New Methods for New Physics

Tilman Plehn

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New Methods
for New Physics

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Supersymmetry
LHC Signals
Masses
Spins
Parameters
Statistics

Outline

TeV–scale supersymmetry

Supersymmetric signatures at LHC

New physics mass measurements

New physics spin measurements
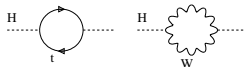
Supersymmetric parameter studies

Statistics and phenomenology

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TeV–scale supersymmetry: 1

Starting from data...

– ...which seems to indicate a light Higgs [e-w precision data]

– problem of light Higgs: mass driven to cutoff of effective Standard Model:
$$\delta m_H^2 \propto g^2 (2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2) \Lambda^2$$

$\Rightarrow$ easy solution: counter term to cancel loops $\Rightarrow$ artificial, unmotivated, ugly

$\Rightarrow$ or new physics at TeV scale: supersymmetry
extra dimensions
little Higgs (pseudo–Goldstone Higgs)
Higgsless, composite Higgs, TopColor,
YourFavoriteNewPhysics...

$\Rightarrow$ typically cancellation by new particles or discussing away high scale

$\Rightarrow$ beautiful concepts, but problematic at TeV scale [data seriously in the way]

$\Rightarrow$ new physics models in baroque state

Idea of supersymmetry:

cancellation of divergences through statistics factor (-1)

[SM fermions to scalar; SM gauge bosons to fermions; SM scalars to fermions]

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TeV–scale supersymmetry: 2

SUSY breaking: (yet) unobserved partners heavy

- link to BSM dark matter [Falk,...]
- link to BSM $(g-2)_\mu$? [Stöckinger, Kaoru's talk]
- link to flavor physics and baryogenesis? [Standard Model fine??]
- mechanism for SUSY masses unknown [soft SUSY breaking mediated somehow?]

  maximally blind mediation: mSUGRA [not a LHC paradigm!]
  scalars: m_0, fermions: $m_{1/2}$, tri-scalar term: A_0
  plus sign(μ) and $\tan\beta$ in Higgs sector
- alternatives: gauge, anomaly, gaugino mediation $\cdots$?
- $\Rightarrow$ measure spectrum at LHC instead

LHC phenomenology: MSSM

- conjugate Higgs field not allowed
  - $\rightarrow$ give mass to t and b?
  - $\rightarrow$ two Higgs doublets
- SUSY Higgs alone interesting
- $\Rightarrow$ would be another talk...
- $\Rightarrow$ SUSY partners at LHC

		spin	d.o.f.	
fermion	f_L, f_R	1/2	1+1	
$\rightarrow$ sfermion	$\tilde{f}_L$, $\tilde{f}_R$	0	1+1	
gluon	G_μ	1	n-2	
$\rightarrow$ gluino	$\tilde{g}$	1/2	2	Majorana
gauge bosons	γ, Z	1	2+3	
Higgs bosons	h^o, H^o, A^o	0	3	
$\rightarrow$ neutralinos	$\tilde{\chi}_i^o$	1/2	$4 \cdot 2$	LSP?
gauge bosons	$W^\pm$	1	$2 \cdot 3$	
Higgs bosons	$H^\pm$	0	2	
$\rightarrow$ charginos	$\tilde{\chi}_i^\pm$	1/2	$2 \cdot 4$	
graviton	G	2	2	
$\rightarrow$ gravitino	$\tilde{G}$	3/2	2	tough

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Supersymmetry at LHC: 1
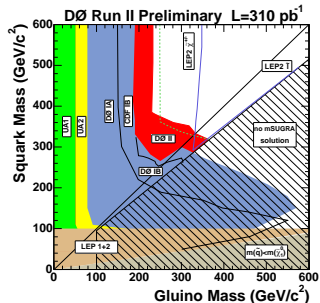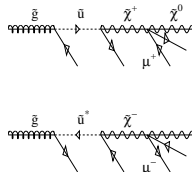
Inclusive: squarks and gluinos at Tevatron

– squarks, gluinos strongly interacting
$p\bar{p} \rightarrow \tilde{q}\tilde{q}^*, \tilde{q}\tilde{g}, \tilde{g}\tilde{g}$ [best if $m(\tilde{q}) \sim m(\tilde{g})$]

– large rates at hadron colliders

– decays to jets and LSP
$\tilde{g} \rightarrow \tilde{q}\bar{q}, \tilde{q}_L \rightarrow q\tilde{\chi}_2^0, \tilde{q}_R \rightarrow q\tilde{\chi}_1^0$

[additional jets and leptons possible]

– gaugino mass unification assumed for details

$\Rightarrow$ we know inclusive jets plus LSP

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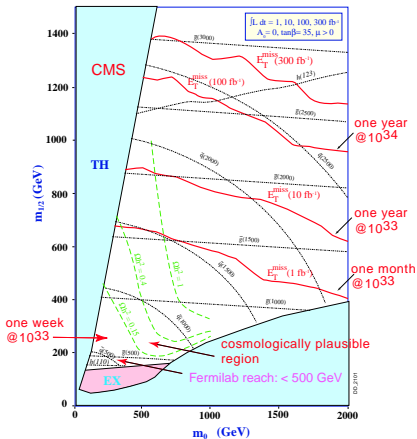D0 Run II Preliminary L=310 pb^{-1}

When do we see SUSY–QCD?

– gluinos: strongly interacting Majorana fermions

– first jet in gluino decay: q or $\bar{q}$

– final–state leptons with both charges

⇒ like–sign dileptons from $\tilde{g}\tilde{g}$ [Barger,...; Barnett,...; Baer,...]

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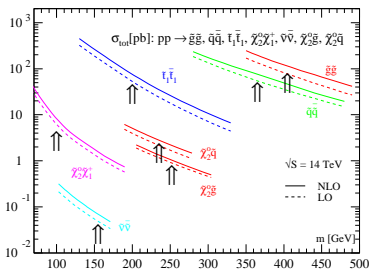
LHC Signals

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Supersymmetry at LHC: 2

New physics at the LHC

(1) possible discovery — signals for new physics, exclusion of parameter space

(2) measurements

(3) parameter studies

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Supersymmetry at LHC: 2

New physics at the LHC

(1) possible discovery — signals for new physics, exclusion of parameter space

(2) measurements — masses, cross sections, decays

(3) parameter studies — MSSM Lagrangean, SUSY breaking

$\Rightarrow$ approach independent of new physics model

Some SUSY signals at LHC [NLO: Prospino2]

– jets and $\not{E}_T$: $pp \to \tilde{q}\tilde{q}^*, \tilde{g}\tilde{g}, \tilde{q}\tilde{g}$

– like–sign dileptons: $pp \to \tilde{g}\tilde{g}$

– funny tops: $pp \to \tilde{t}_1 \tilde{t}_1^*$

– tri-leptons: $pp \to \tilde{\chi}_2^0 \tilde{\chi}_1^-$

  $[\tilde{\chi}_2^0 \to \tilde{\ell}\ell \to \tilde{\chi}_1^0 \ell\bar{\ell}; \tilde{\chi}_1^- \to \tilde{\chi}_1^0 \ell\bar{\nu}]$

$\Rightarrow$ inclusive: similar to Tevatron

$\Rightarrow$ exclusive: enough events for studies

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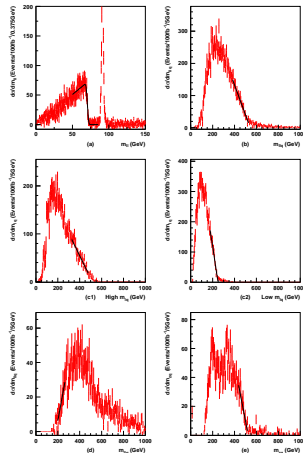Tilman Plehn

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New physics mass measurements: 1

Spectra from cascade decays

– decay $\tilde{g} \to \tilde{b}\bar{b} \to \tilde{\chi}_2^0 b\bar{b} \to \mu^+\mu^- b\bar{b}\tilde{\chi}_1^0$ [better not via Z or to τ]

– cross sections some 100 pb [more than 3×10^7 events]

– thresholds & edges [$m_{\ell\ell}^2 < (m_{\tilde{\chi}_2^0}^2 - m_{\tilde{\ell}}^2)(m_{\tilde{\ell}}^2 - m_{\tilde{\chi}_1^0}^2)/m_{\tilde{\ell}}^2$]

– detector resolution, calibration,
systematic errors, shape analysis,
cross sections as input?

⇒ spectrum information from decay kinematics

[Hinchliffe,...;Allanach,...; not only SUSY: Meade & Reece]

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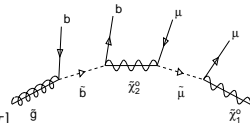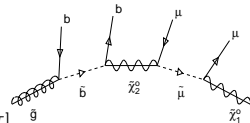LHC Signals
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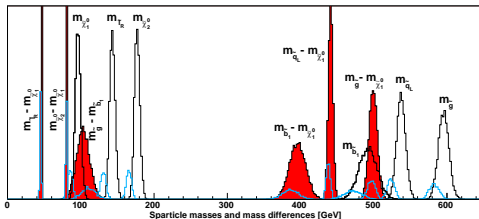# New physics mass measurements: 1

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  cross sections as input?

$\Rightarrow$ spectrum information from decay kinematics [mass differences with smaller errors]
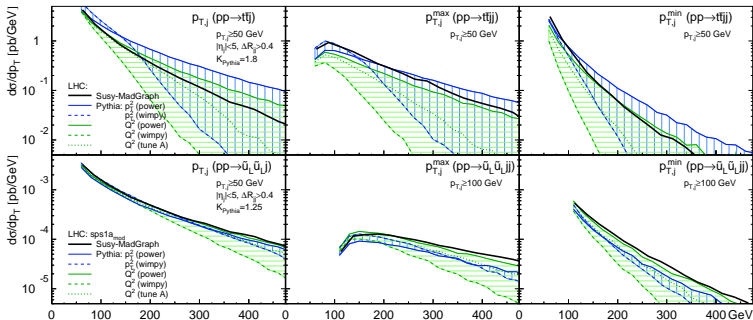
Gluino mass from kinematic endpoints

– all decay jets *b*-tagged [Gjelsten, Miller, Osland]

– most of time: cascade assumption correct

$\Rightarrow$ gluino mass to $\sim 1\%$

  [theoretically defined?]

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New physics mass measurements: 2

Squarks and gluinos always with many jets [TP, Rainwater, Skands]

- cascade studies sensitive to jet simulation?
- matrix element $\tilde{g}\tilde{g}$+2j and $\tilde{u}_L\tilde{g}$+2j [$p_{T,j} > 100$ GeV]
- compared with Pythia shower [tuned at Tevatron]
- ⇒ QCD no killer for decay analyses [the heavier the better]

σ [pb]	$t\bar{t}_{600}$	$\tilde{g}\tilde{g}$	$\tilde{u}_L\tilde{g}$
σ_{0j}	1.30	4.83	5.65
σ_{1j}	0.73	2.89	2.74
σ_{2j}	0.26	1.09	0.85

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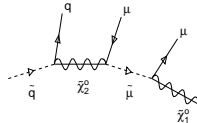## SUSY plus jets: complex final states [Smadgraph: Cho, Hagiwara, Kanzaki, TP, Rainwater, Stelzer]

– Majoranas and fermion number violation in Madgraph

– tested set of Feynman rules [400+ processes: Madgraph - Whizard (Reuter) - Sherpa (Schumann)]

– implemented in Madevent [Alwall, Maltoni: Louvain group]

⇒ publicly available: http://madgraph.phys.ucl.ac.be

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New physics spin measurements: 1

All new physics is hypothesis testing

– assume squark cascade observed

$\Rightarrow$ strongly interacting scalar?

$\Rightarrow$ straw-man model where squark is a fermion: universal extra dimensions

[Appelquist, Cheng, Dobrescu; Cheng, Matchev, Schmaltz; spectra degenerate —ignore; cross section larger —ignore]

Squark–slepton cascade   [Smillie, Webber, Athanasiou, Lester]

– decay chain $\tilde{q} \to \tilde{\chi}_2^0 \to \tilde{\ell} \to \tilde{\chi}_1^0$

– trick 1: compare with KK q, Z, ℓ, γ

– trick 2: 'invariant angles'
$\Rightarrow \hat{m} = m_{j\ell}/m_{j\ell}^{\max}$ most promising   [Barr]

– typically largest $pp \to \tilde{q}\tilde{g}$

– trick 3: production asymmetry $\tilde{q} : \tilde{q}^* \sim 2 : 1$
$\Rightarrow \mathcal{A} = [\sigma(j\ell^+) - \sigma(j\ell^-)]/[\sigma(j\ell^+) + \sigma(j\ell^-)]$
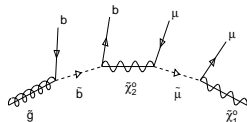

Masses or spin or both?   [Arkani-Hamed,...]

– masses from kinematic endpoints   [use $m_{\ell j}, m_{\ell\ell}, m_{j\ell\ell} \ldots$]

– spins from distributions between endpoints   [endpoints identical in SUSY and UED]

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New physics spin measurements: 2

Back to sign of SUSY–QCD

– like–sign dileptons indicate Majorana fermion?

– always like–sign dileptons from bosonic gluon

$\Rightarrow$ show gluino fermionic

$\Rightarrow$ compare with usual straw man [UED–Madgraph: Alves]

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$\Rightarrow$ show gluino fermionic
$\Rightarrow$ compare with usual straw man [UED–Madgraph: Alves]

Gluino–bottom cascade [Alves, Eboli, TP]

– decay chain like for gluino mass
– compare with first KK g, q, Z, ℓ, γ

– replace initial–state asymmetry by b vs. $\bar{b}$
– independent of production channels
– asymmetry to write down:
$\mathcal{A} = [\sigma(b\ell^+) - \sigma(b\ell^-)]/[\sigma(b\ell^+) + \sigma(b\ell^-)]$

[still visible after cuts and smearing]

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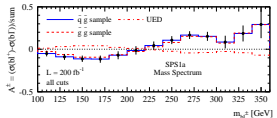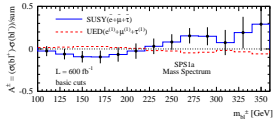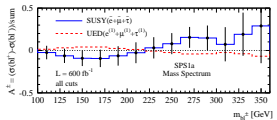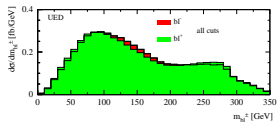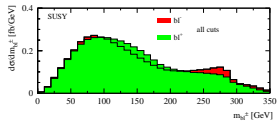- ⇒ compare with usual straw man [UED–Madgraph: Alves]

Gluino–bottom cascade [Alves, Eboli, TP]

- – exchange $\tilde{\ell}_{LR}$ in cascade
- – test of lepton-ino couplings
- – stau mixing [Choi, Hagiwara, Kim, Mawatari, Zerwas]

- – purely hadronic ϕ_{bb} [TP, Plümacher, Reinartz]
- – independent of weak decays
- – sensitive to gluino/KK-gluon boost

- – compare two SUSY hypotheses
- – neutralino–sneutrino LSP [TP, Pradler, Steffen]

⇒ **masses and spins accessible in decays at LHC**

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Supersymmetric parameters: 1

Theory output from LHC: SUSY parameters

– parameters: weak-scale Lagrangean [Sfitter: Lafaye, TP, Rauch, D Zerwas; Fittino; Harvard]

– measurements: masses or edges
branching fractions
cross sections

– errors: general correlation, statistics & systematics & theory

– problem in grid: huge phase space, local minimum?
problem in fit: domain walls, global minimum?

First go at problem

– ask a friend how SUSY is broken $\Rightarrow$ mSUGRA

– fit m_0, $m_{1/2}$, A_0, $\tan\beta$, $\mathrm{sign}(\mu)$, y_t, ...

– no problem, include indirect constraints [Ellis, Heinemeyer, Olive, Weiglein,..]

$\Rightarrow$ probability map as of today [Allanach, Lester, Weber]

$\Rightarrow$ best fit from LHC/ILC measurements

	SPS1a	ΔLHC masses	ΔLHC edges	ΔILC	ΔLHC+ILC
m_0	100	3.9	1.2	0.09	0.08
$m_{1/2}$	250	1.7	1.0	0.13	0.11
$\tan\beta$	10	1.1	0.9	0.12	0.12
A_0	-100	33	20	4.8	4.3

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MSSM instead of mSUGRA [TP, Lafaye, D Zerwas]

– (1) grid for closed subset
(2) fit of other parameters
(3) complete fit

– LHC+ILC perfect [Weiglein etal]

⇒ too few measurements?
secondary minima? ...

	LHC	ILC	LHC+ILC	SPS1a
$\tan\beta$	10.22±9.1	10.26±0.3	10.06±0.2	10
M_1	102.45±5.3	102.32±0.1	102.23±0.1	102.2
M_3	578.67±15	fix 500	588.05±11	589.4
$M_{\tilde{\tau}_L}$	fix 500	197.68±1.2	199.25±1.1	197.8
$M_{\tilde{\tau}_R}$	129.03±6.9	135.66±0.3	133.35±0.6	135.5
$M_{\tilde{\mu}_L}$	198.7±5.1	198.7±0.5	198.7±0.5	198.7
$M_{\tilde{q}3_L}$	498.3±110	497.6±4.4	521.9±39	501.3
$M_{\tilde{t}_R}$	fix 500	420±2.1	411.73±12	420.2
$M_{\tilde{b}_R}$	522.26±113	fix 500	504.35±61	525.6
A_τ	fix 0	-202.4±89.5	352.1±171	-253.5
A_t	-507.8±91	-501.95±2.7	-505.24±3.3	-504.9
A_b	-784.7±35603	fix 0	-977±12467	-799.4

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Supersymmetric parameters: 2

Probability maps of new physics [Allanach, Roszkowski]

- Bayes' theorem: $p(m|d) = p(d|m)\, p(m)/p(d)$ [p(d) through normalization]
- Pythia/Herwig/Sherpa: data given a model $p(d|m) \sim |\mathcal{M}|^2$
- theorist's prejudice: model $p(m)$
- $\Rightarrow$ given measurements: (1) compute probability map $p(m|d)$ of parameter space
  (2) rank local maxima

Weighted Markov chains [scanning algorithm for many dimensions: Rauch & TP]

- classical: produce representative set of spin states
  compute average energy based on this reduced sample
- $\Rightarrow$ map (chain) based on probability of a state
  expensive energy function on sample

- BSM physics: produce map $p(m|d)$ of parameter points
  evaluate same probability from (binned) density [Allanach,...; Baltz,...; Roszkowski,...]
- $\Rightarrow$ phase–space MCMC approach: weighted chain [two bins with p 1 : 10 with 2 or 11 points]

- already for mSUGRA: MCMC resolution not sufficient
- $\Rightarrow$ use additional probability maximization to rank maxima

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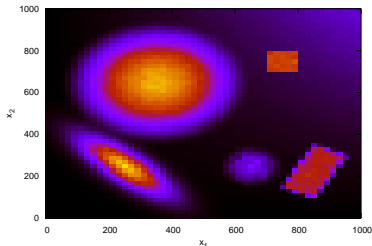Spins

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Toy model [Rauch & TP]

– test function $V(\vec{x})$ in 5 dimensions [general high–dimensional extraction tool]

– Sfitter output #1: probability map
Sfitter output #2: list of local maxima [best fit]

V=74.929 @(655.00,253.72,347.83,348.57,349.59)

V=59.972 @(850.04,224.99,650.00,649.99,654.56)

V=58.219 @(849.97,225.01,587.08,650.01,650.02)

V=25.110 @(750.00,749.99,450.00,450.01,450.01)

V=16.042 @(245.45,253.44,552.51,542.58,544.75)

V=12.116 @(350.70,650.40,650.36,650.40,650.38)

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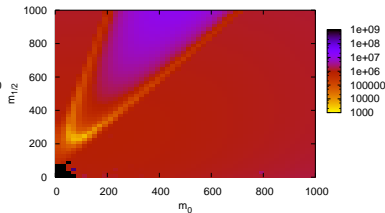Spins

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mSUGRA with LHC measurements alone

– SPS1a kinematic edges with free m_t

– as of yesterday: Sfitter probability maps [Lafaye, TP, Rauch, D Zerwas]

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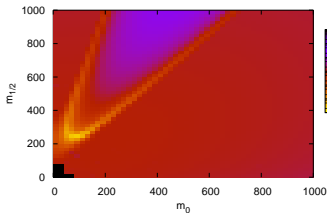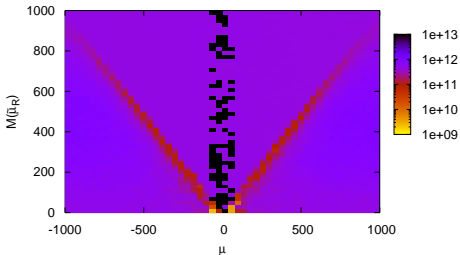LHC Signals
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– Pythia/Herwig/Sherpa: data given a model $p(d|m) \sim |\mathcal{M}|^2$

– theorist's prejudice: model $p(m)$

$\Rightarrow$ given measurements: (1) compute probability map $p(m|d)$ of parameter space
(2) rank local maxima

MSSM with LHC measurements alone

– SPS1a kinematic edges and free m_t

– as of yesterday: Sfitter probability map [Lafaye, TP, Rauch, D Zerwas]

New Methods
for New Physics

Tilman Plehn

Supersymmetry

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Statistics

Statistics and phenomenology: 1

Problems in the spin extraction

– unclear if spin information available   [top partners: Meade & Reece]

⇒ when can we distinguish two hypotheses?

Statistics: Neyman–Pearson lemma

– correct hypothsis m_1: SUSY cascade
   wrong hypothsis m_2: UED cascade

⇒ likelihood ratio $p(d|m_1)/p(d|m_2)$ best estimator

   [lowest probability to mistake right for fluctuation of wrong (type-II error)]

– likelihood $p(d|m) \sim |\mathcal{M}|^2$

⇒ compute maximum statistical significance   [Cramer, TP]

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⇒ when can we distinguish two hypotheses?

Statistics: Neyman–Pearson lemma

– correct hypothisis m_1: Higgs signal in WBF $H \rightarrow \mu\mu$ [TP, Rainwater]
wrong hypothesis m_2: background

⇒ likelihood ratio $p(d|m_1)/p(d|m_2)$ best estimator

[lowest probability to mistake right for fluctuation of wrong (type-II error)]

– likelihood $p(d|m) \sim |\mathcal{M}|^2$
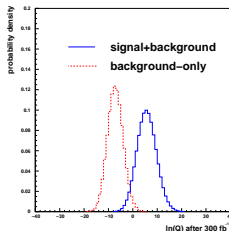
⇒ compute maximum statistical significance [Cramner, TP]

$CL_b(q) = \int_q^\infty dq' \rho_b(q')$ [5σ is $CL_b = 2.85\,10^{-7}$]

'Matrix element method' [CDF, D0; McElrath]

– compute likelihood of top events estimating $|\mathcal{M}|^2$

– maximize likelihood $p(d|\text{SM}, m_t)$ as function of m_t...

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Statistics and phenomenology: 2

Maximum significance for LHC signals

– example: combined n-event Poisson $\;[p(n|s+b) = e^{-(s+b)} (s+b)^n/n!]$

$$q = \log \frac{p(n|s+b)}{p(n|b)} = -s + n \, \log \left(1 + \frac{s}{b} \right) \longrightarrow -\sum_j s_j + \sum_j n_j \, \log \left(1 + \frac{s_j}{b_j} \right)$$

– phase space integration over $p(d|s,b) \sim |\mathcal{M}_{s,b}|^2$ [LEP–Higgs inspired]

$$q(\vec{r}) = -\sigma_s \mathcal{L} + \log \left(1 + \frac{|\mathcal{M}_s(\vec{r})|^2}{|\mathcal{M}_b(\vec{r})|^2} \right)$$

– probability distribution function via Fourier transform: $\rho_{s,b}(q)$

$\Rightarrow$ compute $CL_b(q)$

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Semi–realistic results   [Cranmer & TP]

– irreducible & unsmeared

$$\sigma_{tot} = \int d\vec{r} \, M(\vec{r}) \, d\sigma(\vec{r})$$

– smearing $\Delta m_{\mu\mu}^{\text{width}} \ll \Delta m_{\mu\mu}^{\text{meas}}$ [unobserved dimensions]

$$\sigma_{tot} = \int d\vec{r}_\perp dr_m^* \int_{-\infty}^{\infty} dr_m \, M(\vec{r}) \, d\sigma(\vec{r}) \, W(r_m, r_m^*)$$

– acceptance cuts to reduce phase space...   [bad measurements]

$\Rightarrow$ WBF $H \to \mu\mu$: 3.5σ in 300 fb^{-1}

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Estimate power of analyses [Cramer, TP, Reuter]

– numerical evaluation instantaneous [sanity–check neural nets?]

– implementation into Whizard on the way

– cannot claim if search is possible

– but can tell if search is impossible

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New physics at the LHC

A lot has been done

   – higher–order calculations

   – improved background estimates

   – web–based signal event generators

   – mass and spin measurements

   – parameter extraction/probability maps

   – ....

A lot is still left to do

   – more higher–order calculations

   – even better background estimates

   – QCD effects on new physics measurements

   – scans of high–dimensional parameter spaces

   – statistics tools for phenomenologists

   – ....

   $\Rightarrow$ even exciting times require serious work