Confusions in Cascades – Disentangling New Physics in LHC cascades

Jürgen Reuter

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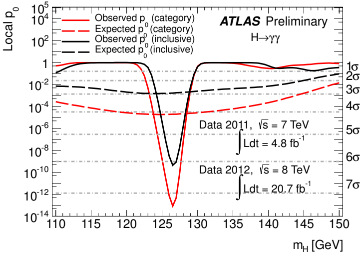
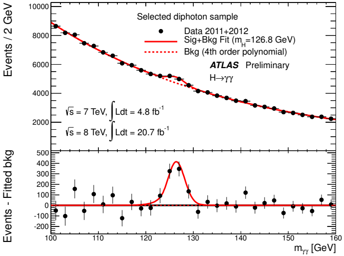
JRR/Wiesler, 1212.5559 [hep-ph], EPJC 73 (2013) 2355; Pietsch/JRR/Sakurai/Wiesler, JHEP 1207 (2012) 148; JRR/Wiesler, PRD84 (2011) 015012; Hagiwara/Kilian/Krauss/Ohl/Plehn/Rainwater/JRR/Schumann, PRD73 (2006) 055005

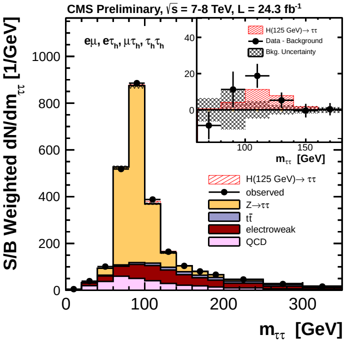
IFT Seminar, Madrid, March 21st, 2013

Standard Model Triumph:

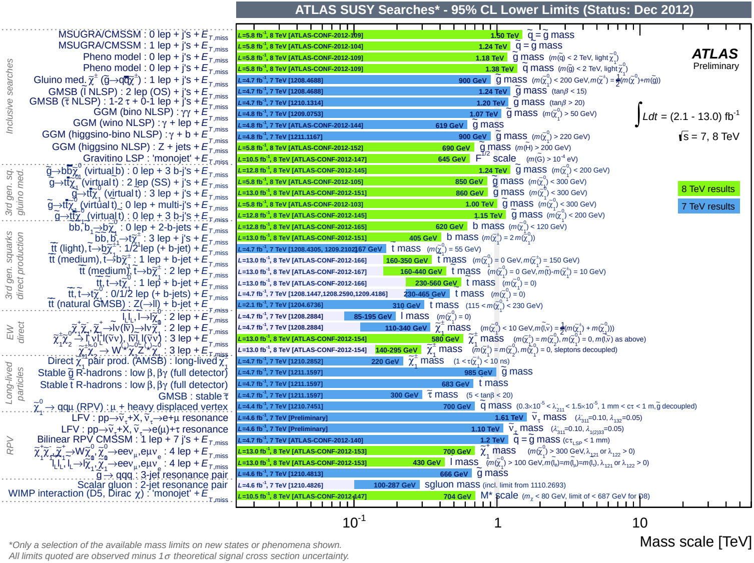
- 2012: Discovery of a Higgs boson





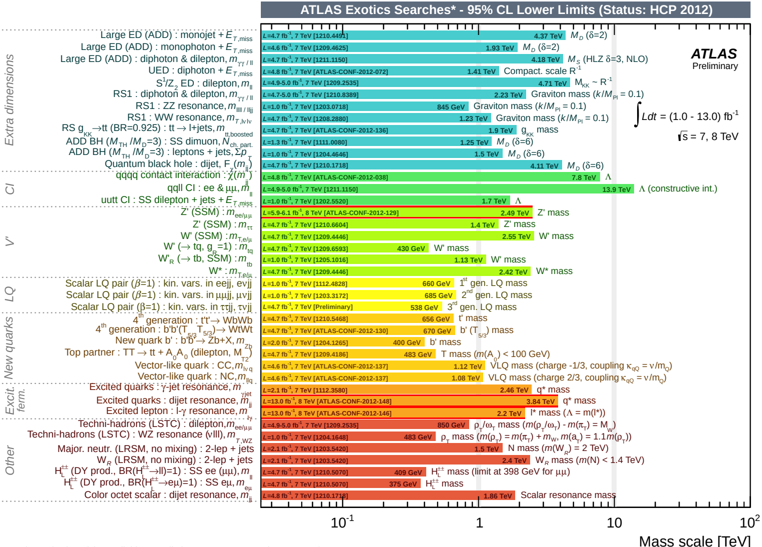


... and what now?



*Only a selection of the available mass limits on new states or phenomena shown.
All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

... and what now?



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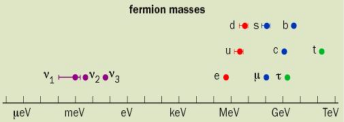
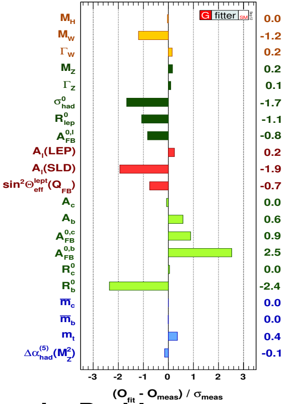
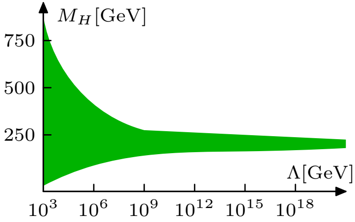
Doubts on the Standardmodel

- describes microcosm (too good?)
- 28 free parameters



- Higgs ?, form of Higgs potential ?





Hierarchy Problem

chiral symmetry: $\delta m_f \propto v \ln(\Lambda^2/v^2)$

no symmetry for quantum corrections to Higgs mass

$$\boxed{\delta M_H^2 \propto \Lambda^2 \sim M^2_{\text{Planck}} = (10^{19})^2\,\text{GeV}^2}$$

$(125\,\text{GeV})^2$ = (1000000000000000000000000000000020000 –

1000000000000000000000000000000000000) GeV^2

Electroweak vacuum stability

- Most recent analysis: Metastable vacuum with lifetime longer than the age of the universe Degrassi et al., arXiv:1205.6497

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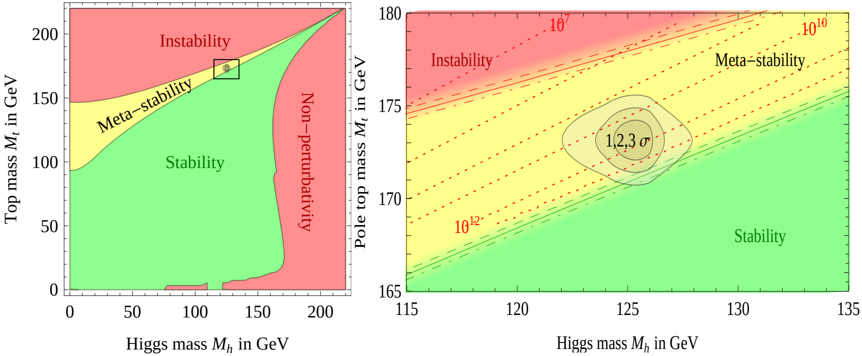

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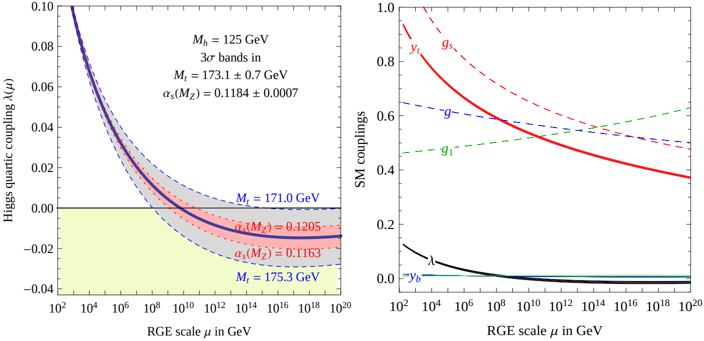

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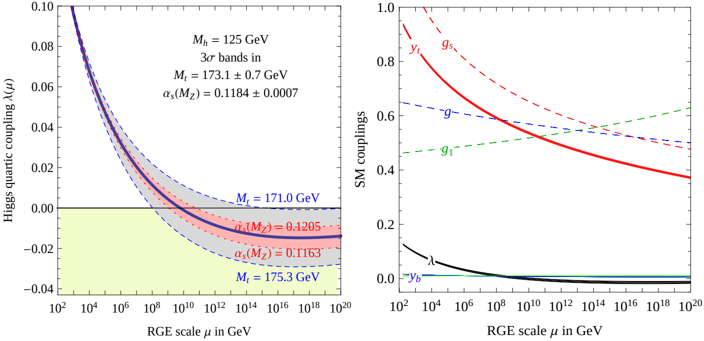
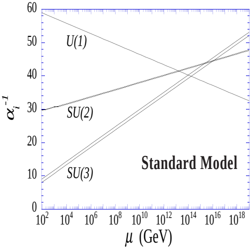


- Could the Higgs field ever have fallen in the correct vacuum?

Hertzberg, arXiv:1210.3624

Open Questions



- Unification of all interactions (?)
- Baryon asymmetrie $\Delta N_B - \Delta N_{\bar{B}} \sim 10^{-9}$
  missing CP violation
- Flavour: three generations
- Tiny neutrino masses: $m_\nu \sim \frac{v^2}{M}$
- Dark Matter:
  - stable
  - only weakly interacting
  - $m_{DM} \sim 100\,$GeV
- Quantum theory of gravity
- Cosmic inflation
- Cosmological constant

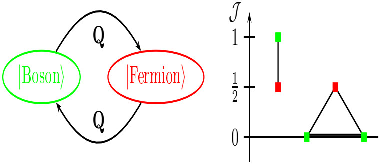
Galaxy Cluster Abell 520
HST WFPC2 • CFHT • CXO

NASA, ESA, CFHT, CXO, M.J. Jee (University of California, Davis), and A. Mahdavi (San Francisco State University) STScI-PRC12-10a

Supersymmetry

Spin-Statistics: M_H stabilized to all orders

connects space-time & gauge symmetries



Partner particles shifted by half-interger in spin

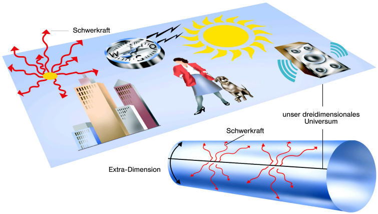
Grand Unification: weak interactions to very high scales

R-Parity: Dark Matter

Extra Dimensions

Hierarchy problem solved by elimination of hierarchy

Higher-dimensional space-time symmetry



Partner particles shifted by integer in spin

Possible strong interactions at TeV scale

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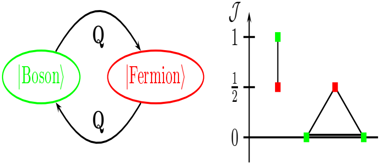

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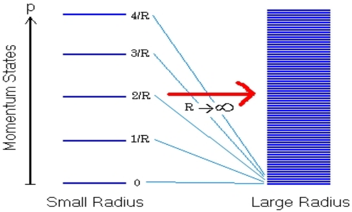

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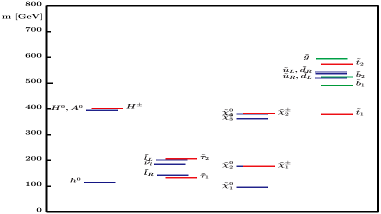

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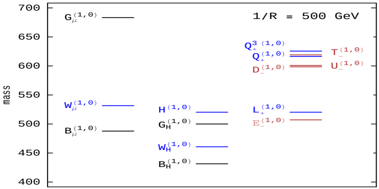

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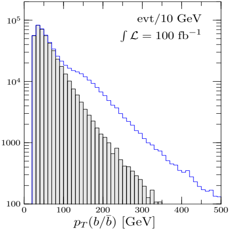


Decay products of heavy particles:

- high-p_T Jets
- many hard leptons

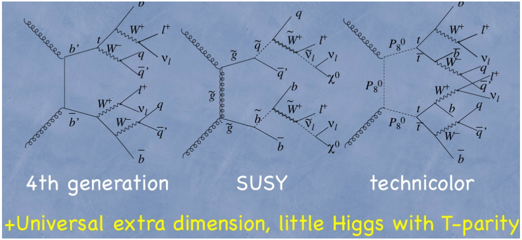
Production of colored particles

weakly interacting particles only in decays

Dark Matter ⇔ discrete parity (R, T, KK)

- only pairs of new particles ⇒ high energies, long decay chains
- Dark Matter ⇒ large missing energy in detector ($\not{E}_T$)

Different Models/Decay Chains — same signatures



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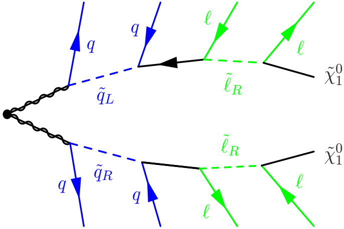

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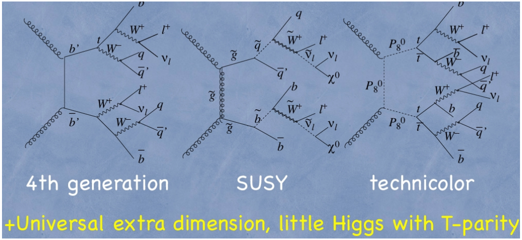
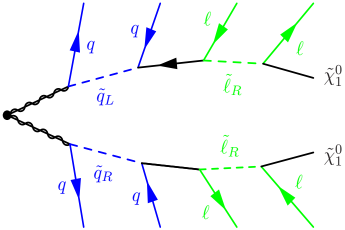


4th generation SUSY technicolor

+Universal extra dimension, little Higgs with T-parity

Search for New Particles



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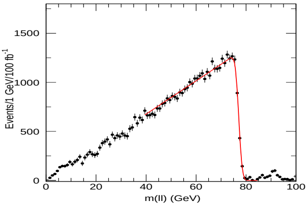
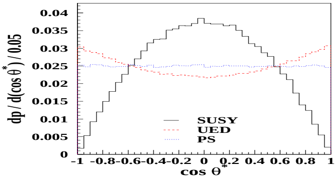
Mass of new particles: end points of decay spectra





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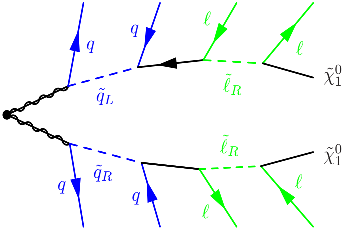

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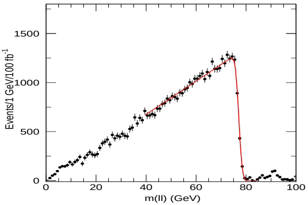
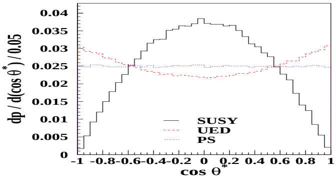
Spin of new particles: Spin of new particles: angular correlations, . . .





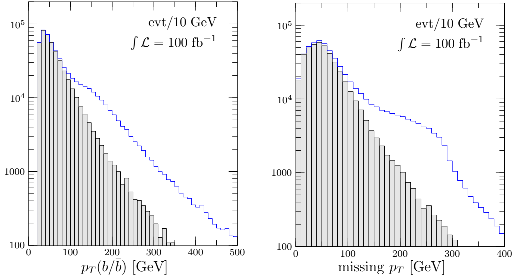
LHC Warm-Up: Sbottom Production

Hagiwara/…/JRR/…, PRD 73 (2006) 055005

$\tilde{b}_1$ production with subsequent decay $\tilde{b}_1 \to \tilde{\chi}^0_1 b$

Process $A_1 A_2 \to P^{(*)} \to F_1 F_2$, 3 different steps:

Narrow Width (NWA)	$\sigma(A_1 A_2 \to P) \times \mathrm{BR}(P \to F_1 F_2)$
Breit-Wigner	$\sigma(A_1 A_2 \to P) \times \frac{M_P^2 \Gamma_P^2}{(s - M_P^2)^2 + \Gamma_P^2 M_P^2} \times \mathrm{BR}(P \to F_1 F_2)$
Full matrix element	$\sigma(A_1 A_2 \to F_1 F_2)$



$pp \to b\bar{b}\tilde{\chi}^0_1\tilde{\chi}^0_1$

Main background:
$gg \to b\bar{b}\nu\bar{\nu}$

Signal jets harder

LHC Warm-Up: Sbottom Production

Hagiwara/…/JRR/…, PRD 73 (2006) 055005

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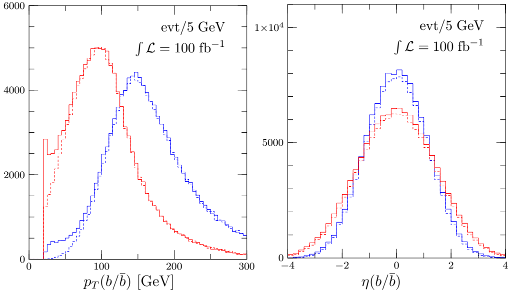


PS: Harder jet more central

Off-shell effects ($b\bar{b}Z^*$): only for low $p_{T,b}$ ⟶ cut out

Not generally guaranteed

ISR: Bottom Jet Radiation

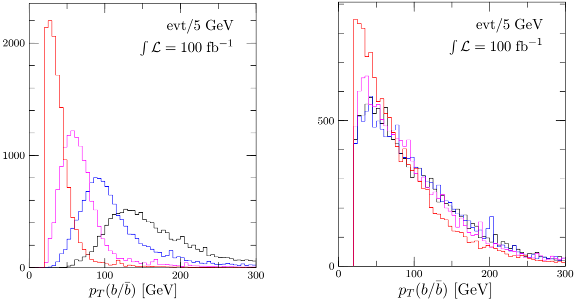
Hagiwara/. . . /JRR/. . . , PRD 73 (2006) 055005

$g \to b\bar{b}$-Splitting, b-ISR as combinatorial background

$pp \to \tilde{\chi}_1^0\tilde{\chi}_1^0 b\bar{b}b\bar{b}$: 32112 diagrams, 22 color flows, ~ 4000 PS channels

$\sigma(pp \to b\bar{b}\tilde{\chi}_1^0\tilde{\chi}_1^0) = 1177\,\text{fb} \quad \longrightarrow \quad \sigma(pp \to b\bar{b}b\bar{b}\tilde{\chi}_1^0\tilde{\chi}_1^0) = 130.7\,\text{fb}$

Forward discrimination of ISR and decay-b jets difficult:



Only the most forward b jet is softer

ISR: Bottom Jet Radiation

Hagiwara/…/JRR/…, PRD 73 (2006) 055005

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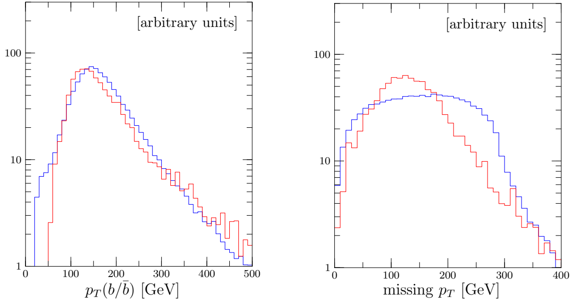
Only small differences in $p_{T,b}$, PDF: maximum at a smaller value



shifted to smaller $\not{p}_T$: light particles balance out the event

WHIZARD

Kilian/Ohl/JRR: DESY/Freiburg/Siegen/Würzburg, hep-ph/0102195, EPJC 71 (2011) 1742

- Multi-Purpose event generator for collider and astroparticle physics
- Acronym: **W**, **HI**ggs, **Z**, **A**nd **R**espective **D**ecays (deprecated)
  - Fast adaptive multi-channel Monte-Carlo integration
  - Very efficient phase space and event generation
  - Optimized/-al matrix elements
    uses the color flow formalism Kilian/Ohl/JRR/Speckner, JHEP 1210 (2012) 022
  - Recent version: 2.1.1 (18.09.2012) [2.2.0 will come Apr 8, 2013]
    `http://projects.hepforge.org/whizard`
  - Parton shower ($k^\perp$-ordered and analytic) Kilian/JRR/Schmidt/Wiesler, JHEP 1204 (2012) 013
  - Underlying Event: preliminary version
  - 2.0 Features: ME/PS matching, cascades, shared library
  - Working on: NLO automation, general Lorentz structures etc.
- Interface to `FeynRules` Christensen/Duhr/Fuks/JRR/Speckner, EPJC 72 (2012) 1990
- Versatile input language: SINDARIN

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- Focus: LHC, ILC, CLIC, SM, QCD, BSM

MODEL TYPE	with CKM matrix	trivial CKM
QED with e, μ, τ, γ	–	`QED`
QCD with d, u, s, c, b, t, g	–	`QCD`
Standard model	`SM_CKM`	`SM`
SM with anomalous couplings	`SM_ac_CKM`	`SM_ac`
SM with anomalous top couplings	—	`SM_top`
SM with K matrix	—	`SM_KM`
MSSM	`MSSM_CKM`	`MSSM`
MSSM with Gravitinos	—	`MSSM_Grav`
NMSSM	`NMSSM_CKM`	`NMSSM`
extended SUSY models	—	`PSSSM`
Littlest Higgs	—	`Littlest`
Littlest Higgs with ungauged $U(1)$	—	`Littlest_Eta`
Littlest Higgs with T parity	—	`Littlest_Tpar`
Simplest Little Higgs (anomaly free)	—	`Simplest`
Simplest Little Higgs (universal)	—	`Simplest_univ`
UED	—	`UED`
3-Site Higgsless Model	—	`Threeshl`
Noncommutative SM (inoff.)	—	`NCSM`
SM with Z'	—	`Zprime`
SM with Gravitino and Photino	—	`GravTest`
Augmentable SM template	—	`Template`

easy to
implement new models

- Interface to `FeynRules` Christensen/Duhr/Fuks/JRR/Speckner, EPJC 72 (2012) 1990
- Versatile input language: SINDARIN

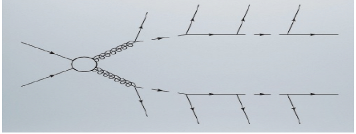
I: Off-Shell Effects

Confusions from Off-Shell Effects: Fat Gluinos

- SUSY: weakly coupled + discrete parity $\Longrightarrow$ Narrow resonances
- Exception: some Higgses ... and **Gluino**
- Width-to-mass ratio $\gamma := \Gamma/M \sim$ few to 15-20 %
  Theoretical upper limit $\gamma \sim 32\%$ (without invisible or exotic decays)
- Example realization: GMSB $\boxed{M_{\tilde{g}} \sim 2\,\text{TeV} \qquad \Gamma_{\tilde{g}} \sim 240\,\text{GeV}}$
- Plan: scan over “fat gluinos” in “full” simulation
- Comparison between SUSY vs. UED
- Generic scan over 5 values: $\gamma \in \{0.5\%, 2.5\%, 5\%, 10\%, 15\%\}$
- Look for impact on mass and spin observables

Gluinos beyond factorization

- Standard Gluino Cascade: $2 \to 10$ Numerically challenging (PS!!!)



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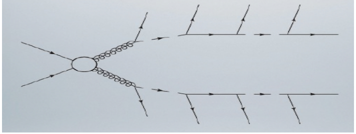
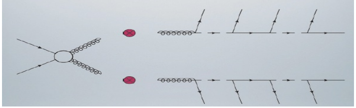


- Factorization in Narrow-Width-Approximation (NWA)



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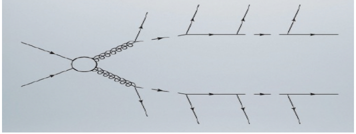

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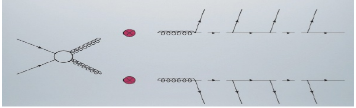
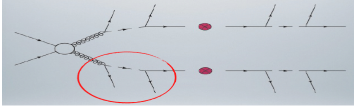


- Trade-off accuracy vs. speed



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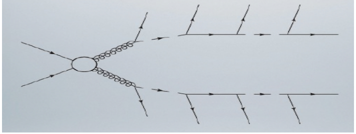

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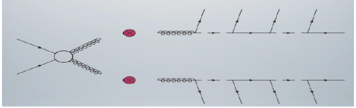

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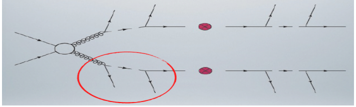


- ▶ Simulate production and first decay with full matrix elements
- ▶ Factorize additional decays with NWA

Simulation Setup

- Parton level studies with WHIZARD Kilian/Ohl/JRR, EPJC 71 (2011) 1742
- Investigation of ISR, combinatoris, detector effects later

  Pietsch/JRR/Sakurai/Wiesler, JHEP 1207 (2012) 148
- For each point (UED and SUSY) normalized sets (5k events)

  Corresponds roughly to event numbers for 300 fb^{-1}

  To study statistics vs. systematics some samples for 25k events
- pMSSM19 benchmark scenario

M_1	M_2	M_3	A_t	A_b	A_τ	μ	M_A	$m_{\tilde{l}_L}$	$m_{\tilde{\tau}_L}$
150	250	1200	4000	4000	0	1500	1500	1000	1000

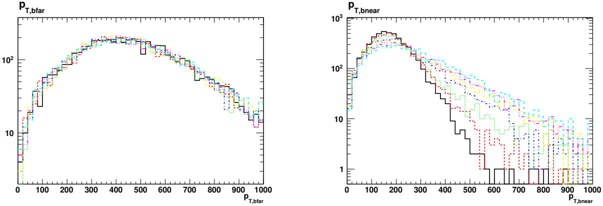
$m_{\tilde{l}_R}$	$m_{\tilde{\tau}_R}$	$m_{\tilde{q}_L}$	$m_{\tilde{q}_L^3}$	$m_{\tilde{q}_R^u}$	$m_{\tilde{q}_R^d}$	$m_{\tilde{t}_R}$	$m_{\tilde{b}_R}$	$\tan\beta$	
200	1000	1000	1000	1000	1000	4000	1000	10	

- … and similar datapoint for UED (for spin determination)
- Setup of (exclusive) decay chains

$$\begin{aligned} \tilde{g}[1] &\quad \to b\tilde{b}_i \to b\bar{b}\tilde{\chi}_2^0 \to b\bar{b}l^\pm\tilde{l}_R^\mp \to b\bar{b}l^\pm l^\mp\tilde{\chi}_1^0 \\ \tilde{g}[2] &\quad \to d\tilde{d}_L \to d\bar{d}\tilde{\chi}_1^0 \end{aligned}$$

Mass determination and "fat" gluinos

- Decay chain: $\tilde{g}[1] \to b\tilde{\bar{b}}_i \to b\bar{b}\tilde{\chi}_2^0 \to b\bar{b}l^\pm\tilde{l}_R^\mp \to b\bar{b}l^\pm l^\mp\tilde{\chi}_1^0$
- Far b jet not affected, but the near one! black: 0.5%, red: 2.5%, green: 5%, blue: 10%, yellow: 15%



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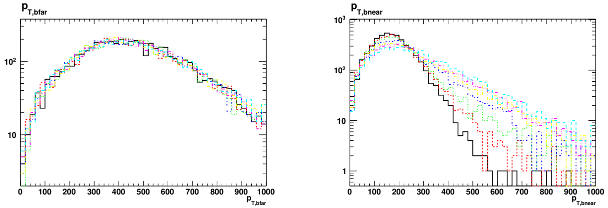
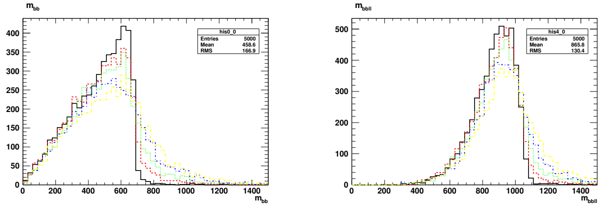


- Mass edges: . . . two b jets . . . or . . . two bs, two leptons

$$(m_{bb}^{max})^2 = \frac{(m_{\tilde{g}}^2 - m_{\tilde{b}}^2)(m_{\tilde{b}}^2 - m_{\tilde{\chi}_2}^2)}{m_{\tilde{b}}^2} = 680 \text{ GeV} \qquad (m_{bb\ell\ell}^{max})^2 = 1093 \text{ GeV}$$



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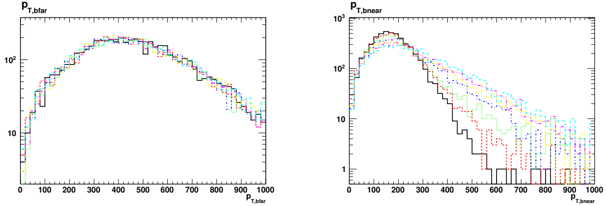

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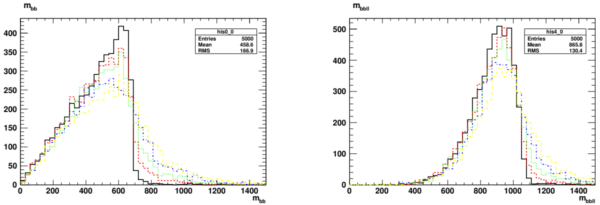

- **Uncertainties of several hundreds of GeV**

Numerical Endpoint Estimation: Edge-to-bump method

- Trying to find edges by fitting lines very human-biased and error-prone
- Idea: do a naive kink fit $\mathcal{O}(1000)$ times
- Edge-to-bump method Curtin, 2012

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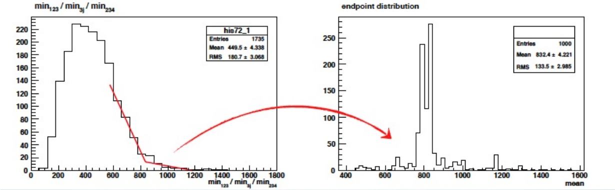

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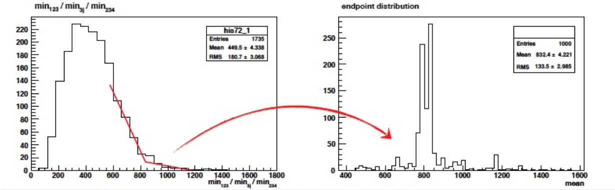
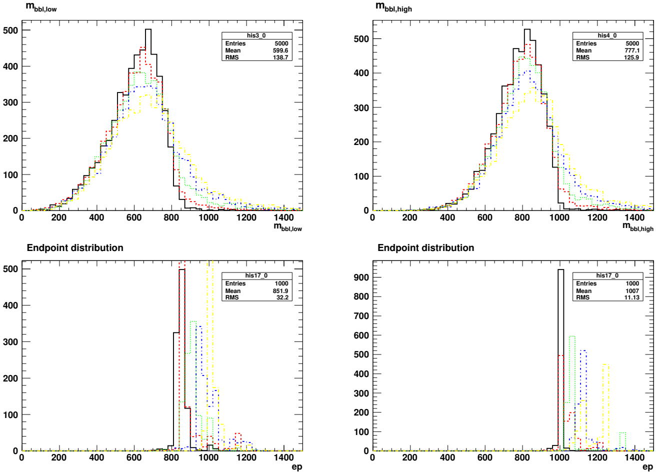


- Analyze resulting distribution of fit values
- Distribution of values measure/estimate for uncertainty

More Examples

- $m_{bb\ell}^{low}$, $m_{bb\ell}^{high}$: two endpoints in $m_{bb\ell}$



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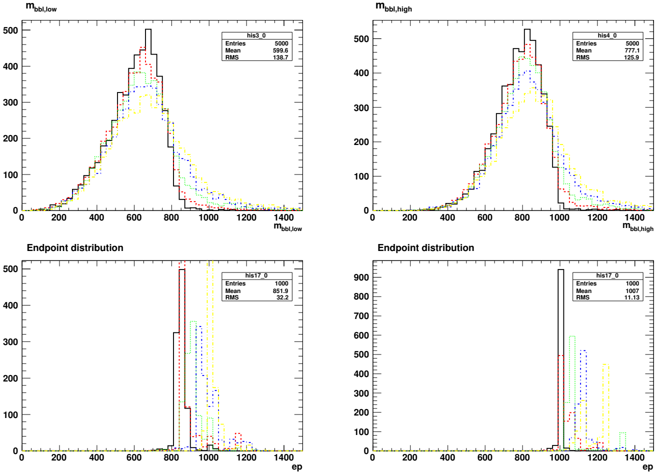

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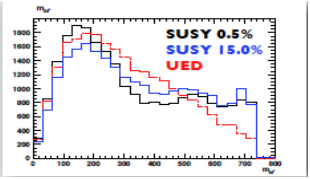
- Endpoints severely degraded (at parton level!!)

Spin Determination (I)

- **Method I**: Shape asymmetry of $m_{b\ell}$

$$\boxed{A^{\pm}[m_{b\ell}] = \frac{d\sigma/dm_{b\ell^+} - d\sigma/dm_{b\ell^-}}{d\sigma/dm_{b\ell^+} + d\sigma/dm_{b\ell^-}}}$$

Alves/Eboli/Plehn, 2006



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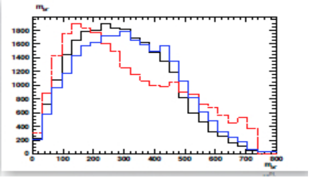

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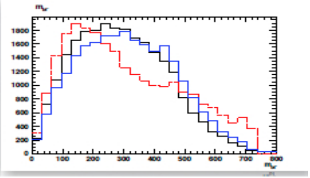

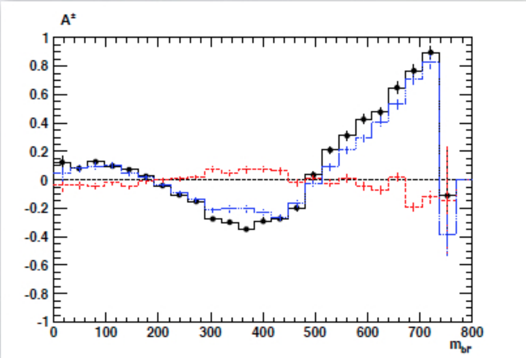

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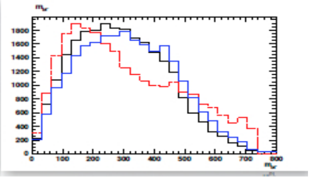

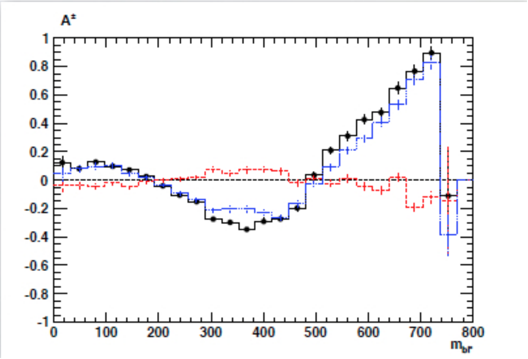

- **Shape asymmetry not affected by fat gluino!**

Spin Determination (II)

- **Method II**: Angular correlations and asymmetries

1. $$\boxed{\cos\theta^*_{jj} = \tanh\left(\frac{\Delta\eta_{jj}}{2}\right)}$$

Moortgat-Pick/Rolbiecki/Tattersall, 2011

2. $$\boxed{\Delta\phi_{bb} = |\phi(b_1) - \phi(b_2)|}$$

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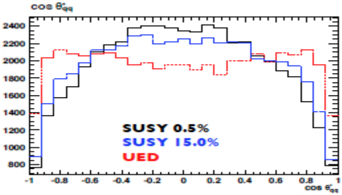

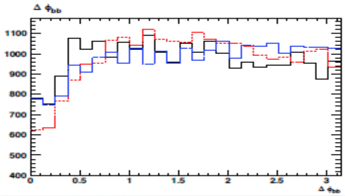

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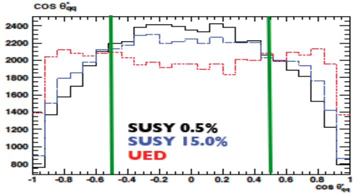

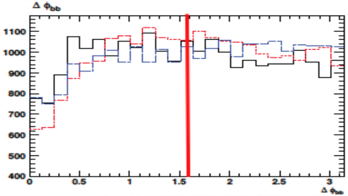

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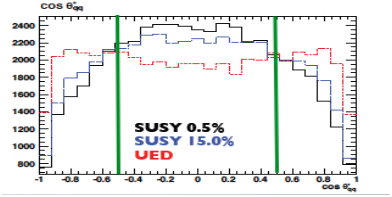

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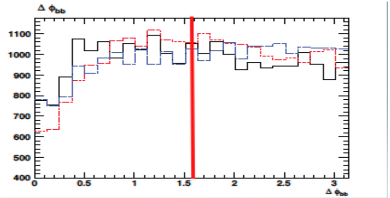

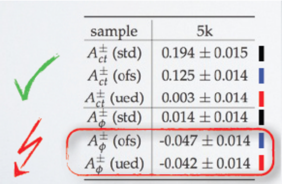

sample	5k	
$A^\pm_{ct}$ (std)	0.194 ± 0.015	■
$A^\pm_{ct}$ (ofs)	0.125 ± 0.014	🟦
$A^\pm_{ct}$ (ued)	0.003 ± 0.014	🟥
$A^\pm_{\phi}$ (std)	0.014 ± 0.014	■
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II. Combinatorics

Generic Backgrounds

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- Dijet itself suffers a lot from both backgrounds
- Motivation: Study fully inclusive dijet measurement

Pietsch/JRR/Sakurai/Wiesler, JHEP 1207 (2012) 148

Simplified Models and Scenarios

- Sleptons, Higgsinos, third generation decoupled
- Higgs at 125 GeV $\Rightarrow$ heavy scalars, light gauginos
- Gauginos fix, vary squark masses in three scenarios

$m_{\tilde{g}}$	$m_{\tilde{w}}$	$m_{\tilde{b}}$
1200 GeV	400 GeV	200 GeV

Scenario	**A**	**B**	**C**
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A
- Small mass difference
- Associated production dominant
- Squark decay to light gauginos
- One signal gluino / squark bg

B
- Moderate mass difference
- Associated and pair production
- Squark decay also to gluino
- Two signal gluinos / many jets

C
- Squarks decoupled
- Pair production only
- Two signal gluinos
- Lowest combinatorial bg

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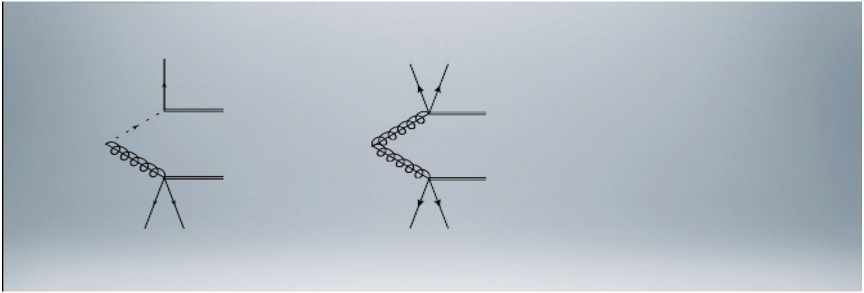
- Baseline selection CMS-SUS-10-005
  - $H_T > 800$ GeV
  - $E_T^{miss} > 200$ GeV
  - $\Delta\phi(j_{1,2}, E_T^{miss}) > 0.5$

Event topologies



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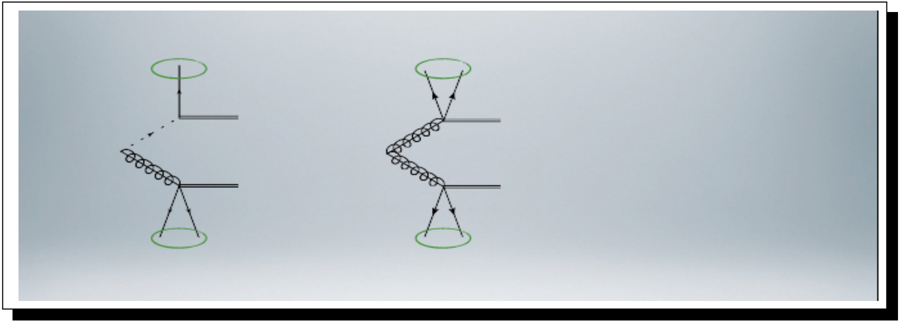

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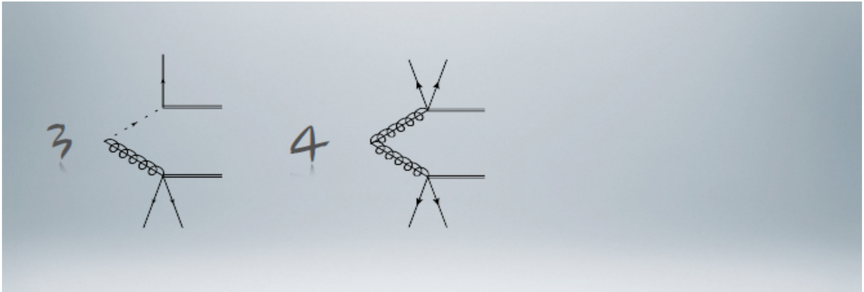

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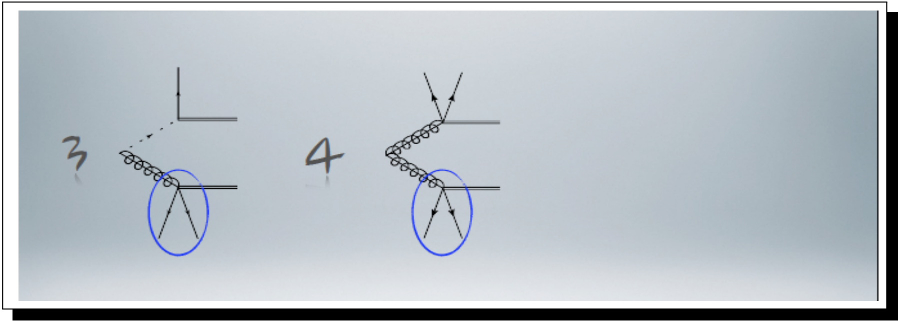

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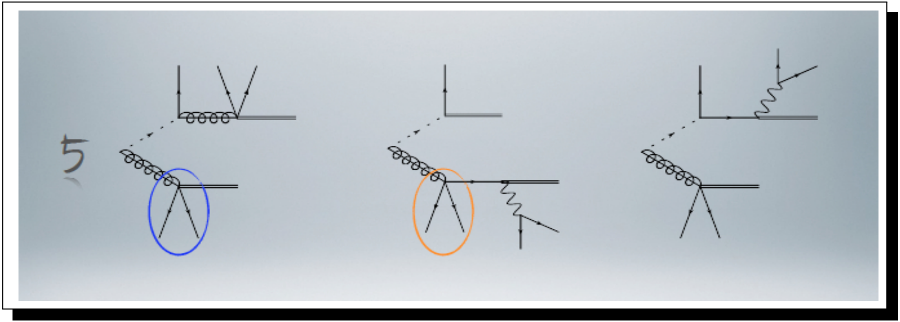
ONLY bino edges in 3-4 partons

Event topologies



- Couting number of visible decay products (parton level)

BOTH bino and wino edges

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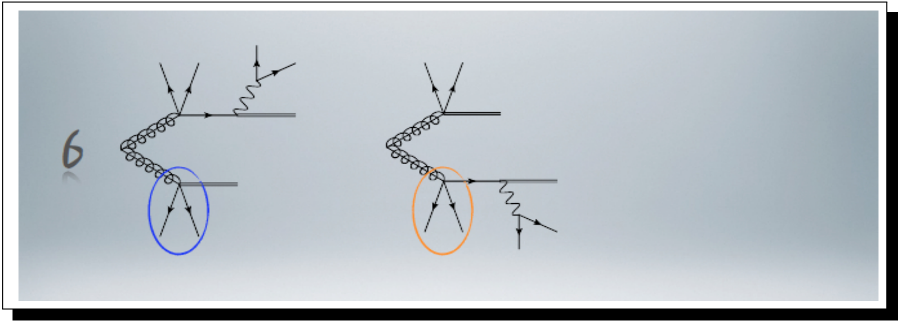

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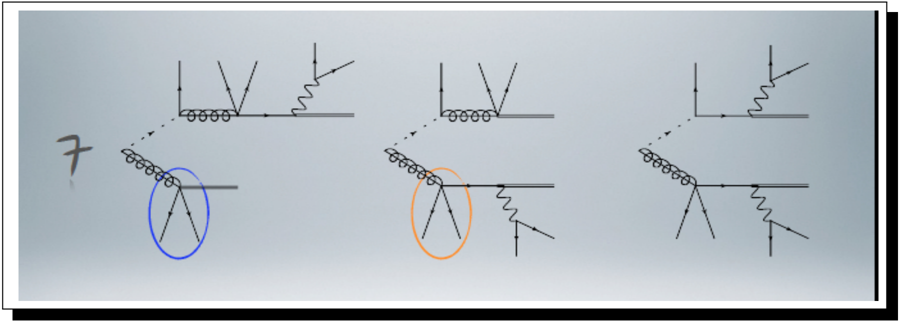

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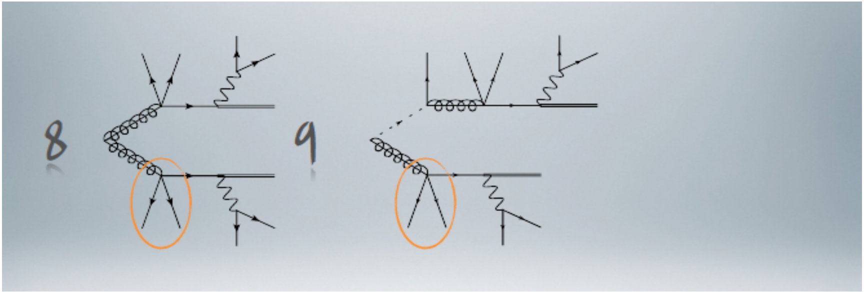

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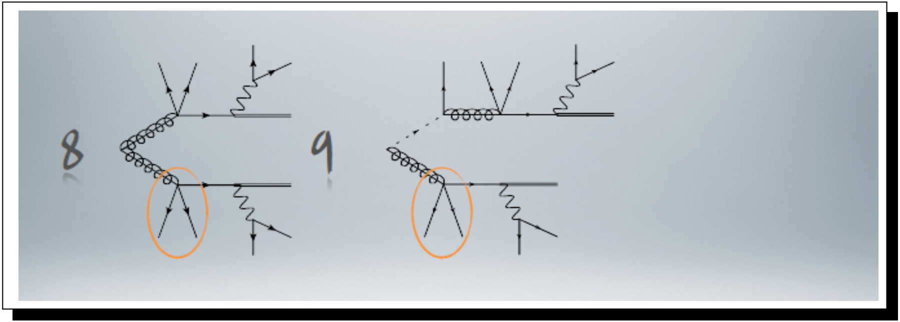


- Couting number of visible decay products (parton level)

ONLY bino edges in 3-4 partons

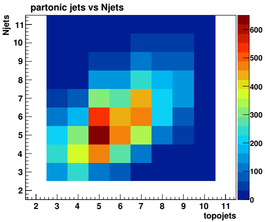
- Use selection criterion

≤ 4 particles	$\longleftrightarrow$	bino edge
≥ 8 particles	$\longleftrightarrow$	wino edge

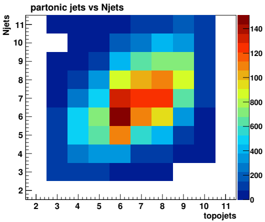
Parton-Jet Correspondence

- This was parton level? What about hadron level?

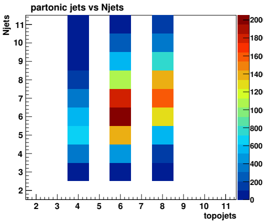
A



B



C



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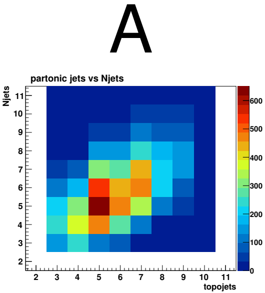

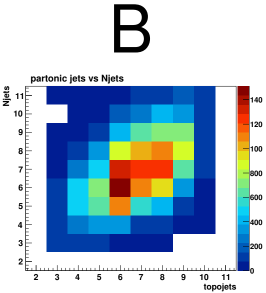

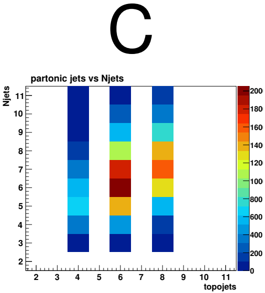

⇒ Substantial correlation of parton and detector level jets

- Refine selection criteria

Bino: 4-5 jets lepton veto

Wino: $\geq$ 6 jets one lepton

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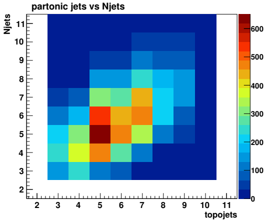

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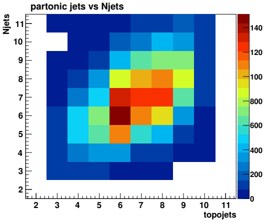

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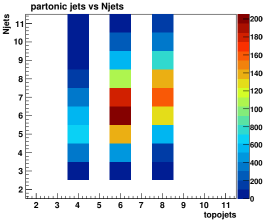


$\Rightarrow$ Substantial correlation of parton and detector level jets

- Refine selection criteria

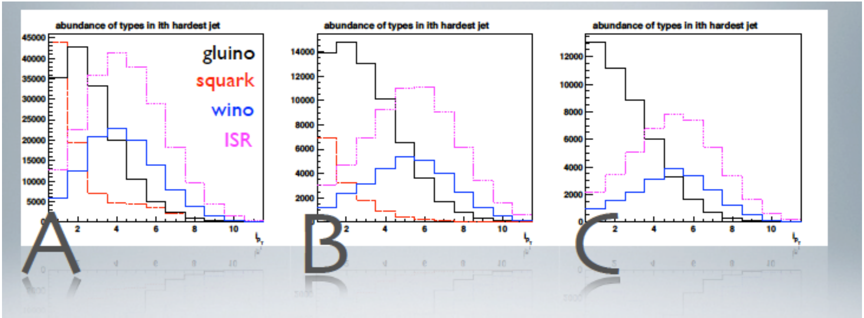
Bino: 4-5 jets lepton veto

Wino: $\geq$ 6 jets one lepton

- Lepton indicates presence of wino
- Fewer jets $\Rightarrow$ less combinatorics

Origin of Jets

- Abundances of jet origins in the ith hardest jet



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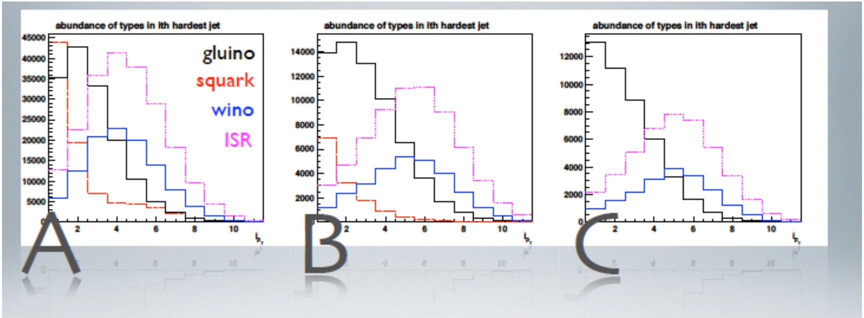


- Gluino jet very likely in the first 3 bins
- Severe squark contamination for $i = 1$ in scenario A & B
  - Define new variables
  - min procedure reduces impact on combinatorics

$$\begin{aligned} min_{3j} &= \min_{k=1,2} m_{3,k} \\ min_{123} &= \min_{i,j=1,2,3} m_{i,j} \\ min_{234} &= \min_{i,j=2,3,4} m_{i,j} \end{aligned}$$

Compare to existing methods

- Hemisphere method CMS TDR 2007
  1. Hemisphere algorithm to divide event
  2. Combine two hardest objects from each side

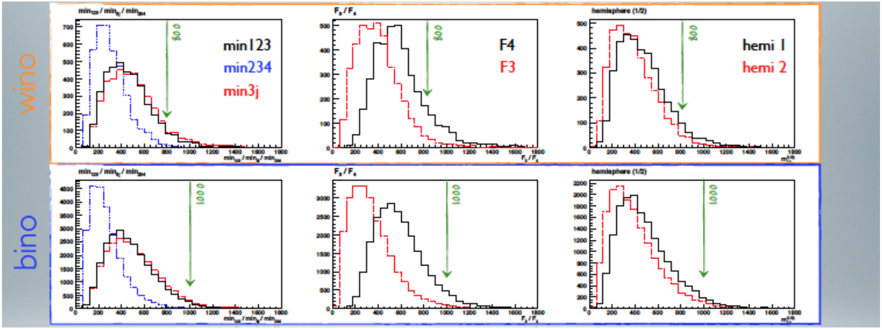
$$\boxed{m_{12}^{1/2}}$$

- Topology method (for exclusive 4 jets + MET) Bai/Cheng, 2011
  - Dijet variables for identification of topology 3+1 or 2+2

$$F_3(p1,p2,p3,p4) = m_{k,l}, \quad \text{for } \epsilon_{ijkl} \neq 0 \text{ and } \max_{r,s=1,\ldots,4} \{m_{r,s}\}$$

$$F_4(p1,p2,p3,p4) = \min_{i,j=1,\ldots,4} \{\max(m_{i,j}, m_{k,l})\}, \quad \epsilon_{ijkl} \neq 0$$

Scenario A



- Bino selection: slight overshoot of true endpoints
- Wino selection: diffuse endpoints & a visible kink
- min and hemisphere variables give best results

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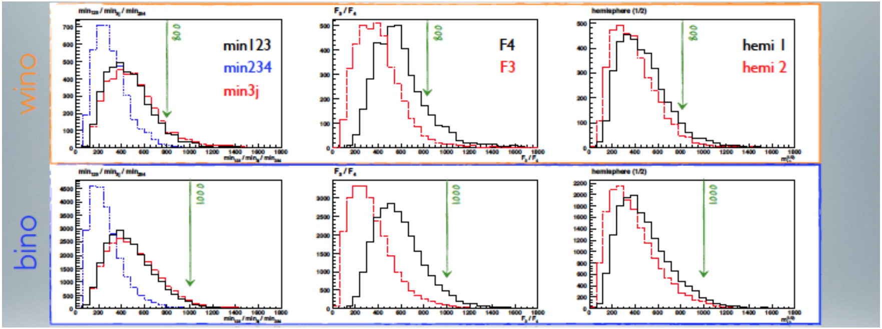

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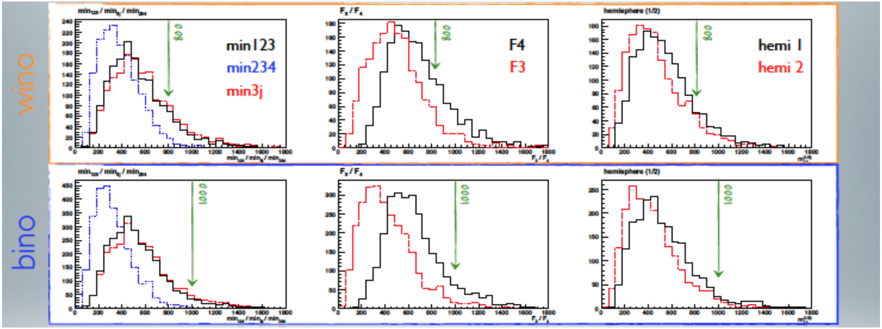
Scenario B



- Bino selection: shallow endpoints, only vague kink structure
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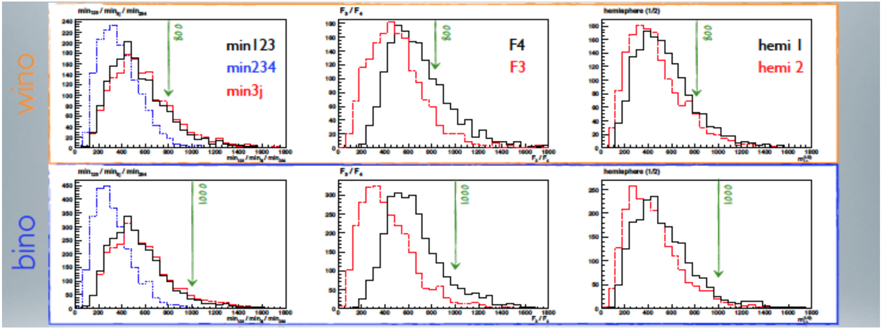
- min_{234} (wino) and hemi I (bino) work best

Scenario B



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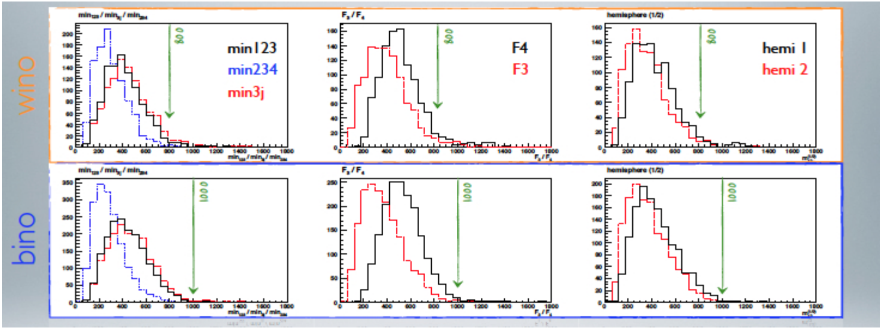
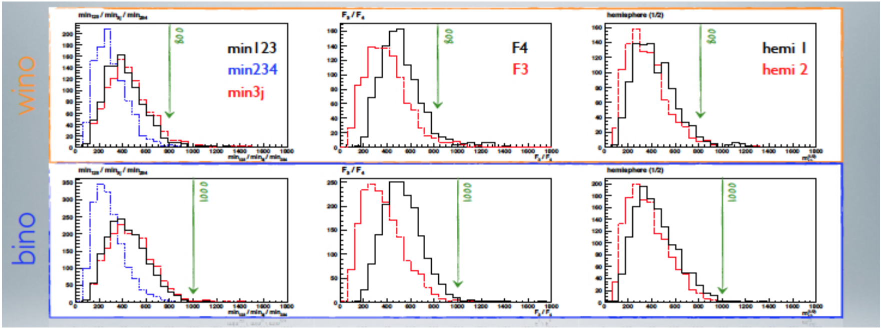


- Bino selection: clear endpoints, slight underestimation
- Wino selection: solid kinks, only few events beyond true endpoint
- all variables promising, good control of backgrounds

Scenario C



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Numerical Endpoint Estimation

Pietsch/JRR/Sakurai/Wiesler, JHEP 1207 (2012) 148

endpt.	min_{123}	min_{234}	min_{3j}	$m_{12}^{(1)}$	$m_{12}^{(2)}$	F_3	$F4$
scenario A							
bino	1106 ± 52	570 ± 14	1125 ± 106	822 ± 21	**1012 ± 104**	686 ± 33	1191 ± 132
wino	908 ± 83	665 ± 34	948 ± 99	932 ± 31	**780 ± 26**	**794 ± 33**	1031 ± 53
scenario B							
bino	**986 ± 36**	773 ± 147	**1028 ± 34**	**1010 ± 6**	794 ± 49	766 ± 25	1046 ± 66
wino	895 ± 23	**748 ± 68**	892 ± 18	958 ± 10	**819 ± 47**	911 ± 51	928 ± 37
scenario C							
bino	812 ± 24	545 ± 8	**921 ± 37**	816 ± 29	721 ± 90	708 ± 22	**894 ± 57**
wino	778 ± 23	577 ± 19	**804 ± 6**	769 ± 47	764 ± 14	708 ± 38	**793 ± 7**

- Accurate estimates in all scenarios possible
- slight underestimation for bino in scenario A
- Very important to choose the correct variable!

III. Combinatorics (fake)

Fake combinatorics from exotic particles

- Fake combinatorics: Wrong underlying model assumptions

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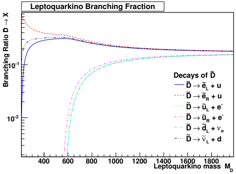
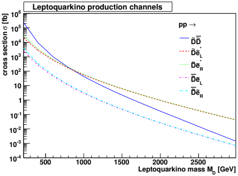
- Chiral Exotics with lepton and baryon number: scalar leptoquarks, SUSY partners: leptoquarkinos





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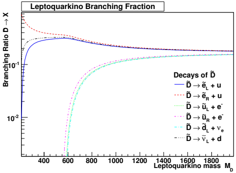
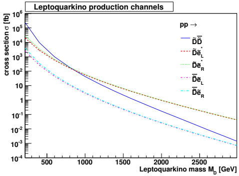
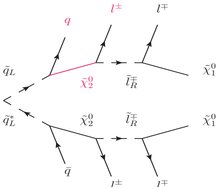
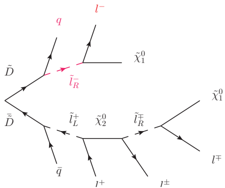




- Identical exclusive final states:



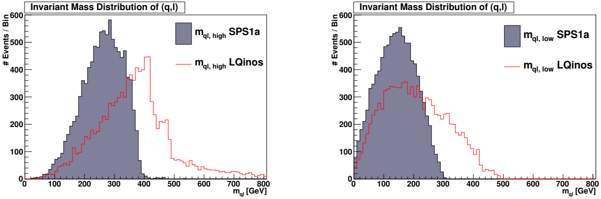


Mass Edges for Leptoquarkinos

JRR/Wiesler, PRD84 (2011) 015012

- Mass edges clearer due to missing spin correlations

$$m_{ql,high} = \max\{m_{ql+}, m_{ql-}\} \qquad m_{ql,low} = \min\{m_{ql+}, m_{ql-}\}$$



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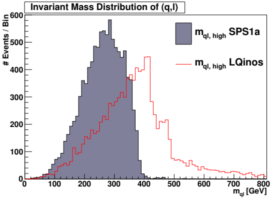
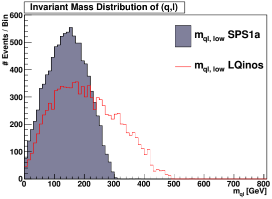
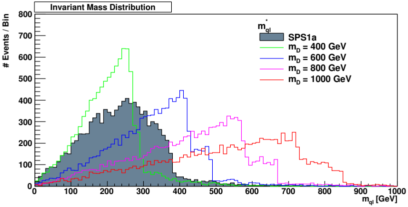




- Combinatorial background: combine softest jet and hardest lepton:

$$m^*_{ql} = m(\min_E\{q_1, q_2\}, \max_E\ \{l^+, l^-\})$$



Discrimination from standard SUSY

JRR/Wiesler, PRD 2011

- Dilepton spectrum: standard SUSY ⇒ same cascade, leptoquarkinos ⇒ different cascades

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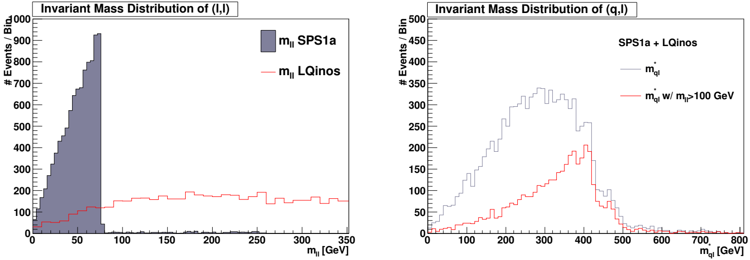
- Dilepton spectrum: standard SUSY ⇒ same cascade, leptoquarkinos ⇒ different cascades
- Cut on kinematic edge in standard dilepton spectra



- S/B estimate, 100 fb^{-1}, 2 OSSF, 2 hard jets, $\not{E}_T$

$m_{\tilde{D}}$	# N(LQino) & N(SUSY)	# N$_{cut}$	S / $\sqrt{\text{S+B}}$
400	8763	5061	54
600	1355	540	15
800	684	102	4
1000	594	24	1

Summary/Conclusions

- New Physics motivated by Hierarchy Problem/Vacuum Stability
- SUSY cascades as standard candles at LHC
- Combinatorial background and smearing from
    - ISR/FSR
    - Combinatorics through presence of two cascades
    - SUSY backgrounds (“signal backgrounds”)
    - Off-shell (and threshold) effects
    - Wrong model assumptions
- Full analysis including all channels/backgrounds with WHIZARD
- Generally trade-off between precision and speed
- Waiting for a signal ...

One Ring to Find them ... One Ring to Rule them Out

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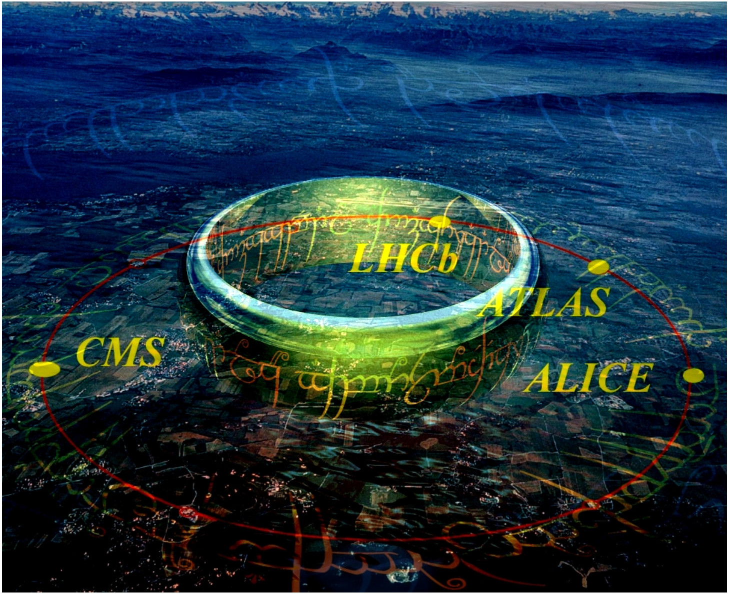

The Gluino – Did we miss the order date!?

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