Comparison of BSM mass determination methods for early (14 TeV) LHC data

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Collider signatures of BSM theories

- **generic feature** of any (reasonable) BSM theory: **observable** deviations from Standard Model predictions

$\Rightarrow$ changed event rates (= modified **cross sections**)

$\Rightarrow$ resonances of new particles (= new **mass eigenstates**)

- to fully determine theory at low energy scale: also need **spins** and **couplings**
- also important: "indirect" measurements through higher order contributions: can give important restrictions
- further task: determine theory at **high scale**
  don't talk about that here
- so far: only collider exclusion limits exist
  (C. Amsler ea: Particle Data Book, http://pdg.lbl.gov/2009/reviews)

\+ also important: astroparticle connection !!

Why masses ??

- first obvious choice: cross section measurements
- however, depend on knowledge of actual **cm energies**
- **usually ”smeared”** (eg bremsstrahlung for ILC) or **unknown** (LHC), ie only obtainable in form of probability distributions (in form of PDFs)
- furthermore, many experimental issues (calibration of detector, ...)
- variables constructed for **mass measurements**: depend less on overall (experimental and theoretical) normalization uncertainties

⇒ construction of Lorentz-invariant mass variables: even cm independent (especially useful for processes at LHC)

⇒ ideal candidates for BSM discoveries and measurements

- spins, couplings: more complicated; next step on the road...

Les Houches mass determination project

Setup

- project started at the **Les Houches 2009 BSM session**
- joint experimental/ theoretical effort
  (56 % /44%; should withhold at least some "reality" criticism ☺)
- generate generic BSM data samples, including **all background**, use **parton showers** and **detector simulation**
- use this data to check several (new/ old) mass determination methods/ proposals
- **why ??** most (newer) variables (invented +) tested for specific scenario points, mainly by authors themselves

$\Rightarrow$ "reality check" still pending

- also: relative low luminosity: $\int \mathcal{L} = 10\,\mathrm{fb}^{-10}$, $\sqrt{s}_{\text{hadr}} = 14\,\mathrm{TeV}$
- **note:**
  ongoing study, started off as non-experts $\Rightarrow$ preliminary results

General features and investigated signal

- general feature for BSM particle decays at LHC: **missing energy** from invisible final states (assumes dark matter candidate !!)
- general feature for BSM particle decays at LHC: **long decay chains** $\Rightarrow$ many intermediate heavy onshell states

most variables make use of at least one of the above

- all studies: **SPS1a**
- generated: **all production channels, all decay channels**

$\Rightarrow$ **samples contain complete signature for this parameter point**

Details on data generation (**R. Brunelière**, T. Lari, S. Sekmen)

- **SUSY spectrum**: generated using **SoftSusy** (B. Allanach, hep-ph/0104145)
- $2 \rightarrow 2$ and $2 \rightarrow 3$ **matrix element generation**: **Madgraph** (T. Stelzer, W. Long, hep-ph/9401258; F. Maltoni, T. Stelzer, hep-ph/0208156)
- **generation of decay chains**: **Bridge** (P. Meade, M. Reece, hep-ph/0703031)
- **parton shower generation**: **Pythia** (in **Madgraph**) (T.Sjostrand, S.Mrenna, P. Skands, hep-ph/0603175)
- **matching** of samples with different jet multiplicities: **MLM matching algorithm** in **Madgraph** (J.Alwall ea, hep-ph/0706.2569; J.Alwall, S. de Visscher, F. Maltoni, hep-ph/0810.5350)
- **detector simulation**: **Delphes** (S. Ovyn, X. Rouby, V. Lemaitre, hep-ph/0903.2225)
- **data analysis**: **ROOT** (http://root.cern.ch)

Messages from Renaud

- in general, **code interfacing works quite well**

Things which were (particularly) great

- **MLM matching** option in Madgraph/ Pythia
- **Delphes** as a (freely accessible) **detector simulation** for quick "first order" results
- should also mention: **FeynRules, MCDB at CERN**
  $\Rightarrow$ both quite useful !!

possible improvements

- even **more models in FeynRules**
- too many steps/ **data storage** in Bridge/ Madgraph interface
- **MLM with 2 extra jets: quite long runtimes**; possibility to define **first/ second generation generic quark/ lepton** could help to reduce combinatorics
- **Delphes output** requires Root libraries: better to have **flat root ntuple format**

Tested methods

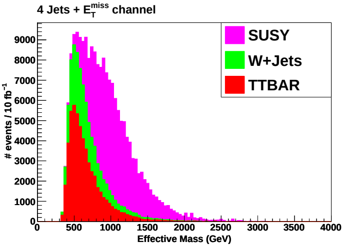
So far, tested and checked the following variables

- **effective mass M_{eff}** (Hinchcliffe, Paige, Shapiro, Soderquist, Yao 97; Torvey 00; ...)
- $\sqrt{\hat{s}}_{\mathrm{min}}$ (Konar, Kong, Matchev 08; ...)
- **transverse mass** (Barger, Han, Phillips 87; ...)
- **M_{T2} and M_{T2}-kink** (Lester, Summer, 99; Cho, Choi, Kim, Park 07, 08; Burns, Kong, Matchev, Park 09; ...)
- **edges** (Hinchcliffe, Paige, Shapiro, Soderquist, Yao 97; Bachacou, Hinchcliffe, Paige 00; ATLAS collaboration 99; Allanach, Lester, Parker, Webber 00; ...)
- **polynomial intersection** (Kawagoe, Nojiri, Polesello 04; Cheng, Gunion, Han, Marandella, McElrath 07; Cho, Choi, Kim, Park 07; Nojiri, Polesello, Tovey 08; Cheng, (Engelhardt,) Gunion, Han, McElrath 08, 09)

of course, due to time constraints, cannot explain all in detail
will focus on applicability, results + drawbacks (so far); ......

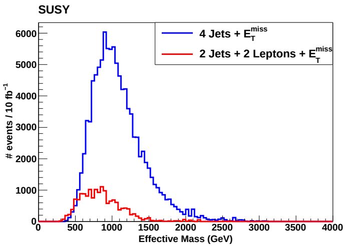
Effective mass (J.-R. Lessard)

- $M_{\mathbf{eff}}$: invented to determine overall mass scale of new physics
- here: studied for $n = 6$ final states, ie 4 visible particles
- variable definition: $M_{\mathrm{eff}} = p_{\mathrm{T},1} + p_{\mathrm{T},2} + p_{\mathrm{T},3} + p_{\mathrm{T},4} + E_{\mathrm{T}}^{\mathrm{miss}}$
- use correlation between M_{eff} and M_{SUSY} to establish the latter



M_{eff}, SUSY + SM background,

4 jet channel



M_{eff}, SUSY only,

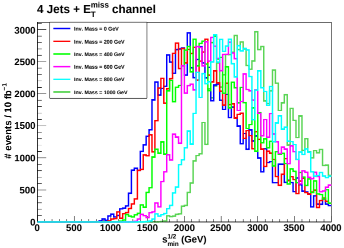
4 jet and 2 jet 2 lepton channel

✓ seems to work; **drawback**: need to simulate BSM parameter points to establish correlation between M_{eff} and M_{SUSY}

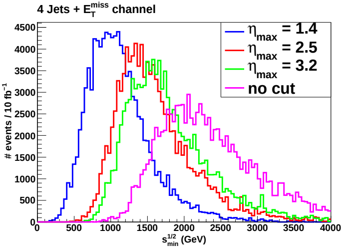
$\sqrt{\hat{s}}_{\min}$ (J.-R. Lessard)

- $\sqrt{\hat{s}}_{\min}$: determine scale of new physics by threshold scan
- **however:** requires mass of invisible final state particle as input
- definition: $\hat{s}^{1/2}_{\min}(M_{\text{inv}}) \equiv \sqrt{E^2 - P_z^2} + \sqrt{(E_T^{\text{miss}})^2 + M_{\text{inv}}^2}$

— high sensitivity to ISR; solution: cut in jet pseudorapidity



$\hat{s}^{1/2}_{\min}$, different values of M_{inv}, no η cut



$\hat{s}^{1/2}_{\min}(0)$ for different values of η_{cut}

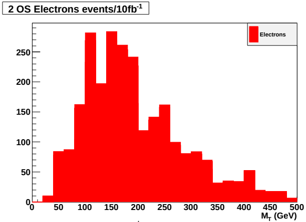
✓ peaked at value different from SM background (not shown);
however: large dependence on η cut !! ⇒ investigate further...

Transverse mass (L. Basso)

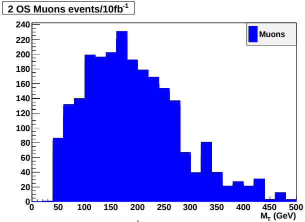
- **transverse mass**: used for events of the type

$$A + X \rightarrow B(\mathrm{vis}) + C(\mathrm{inv}) + X \qquad (1)$$

- **all missing energy is assumed to come from 1 particle !!**
- not true in SUSY $\Rightarrow$ test of an a priori false assumption
- variable definition: $M_T^2 = \left(\sqrt{M^2(\mathrm{vis}) + \vec{p_\mathrm{T}}^{\,2}(\mathrm{vis})} + |\not{p}_\mathrm{T}|\right)^2 - \left(\vec{p_\mathrm{T}}(\mathrm{vis}) + \vec{\not{p}_\mathrm{T}}\right)^2$



M_T for e^+e^- final states



M_T for $\mu^+\mu^-$ final states

✓ works in a sense that it does **not** show behaviour expected from (1); **however:** be aware of "wrong" peak interpretation

M_{T2} and M_{T2}-kink: definition (M. Tytgat)

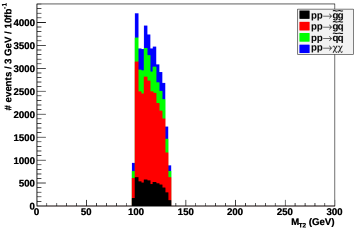
- M_{T2} **variable**: first thought as generalization of M_T: more than one particle can emit "invisible" final state
- between invention (Lester ea, 99) and nowadays use (Burn ea, 09): underwent some major upgrades
- look at $pp \longrightarrow X + \tilde{l}_1 \tilde{l}_2 \longrightarrow X + l_1 \tilde{\chi}_1^0 l_2 \tilde{\chi}_1^0$
- variable definition:

$$M_{T2} \equiv \min_{\not{p}_1 + \not{p}_2 = \not{p}_T} \left[\max \left\{ m_T^2(\mathrm{p}_T^{l_1}, \not{p}_1), m_T^2(\mathrm{p}_T^{l_2}, \not{p}_2) \right\} \right],$$

with $m_T^2(\mathrm{p}_T^{l_i}, \not{p}_i) = m_{l_i}^2 + m_{\tilde{\chi}}^2 + 2(E_{Tl_i} E_{Ti} - \mathrm{p}_{Tl_i} \not{p}_i)$, $E_T = \sqrt{\mathrm{p}_T^2 + m^2}$;
$\not{p}_1 + \not{p}_2 = \not{p}_T$: sample over all possible momenta

- needs LSP mass as input; $M_{T2,\max} = m_{\text{parent}}$
- further improvements (Cho ea 07, Kong ea 09): derive **analytic expressions** for $M_{T2,\max}(m_{\text{parent}}, m_{\text{LSP}}, m_{\text{LSP,test}}, p_{\perp}(X))$
- final step: different functions for $m_{\text{LSP,test}} \gtrless m_{\text{LSP}}$, with functional dependence on $m_{\text{LSP}}, m_{\text{parent}}, p_{\perp}(X)$: $\Rightarrow$ **use these for fits**

M_{T2} and M_{T2}-kink: results (M. Tytgat)

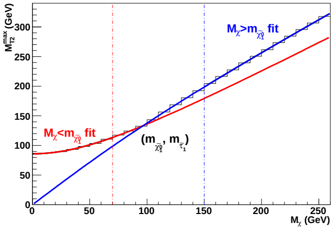


M_{T2}; ss leptons, parton level. Correct $m_{\tilde{\chi}}$

parton level:

✓; maximum value gives

$$m_{\tilde{\tau}} = 130\,\mathrm{GeV}$$



$M_{T2}^{max}(m_{\mathrm{LSP,test}})$, ss leptons, parton level

parton level:

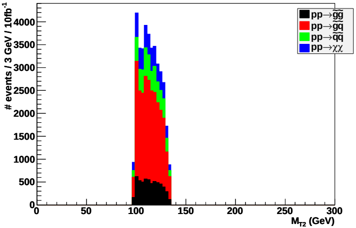
✓; fit results for

$$m_{\mathrm{LSP,test}} \gtrless m_{\mathrm{LSP}}:$$

$$m_{\tilde{\chi}_1^0} = 97 \pm 2\,(96 \pm 4)\ \mathrm{GeV}$$

$$m_{\tilde{\tau}_1} = 133 \pm 3\ (133 \pm 4)\ \mathrm{GeV},$$

M_{T2} and M_{T2}-kink: results (M. Tytgat)

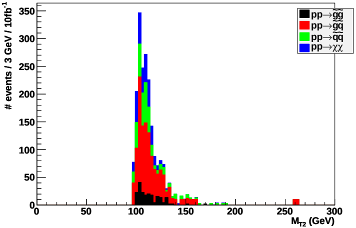


M_{T2}; ss leptons, parton level. Correct $m_{\tilde{\chi}}$

parton level:

✓; maximum value gives

$$m_{\tilde{\tau}} = 130\,\text{GeV}$$



As above, detector level.

detector level:

$M_{T2,\max}$ quite **washed out**

$\Rightarrow$ still some work to do....

Edges: definition (T. Robens, P.v. Weitershausen)

- **Edges** of invariant masses:
  one of the more established methods
- idea: look at decay chain as eg

$$A \rightarrow B + C \rightarrow B + D + E \rightarrow \dots$$

- define Lorentz-invariant masses in the form of

$$m^2_{ab\dots n} = (p_a + p_b + \dots + p_n)^2$$

- assume in between states to be onshell

$\Rightarrow$ inversion formulae for $m_{A,B,\dots}(m_{\text{inv},1;\text{min,max}}, m_{\text{inv},2;\text{min,max}}, \dots)$
"edges" of invariant mass distributions

completely given by phase space

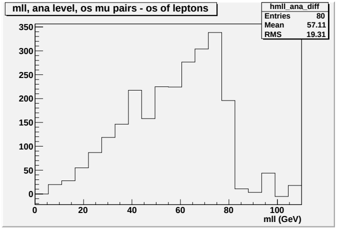
- drawback: hierarchy of chain needs to be known

$\Rightarrow$ different inversion formulae for different "in between" scenarios

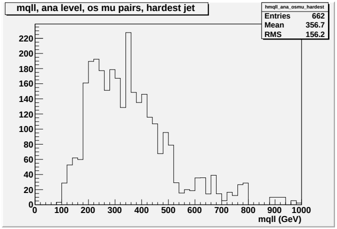
- depending on number of final states, system of equations exact/ over-/ under-constrained

Edges: results (T. Robens, P.v. Weitershausen)

- chain considered here: $\tilde{q} \to \tilde{\chi}_2^0 q \to \tilde{l} l q \to \tilde{\chi}_1^0 l l q$



$m_{\mu^+\mu^-}$, after osof subtr, detector level



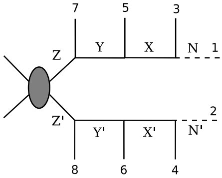
$m_{q\mu\mu}$, detector level. q = hardest jet

m_{ll} for $\mu^+\mu^-$ on detector level, after osof background subtraction: ✓; theoretical max value: $81\,\mathrm{GeV}$

variables involving jets:
biggest problem:
choosing the correct jet
(hardest or second-hardest)
$m_{q\mu\mu}$, hardest jet, detector level; expect
$m_{qll\,\mathrm{max}} \sim 450 - 460\,\mathrm{GeV}$
still some work to be done...

Polynomial intersection: definition (B. McElrath)

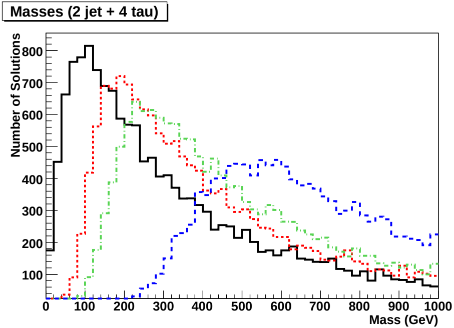
- **polynomial intersection**: very **topology-specific**
- "valid" topology:



- **idea**: assume all particles onshell, use relations as
  $$(M_Z^2 \;=)\,(p_1+p_3+p_5+p_7)^2 \;=\; (p_2+p_4+p_6+p_8)^2$$
  in every step
- combination of 2 events (with **same** topology):
  16 eqns, 16 unknowns ⇒ solvable system
- quite **computer intense** (typically needs a grid to run...)
- code available at
  http://particle.physics.ucdavis.edu/hefti/projects/doku.php?id=wimpmass

Polynomial intersection: results (B. McElrath)

- considered chain: $\tilde{q} \to \tilde{\chi}_2^0 q \to \tilde{\tau}\tau q \to \tilde{\chi}_1^0 \tau\tau q$



M_N, M_X, M_Y, and M_Z polynomial solutions

- expected masses:
  $M_Z \sim 513 - 568\,\mathrm{GeV}$, $M_Y = 181\,\mathrm{GeV}$, $M_X = 135\,\mathrm{GeV}$, $M_N = 97\mathrm{GeV}$

✓ next step: **error reduction** using higher statistics

Summary

- **masses** of new particles:
  one of the first measurements for **any BSM model**
- **scope** of Les Houches mass determination project:
  test different methods on a standard sample in a "realistic" scenario, ie w parton shower, hadronization, detector effects, ...

✓ **tested different** (older/ newer) **methods**

✓ for most methods:
first steps, **pinned down** (known/ unknown) **complications**

- **next steps**: include more variables
- **next steps**: try a "quantitative" comparison
  (to be done w great care)
- so far: most methods applicable, some problems persisting...

only beginning of the study $\Rightarrow$ **more to come...**

! Thanks for listening !

Appendix

Mass determination studies in the last 10+ years...

Mass determination with MET

Very active area of research

Hinchliffe et al., Phys. Rev. D 55, 5520 [arXiv:hep-ph/9610544], Lester and Summers, Phys. Lett. B 463, 99 [arXiv:hep-ph/9906349], Bachacou, Hinchliffe, Paige, Phys. Rev. D 62, 015009 [arXiv:hep-ph/9907518], Tovey, Phys. Lett. B 498, 1 (2001) [arXiv:hep-ph/0006276], Allanach et al., JHEP 0009, 004 (2000) [arXiv:hep-ph/0007009], Barr, Lester, Stephens, J. Phys. G29, 2343 (2003) [arXiv:hep-ph/0304226], Nojiri, Polesello, Tovey, arXiv:hep-ph/0312317, Kawagoe, Nojiri, Polesello, Phys. Rev. D 71, 035008 [arXiv:hep-ph/0410160], Gjelsten, Miller, Osland, JHEP 0412, 003 (2004) [arXiv:hep-ph/0410303], Miller, Osland, Raklev, JHEP 0603, 034 (2006) [arXiv:hep-ph/0510356], Lester, Phys. Lett. B 655, 39 (2007) [arXiv:hep-ph/0603171], Cheng et al., JHEP 0712, 076 (2007) [arXiv:0707.0030], Lester and Barr, JHEP 0712, 102 (2007) [arXiv:0708.1028], Cho, Choi, Kim, Park, Phys. Rev. Lett. 100, 171801 [arXiv:0709.0288], Gripaios, JHEP 0802, 053 (2008) [arXiv:0709.2740], Barr, Gripaios, Lester, JHEP 0802, 014 (2008) [arXiv:0711.4008], Ross and Serna, Phys. Lett. B 665, 212 (2008) [arXiv:0712.0943], Nojiri, Polesello, Tovey, JHEP 0805, 014 (2008) [arXiv:0712.2718], Huang, Kersting, Yang, arXiv:0802.0022, Nojiri et al., JHEP 0806, 035 (2008) [arXiv:0802.2412], Serna, JHEP 0806, 004 (2008) [arXiv:0804.3344], Burns, Kong, Matchev, Park, arXiv:0810.5576, Kersting, Phys.Rev.D79:095018,2009 [arXiv:0901.2765], Alwall et al, arXiv:0905.1201, Cheng et al, arXiv:0905.1344, Matchev et al, arXiv:0906.2417, and many more...

SLAC NATIONAL ACCELERATOR LABORATORY Johan Alwall - SUSY Phenomenology 13

stolen from: J. Alwall, "SUSY Phenomenology at the LHC", DESY Theory workshop 09, http://th-workshop2009.desy.de

MSSM in supersymmetry

- model investigated here: **SUSY** in the **MSSM** version
- **SUSY**: additional symmetry, each particle obtains a partner with $\Delta\, s \;=\; \pm\,\frac{1}{2}$ (but a priori same mass)
- partners not observed: SUSY is broken to give higher masses to new particles
- leftover w $\sim$ 100 new parameters, some constraints $\Rightarrow$ **MSSM** (minimal...)
- studies here: use specific (collider friendly) scenarios SPS1a('), masses $\mathcal{O}(10^2\,\mathrm{GeV})$
- **important feature: new mass eigenstates in the collider-observable range, "standard" (scalar, fermionic) coupling structures**

SPS1a mass spectrum and cross sections

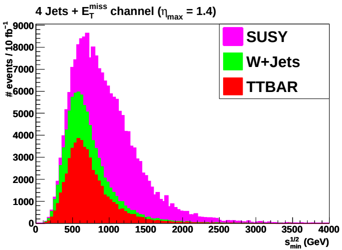
$\tilde{d}_L$	568.4	$\tilde{d}_R$	545.2	$\tilde{u}_L$	561.1	$\tilde{u}_R$	549.3	$\tilde{b}_1$	513.1	$\tilde{b}_2$	543.7	$\tilde{t}_1$	399.
$\tilde{l}_L$	202.9	$\tilde{l}_R$	144.1	$\tilde{\tau}_1$	134.5	$\tilde{\tau}_2$	206.9	$\tilde{\nu}_l$	185.3	$\tilde{\nu}_\tau$	184.7	$\tilde{t}_2$	585.
$\widetilde{\chi}_1^-$	181.7	$\widetilde{\chi}_2^-$	380.0	$\widetilde{\chi}_1^0$	96.7	$\widetilde{\chi}_2^0$	181.1	$\lvert\widetilde{\chi}_3^0\rvert$	363.8	$\widetilde{\chi}_4^0$	381.7	$\tilde{g}$	607.

Relevant masses for SPS1a in GeV. $u = (u, c)$, $d = (d, s)$, $l = (e, \mu)$.

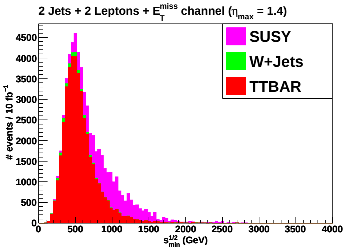
$X_1 X_2$	$2 \rightarrow 2$	$2 \rightarrow 3$
$\tilde{q}\tilde{q}\,(j)$	6.56	7.83
$\tilde{q}\tilde{g}\,(j)$	19.52	21.75
$\tilde{g}\tilde{g}\,(j)$	4.53	5.47
$\widetilde{\chi}\widetilde{\chi}\,(j)$	1.97	4.89

Production cross sections in pb for $p\,p \rightarrow X_1\,X_2$, for a cm energy of 14 TeV. CTEQ6L1 PDFs were used. $2 \rightarrow 3$ sample includes explicitly generated hard jet, where hard is defined by $p_{T,\mathrm{jet}} > 40\,\mathrm{GeV}$.

$\sqrt{\hat{s}}_{min}$: including SM background (J.-R. Lessard)



$\sqrt{\hat{s}}_{min}(0)$, 4 jet channel, SUSY + SM background

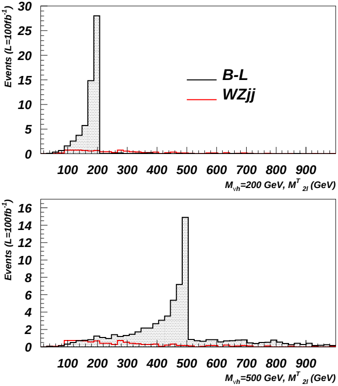


$\sqrt{\hat{s}}_{min}(0)$, 2 jet 2 lepton channel, SUSY + SM background

Transverse mass for U_{B-L} model (L. Basso)

Working example for U_{B-L} $\nu_h \rightarrow W^{\pm} l^{\mp} \rightarrow l^{\pm} l^{\mp} \nu_l$

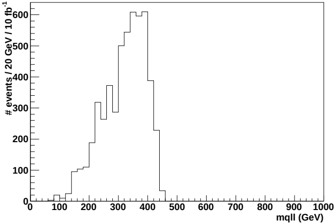
(from L. Basso, A. Belyaev, S. Moretti, and C. Shepherd-Themistocleous, "Phenomenology of the minimal B-L extension of the Standard model: Z' and neutrinos", arXiv:0812.4313v1)



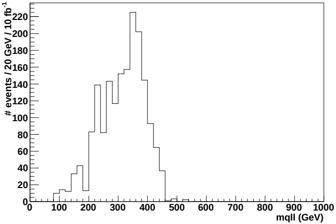
Signal ($M_{\nu_h} = 200$ GeV, top, and $M_{\nu_h} = 500$ GeV, bottom) and background distributions after the Selection #1, #2 and #3 cuts.
(Here, $\mathscr{L} = 100\ \text{fb}^{-1}$.)

Edges: results (T. Robens, P.v. Weitershausen)

$m_{q\mu\mu}$ on **parton** and **detector** level, "correct" jet choice



$m_{q\mu\mu}$, parton level, correct quark choice.



$m_{q\mu\mu}$, detector level, "correct" jet choice.

✓ $m_{ll,\max} \sim 450 - 460\,\mathrm{GeV}$.

✓

$\Rightarrow$ in principle, no contamination by detector effects etc...
("correctness" determined by χ^2 minimization)

Polynomial intersection: definition (B. McElrath)

Number of unknowns and constraints for 2 events (1)

- **event 1)**:

$$\begin{array}{lrcl} (M_Z^2 =) & (p_1+p_3+p_5+p_7)^2 & = & (p_2+p_4+p_6+p_8)^2, \\ (M_Y^2 =) & (p_1+p_3+p_5)^2 & = & (p_2+p_4+p_6)^2, \\ (M_X^2 =) & (p_1+p_3)^2 & = & (p_2+p_4)^2, \\ (M_N^2 =) & p_1^2 & = & p_2^2. \end{array}$$

$$p_1^x + p_2^x = p_{\text{miss}}^x, \quad p_1^y + p_2^y = p_{\text{miss}}^y.$$

- 8 unknowns ($p_{1,2}$), 6 constraints

$\Rightarrow$ system cannot be solved.

Polynomial intersection: definition (B. McElrath)

Number of unknowns and constraints for 2 events (2)

- **event 2)**:
  add second event, have

$$
\begin{aligned}
q_1^2 &= q_2^2 = p_2^2, \\
(q_1+q_3)^2 &= (q_2+q_4)^2 = (p_2+p_4)^2, \\
(q_1+q_3+q_5)^2 &= (q_2+q_4+q_6)^2 = (p_2+p_4+p_6)^2, \\
(q_1+q_3+q_5+q_7)^2 &= (q_2+q_4+q_6+q_8)^2 \\
&= (p_2+p_4+p_6+p_8)^2,
\end{aligned}
$$

$$q_1^x + q_2^x = q_{\text{miss}}^x, \quad q_1^y + q_2^y = q_{\text{miss}}^y.$$

- in total $8+8=16$ unknowns, $10+6=16$ constraints:

  $\Rightarrow$ **solvable system !!**

- more details in: Cheng, (Engelhardt), Gunion, Han, McElrath, arXiv:0802.4290, 0905.1344