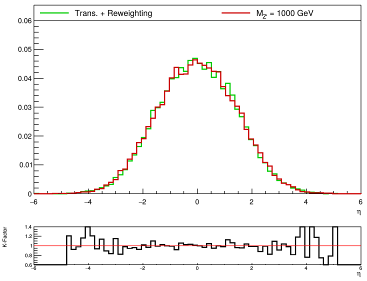
Without PDF reweighting

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



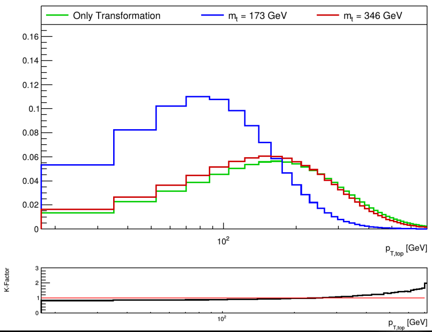
With PDF reweighting

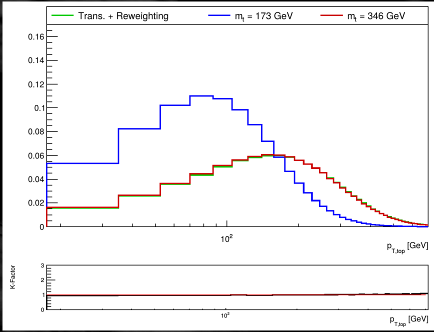
- ♖ PDF reweighting corrects production angles



Muon rapidity

Top production example



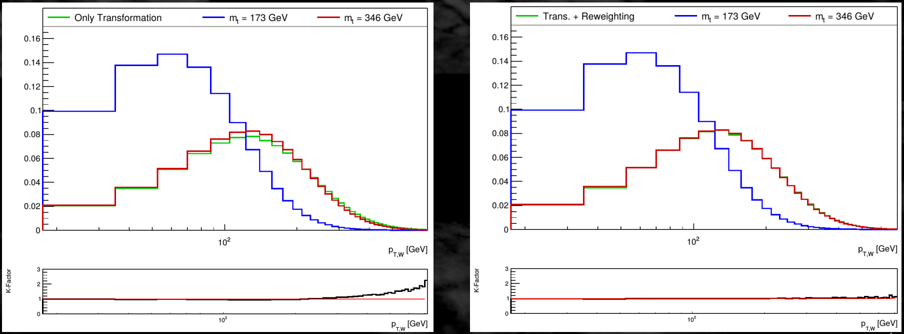


$p_T(top)$

Toy top model

- Double top mass
- All distributions reproduced to high accuracy

♔ Decay distributions, $t \to W^{\pm} b$



$p_T(W^{\pm})$

Toy top model

- ♙ Decays are also reproduced accurately
- ♖ Again reweighting is vital in addition to the kinematic transformations

♔ Future plans

Works well for Z' and toy top model

- ♖ Apply to SUSY and recalculate exclusions
- ♘ Completely testable for any parameter point

Generalise

- ♙ Algorithm should work automatically with any BSM model
- ♘ 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

♔ (Very-) High dimensional fits

Lack of SUSY signal at LHC

- ♙ Probably means we should look beyond simplest models
- ♖ Increasingly popular are PMSSM-11 (or -19)
- ♘ Naively means we need to sample $\sim 10^{19}$ parameter points
  - ♗ Obviously impossible!
- ♕ Can we be more intelligent?

♔ (Very-) High dimensional fits

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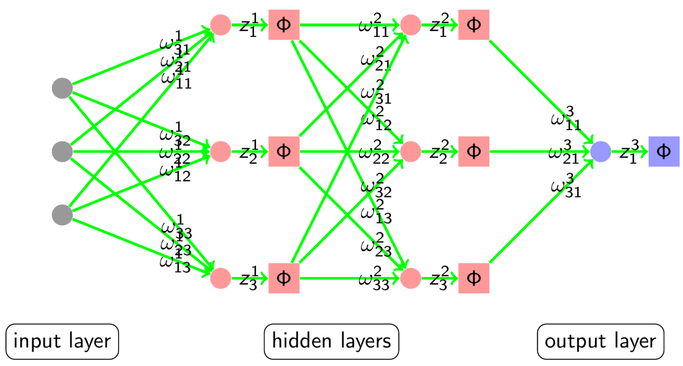
Deep learning

- ♙ Deep learning is the new buzzword in silicon valley!
  - ♖ Use many layered neural net to learn complex functions

Basics of neural nets



Ideas

- Input parameters connected to output by layers of nonlinear functions
  - Essentially a highly nonlinear multivariate interpolator

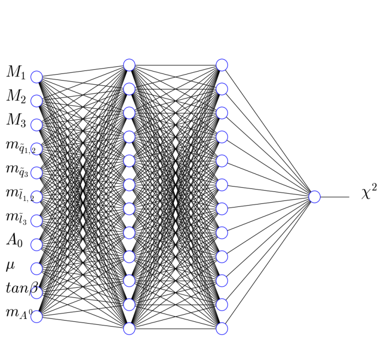
Work in progress with Philip Bechtle, Matthias Hamer, Michael Kraemer, Tim Keller, Jan Schuette-Engel and Bjoern Sarrazin

♔ Two different methods

Want to predict the combined χ^2 of many LHC signal regions

♔ Two different methods

Want to predict the combined χ^2 of many LHC signal regions

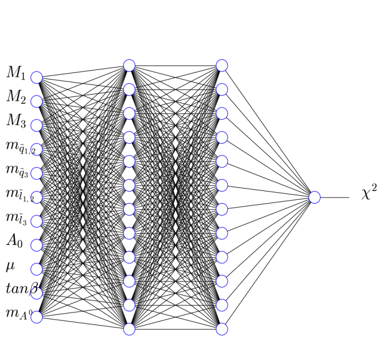


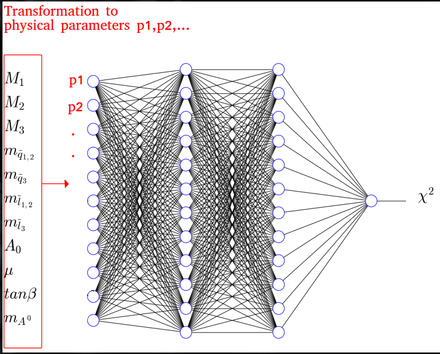
Direct approach

- ♙ Input are SUSY model parameters
- ♖ Optimise for speed

♔ Two different methods

Want to predict the combined χ^2 of many LHC signal regions





Direct approach

- Input are SUSY model parameters
- Optimise for speed

Reparameterised approach

- First calculate physical parameters
- Generalise to other models

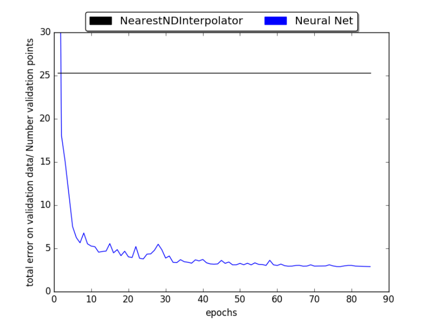
♔ Reparameterisation method

Physical parameters

- ♙ Calculate average number (and standard deviation) of particles produced at LHC in BSM model
- ♖ Also calculate average maximum energy (and standard deviation) of each particle
- ♘ Including on-shell SM resonances

$\langle N_{jet} \rangle$	$\langle \sigma_{N_{jet}} \rangle$	$\langle E^{\max}_{jet} \rangle$	$\langle \sigma_{E^{\max}_{jet}} \rangle$
$\langle N_{e-} \rangle$	$\langle \sigma_{N_{e-}} \rangle$	$\langle E^{\max}_{e-} \rangle$	$\langle \sigma_{E^{\max}_{e-}} \rangle$
$\langle N_{e+} \rangle$	$\langle \sigma_{N_{e+}} \rangle$	$\langle E^{\max}_{e+} \rangle$	$\langle \sigma_{E^{\max}_{e+}} \rangle$
$\langle N_{\ldots} \rangle$	$\langle \sigma_{N_{\ldots}} \rangle$	$\langle E^{\max}_{\ldots} \rangle$	$\langle \sigma_{E^{\max}_{\ldots}} \rangle$
$\langle N_{W+} \rangle$	$\langle \sigma_{N_{W+}} \rangle$	$\langle E^{\max}_{W+} \rangle$	$\langle \sigma_{E^{\max}_{W+}} \rangle$
$\langle N_{W-} \rangle$	$\langle \sigma_{N_{W-}} \rangle$	$\langle E^{\max}_{W-} \rangle$	$\langle \sigma_{E^{\max}_{W-}} \rangle$
$\langle N_{\ldots} \rangle$	$\langle \sigma_{N_{\ldots}} \rangle$	$\langle E^{\max}_{\ldots} \rangle$	$\langle \sigma_{E^{\max}_{\ldots}} \rangle$

♚ Results



SUSY parameter net

- χ^2 lies in range 80-250
- Net is vast improvement over nearest neighbour interpolator

Training

- Adjust weights and biases Minimise:

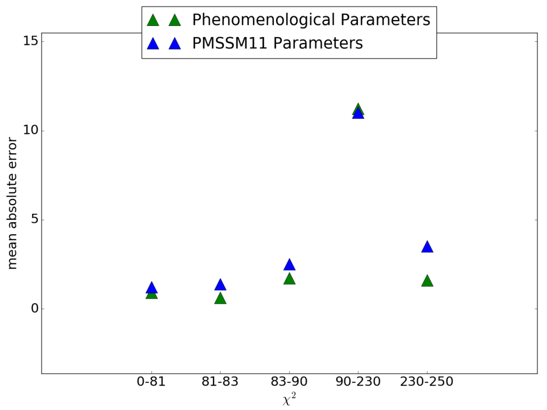
$$\sum_{\text{training data}} (\chi^2_{\text{output}} - \chi^2_{\text{desired}})^2$$

Validation

- Check net generalises with validation set

$$\sum_{\text{validation set}} (\chi^2_{\text{output}} - \chi^2_{\text{desired}})^2$$

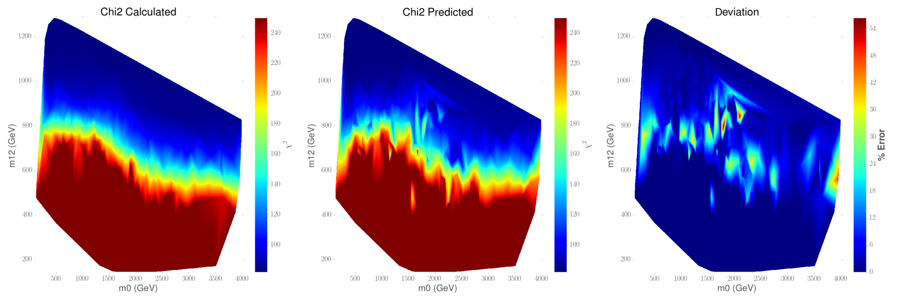
♔ Results



Does reparameterisation help?

- ♙ Final results are very similar
- ♖ SUSY parameter net is far faster (ms vs $\sim$ 6s)
- ♘ Net has best performance in region of interest

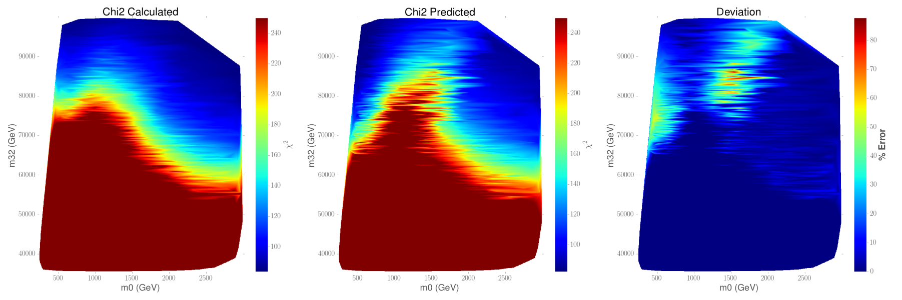
♔ Reparameterisation → Other models



CMSSM → 4 (+ sign) parameters

- ♙ Neural Net does reproduce χ^2 well → up to 50% error
- ♖ NOT a subset of PMSSM-11 → RGE's split scalar masses
- ♘ Can we understand physically why the net fails?

♚ Reparameterisation → Other models



AMSB → 3 parameters

- ♙ Again Neural Net fails → up to 80% error
- ♖ Source is stop-sbottom mass splitting
  - 100% $\tilde{g} \to \tilde{t}t$ decay in this model
  - $m_{\tilde{t}} = m_{\tilde{b}}$ means this never happens in PMSSM-11
  - Neural net never samples points with $\langle N_t \rangle = 4$
- ♘ In the case, solution is trivial to move to PMSSM-12

♔ Summary

Automatic model testing now a reality

- ♙ Tools simple and easy to use

Simplified Models

- ♖ Rapid model testing

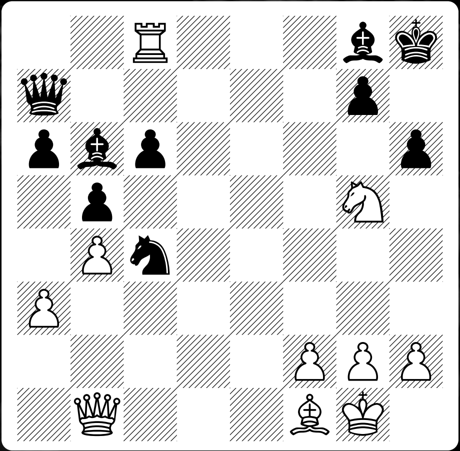
Fast simulation

- ♘ Model agnostic
- ♗ Allows for fitting to LHC signals

New ideas still needed for speed and accuracy

- ♔ Machine Learning is another option

Are you ready . . .



. . . to CheckMATE?