New Methods for New Physics

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Outline

TeV–scale supersymmetry

Supersymmetric signatures at LHC

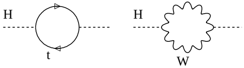
New physics mass measurements

New physics spin measurements

Supersymmetric parameter studies

Under construction

TeV–scale supersymmetry: 1



Starting from data...

– ...which seem to indicate a light Higgs

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

$\Rightarrow$ 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 and symmetries

$\Rightarrow$ problematic to realize at TeV scale [data seriously in the way]

Idea of supersymmetry:

cancellation of divergences through statistics factor (-1)

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

TeV–scale supersymmetry: 2

SUSY breaking: (yet) unobserved partners heavy

– mechanism for SUSY masses unknown [soft SUSY breaking mediated somehow?]

– link to flavor physics and baryogenesis/leptogenesis unknown

– link to dark matter promising [Falk,...]

– maximally blind mediation: mSUGRA/cMSSM [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 [Higgs masses free: NUHM]

– 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	$4 \cdot 2$	Majorana
gauge bosons	$W^\pm$	1	$2 \cdot 3$	
Higgs bosons	$H^\pm$	0	2	
$\rightarrow$ charginos	$\tilde{\chi}_i^\pm$	1/2	$2 \cdot 4$	Dirac
graviton	G	2	2	
$\rightarrow$ gravitino	$\tilde{G}$	3/2	2	tough

Supersymmetry at LHC: 1

Inclusive: squarks and gluinos at Tevatron

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

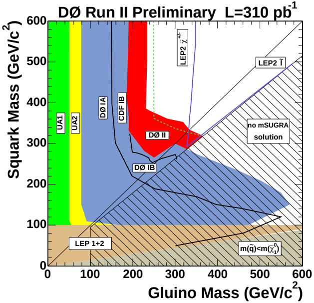
– cross sections large at hadron colliders

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

  [additional jets and leptons possible]

– gaugino mass unification assumed for details

⇒ experienced in inclusive jets plus LSP



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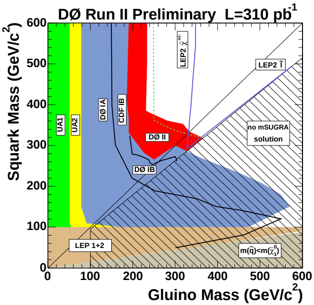


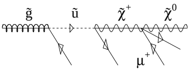
When will I believe we see SUSY–QCD?

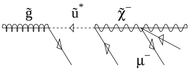
– gluinos Majorana fermions

– jet in gluino decay q or $\bar{q}$

– final–state leptons with both charges

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





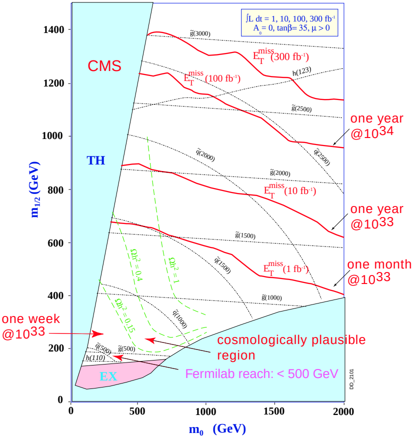
Supersymmetry at LHC: 2

New physics at the LHC

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

(2) measurements

(3) parameter studies



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 [NLO: Prospino2]

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

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

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

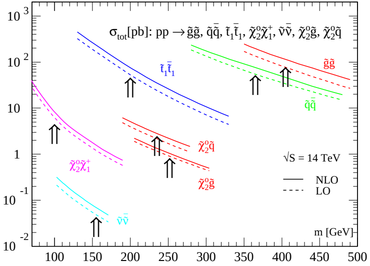
[$\tilde{g} \to \tilde{u}\bar{u} \to \tilde{\chi}_1^+ d\bar{u}$ or $\tilde{g} \to \tilde{u}^* u \to \tilde{\chi}_1^- \bar{d}u$]

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

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

$\Rightarrow$ inclusive: similar to Tevatron

$\Rightarrow$ exclusive: enough events for studies at LHC



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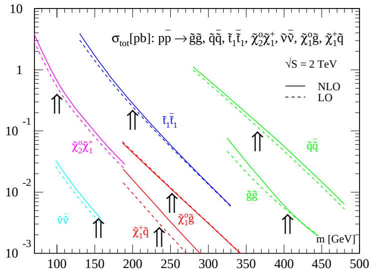
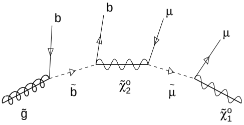


New physics mass measurements: 1



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]

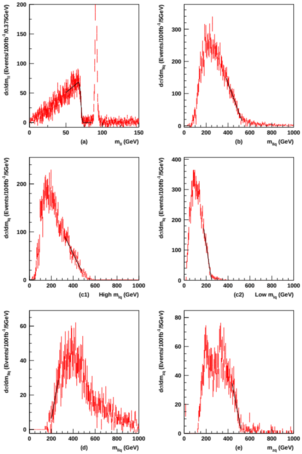
– cross sections some 100 pb [more than 3×10^7 events]

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

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

$\Rightarrow$ spectrum information from decay kinematics

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



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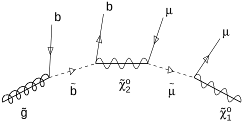

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$\Rightarrow$ spectrum information from decay kinematics [mass differences with smaller errors]

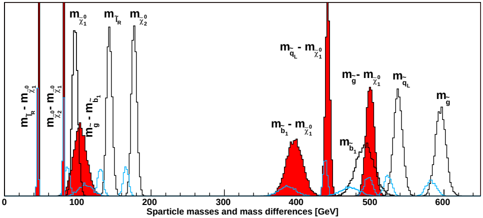
Gluino mass from kinematic endpoints

– $\tilde{b}_L$ in chain, all jets b-tagged [Gjelsten, Miller, Osland]

– most of time: cascade assumption correct

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

[theoretically defined?]



New physics mass measurements: 2

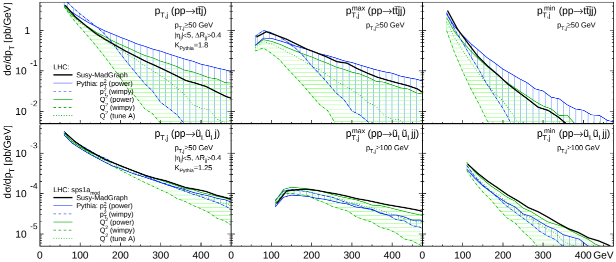
SUSY plus jets: complex final states [Smadgraph: Cho, Hagiwara, Kanzaki, TP, Rainwater, Stelzer]

– Majoranas and fermion number violation in Madgraph
– set of Feynman rules [400+ processes: Madgraph - Whizard (Reuter) - Sherpa (Schumann)]
– available in Madevent [Alwall, Maltoni, Louvain group]

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]
– Pythia shower tuned at Tevatron
$\Rightarrow$ 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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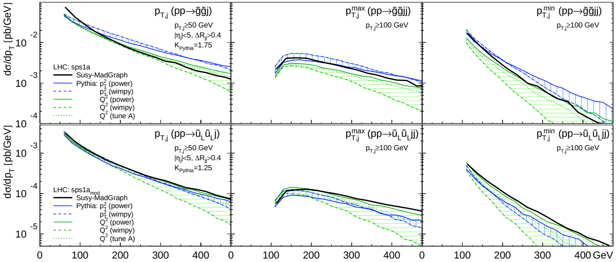
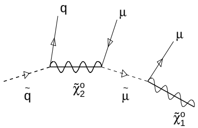


New physics spin measurements: 1



All new physics is hypothesis testing

– assume squark cascade observed

⇒ strongly interacting scalar?

⇒ 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]

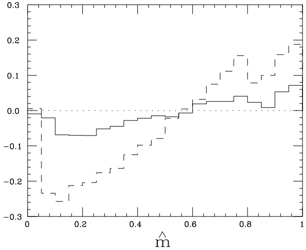
– decay chain $\tilde{\chi}_2^0 \to \ell \tilde{\ell}^* \to \ell \bar{\ell} \tilde{\chi}_1^0$

– trick 1: compare with KK q, Z, ℓ, γ

– trick 2: mass variables, ‘normalized angles’
$\Rightarrow \widehat{m} = m_{j\ell}/m_{j\ell}^{\rm max}$ most promising [Barr]

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

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



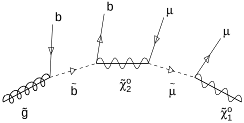
Masses or spin or both? [Arkani-Hamed,...]

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

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

New physics spin measurements: 2

Back to my SUSY–QCD



– given like–sign dileptons, gluino Majorana fermion?

– always like–sign dileptons from bosonic gluon

⇒ show gluino fermionic

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

New physics spin measurements: 2

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Gluino–bottom cascade [Alves, Eboli, TP]

– decay chain like for gluino mass

– compare with first KK g, q, Z, and ℓ

(1) replace initial–state asymmetry by b vs. $\bar{b}$

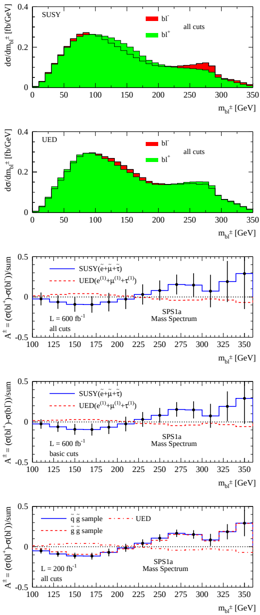
– asymmetry to write down:
$\mathcal{A} = [\sigma(b\ell^+) - \sigma(b\ell^-)]/[\sigma(b\ell^+) + \sigma(b\ell^-)]$

[still visible after cuts and smearing]

– independent on production channels

(2) purely hadronic m_{bb} [sensitive to gluino boost]

⇒ masses and spins accessible at LHC



Supersymmetric parameters: 1

Theory output from LHC: SUSY parameters

– parameters: weak-scale Lagrangean [Sfitter: Lafaye, TP, Rauch, Zerwas; Fittino; Arkani-Hamed,...]

– 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 ⇒ mSUGRA/cMSSM

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

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

⇒ probability map today [Allanach, Lester, Weber]

⇒ best fi t 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/cMSSM [TP, Lafaye, Zerwas]

- (1) grid for closed subset
  (2) fit of other parameters
  (3) complete fit
- LHC+ILC perfect [Weiglein etal]

$\Rightarrow$ 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

Supersymmetric parameters: 2

Bayes' theorem and new physics [Allanach, Roszkowski]

- Pythia/Herwig/Sherpa: data given the model: $p(d|m)$
- theorist's prejudice: model $p(m)$
- new model extraction: $p(m|d) = p(d|m)\, p(m)/p(d)$ [$p(d)$ through normalization]

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

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 MC approach: weighted chain [two bins with p 1 : 10 with 2 or 11 points]

- already for mSUGRA/cMSSM: MC resolution not suffi cient

$\Rightarrow$ use additional probability maximization to rank maxima

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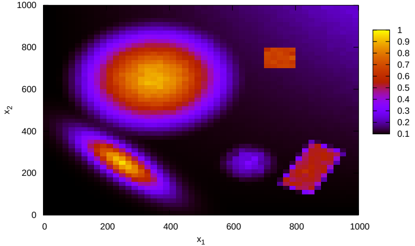
Toy model [Rauch & TP]

– 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



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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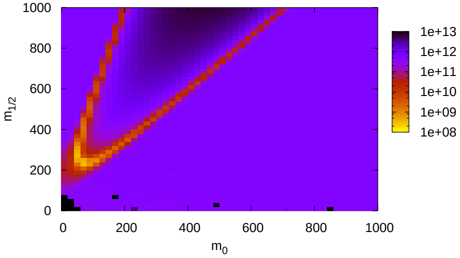
mSUGRA/cMSSM with LHC measurements

– SPS1a kinematic edges and free m_t

– as of yesterday: Sfi tter probability map [Lafaye, TP, Rauch, Zerwas]



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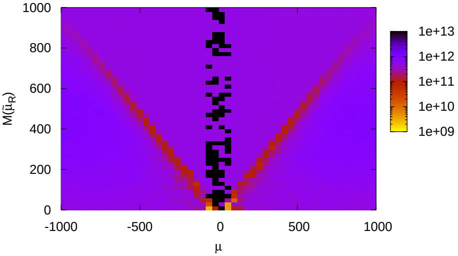

Under construction: 1

Problems in the spin/mass extraction

- strong correlations between masses from edges
- strong correlations between m_{xyz} in cascades
- split of mass and spin extraction artifi cial
- model–independent spin analysis unlikely

$\Rightarrow$ Proper hypothesis treatment

Statistics: Neyman–Pearson lemma

- assume correct hypothsis m_1: SUSY cascade
  assume wrong hypothsis m_2: UED cascade
- likelihood ratio $p(d|m_1)/p(d|m_2)$ most powerful estimator

  [lowest probability to mistake right for fluctuation of wrong (type-II error)]
- probability of event $p(d|m) \sim |\mathcal{M}|^2$
- combined likelihood ratios of events $\rightarrow$ PS integral over likelihood ratio

$\Rightarrow$ Compute maximum statistical signifi cance

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

- compute likelihood of top events estimating $|\mathcal{M}|^2$
- maximize probability $p(d|\text{SM}, m_t)$ as function of m_t...

Under construction: 1

Problems in the spin/mass extraction

– strong correlations between masses from edges

– strong correlations between m_{xyz} in cascades

– split of mass and spin extraction artifi cial

– model–independent spin analysis unlikely

$\Rightarrow$ Proper hypothesis treatment

Statistics: Neyman–Pearson lemma

– assume correct hypothsis m_1: Higgs signal
assume wrong hypothsis m_2: SM background

– likelihood ratio $p(d|m_1)/p(d|m_2)$ most powerful estimator

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

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

– combined likelihood ratios of events $\rightarrow$ PS integral over likelihood ratio

$\Rightarrow$ Compute maximum statistical signifi cance

Under construction: 2

Search for WBF $H \to \mu\mu$ [Cranmer & TP]

– assume correct hypothsis m_{s+b}: Higgs signal
  assume wrong hypothsis m_b: SM background

– likelihood ratio $p(d|m_{s+b})/p(d|m_b)$ most powerful estimator

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

– combined likelihood ratios of events $\to$ PS integral over likelihood ratio

$\Rightarrow$ Compute maximum statistical signifi cance

Maximum signifi cance for LHC signals

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

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

– phase space integration of $s, b \to p(s,b) \sim |\mathcal{M}_{s,b}|^2$ [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: $\rho_{s,b}(q)$

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

Under construction: 2

Search for WBF $H \to \mu\mu$ [Cranmer & TP]

- assume correct hypothsis m_{s+b}: Higgs signal
  assume wrong hypothsis m_b: SM background
- likelihood ratio $p(d|m_{s+b})/p(d|m_b)$ most powerful estimator
- probability of event $p(d|m) \sim |\mathcal{M}|^2$
- combined likelihood ratios of events $\to$ PS integral over likelihood ratio

$\Rightarrow$ Compute maximum statistical signifi cance

Semi–realistic results

- irreducible & unsmeared [full parameter space 1:1]

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

- 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}

$\Rightarrow$ Tool works, new physics one obvious application [Whizard: Cranmer, TP, Reuter]

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
- better background estimates
- QCD effects on new physics measurements
- scanning of high–dimensional parameter spaces
- automized statistics tools for phenomenologists
- ....

$\Rightarrow$ Exciting times require serious work