Determining Masses and Spins of New Particles (with missing energy)

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Outline

- Mass determination
  - M_{T2} and related variables
  - Jet contamination
  - Solving decay chains
  - 'Inclusive' observables
- Spin determination
  - Decay chains
  - Dileptons
  - Three-body decays
  - Cross sections

Mass Determination with ...

- M_{T2} variable
- Jet contamination
- Solving decay chains
- ‘Inclusive’ observables

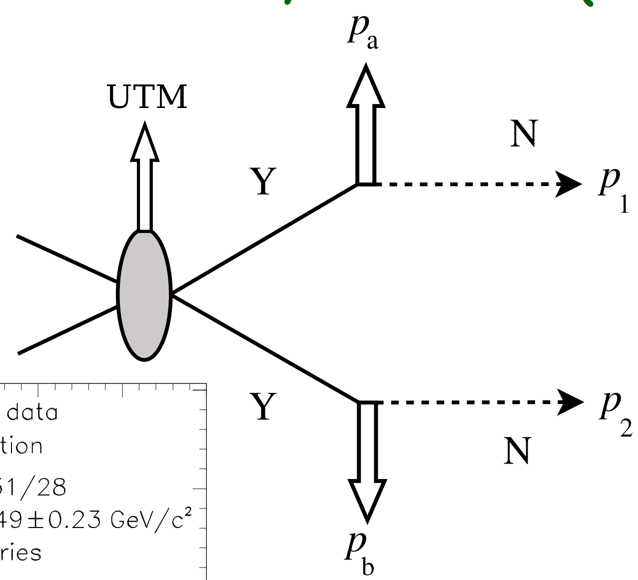
See also: review by Barr & Lester, J.Phys.G 37(2010)123001

Mass determination with M_{T2}

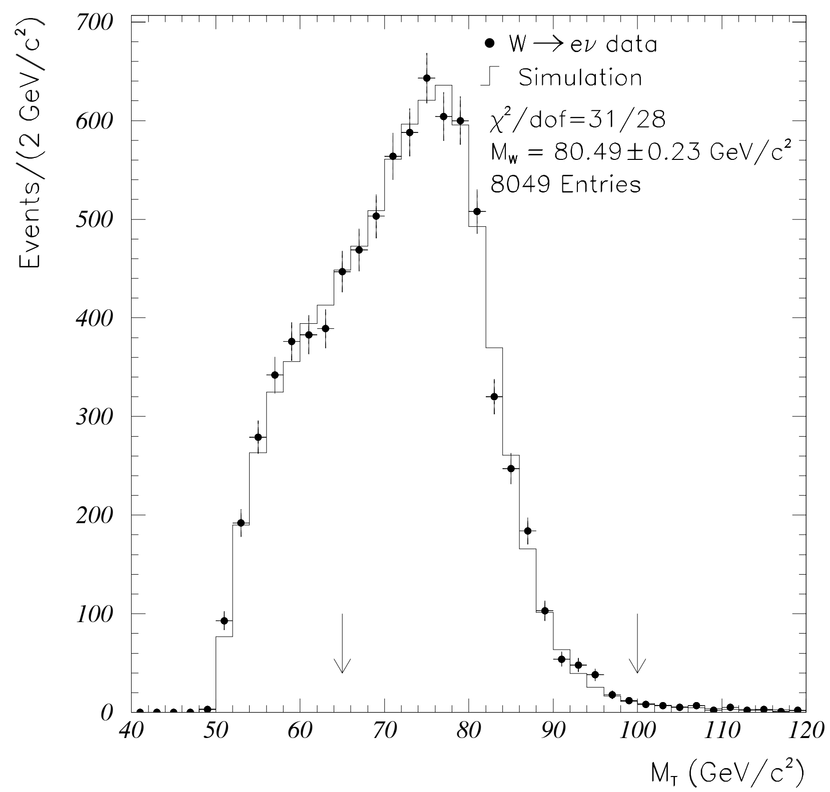
$\mathrm{M_{T2}}$ variable

Lester & Summers, PLB 463(1999)99

- pp→YYX, Y→ aN, Y→ bN
- a,b visible, N invisible
- Transverse mass:



$$m_T^2(\mathbf{p}_T^1,\,\mathbf{p}_T^a;\,\mu_N) = \mu_N^2 + m_a^2$$
$$+2\left(E_T^1 E_T^a - \mathbf{p}_T^1\cdot\mathbf{p}_T^a\right)$$

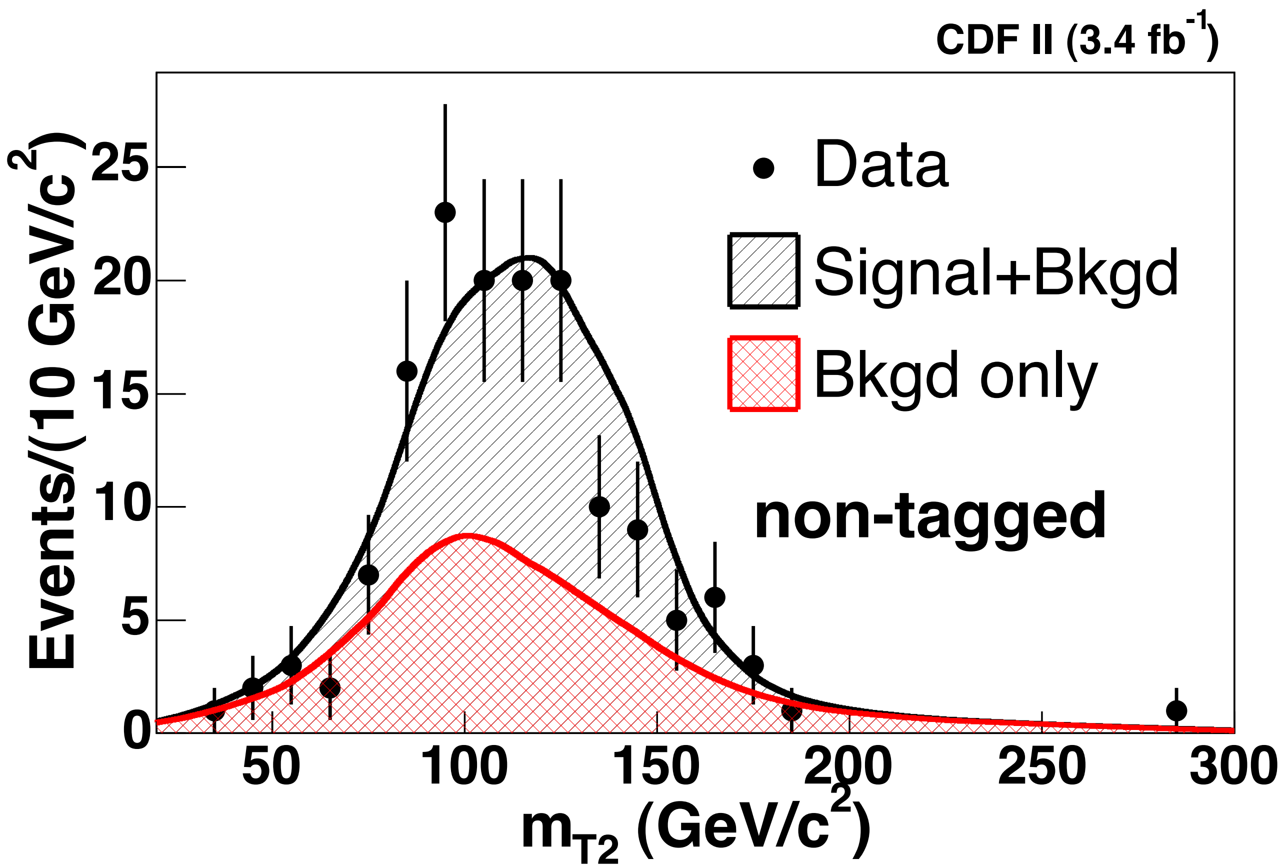


$$m_{T2}^2(\mu_N) \equiv \min_{\mathbf{p}_T^1+\mathbf{p}_T^2=\not{p}_T}\left[\max\{m_T^2(\mathbf{p}_T^1,\,\mathbf{p}_T^a;\,\mu_N),\,m_T^2(\mathbf{p}_T^2,\,\mathbf{p}_T^b;\,\mu_N)\}\right]$$

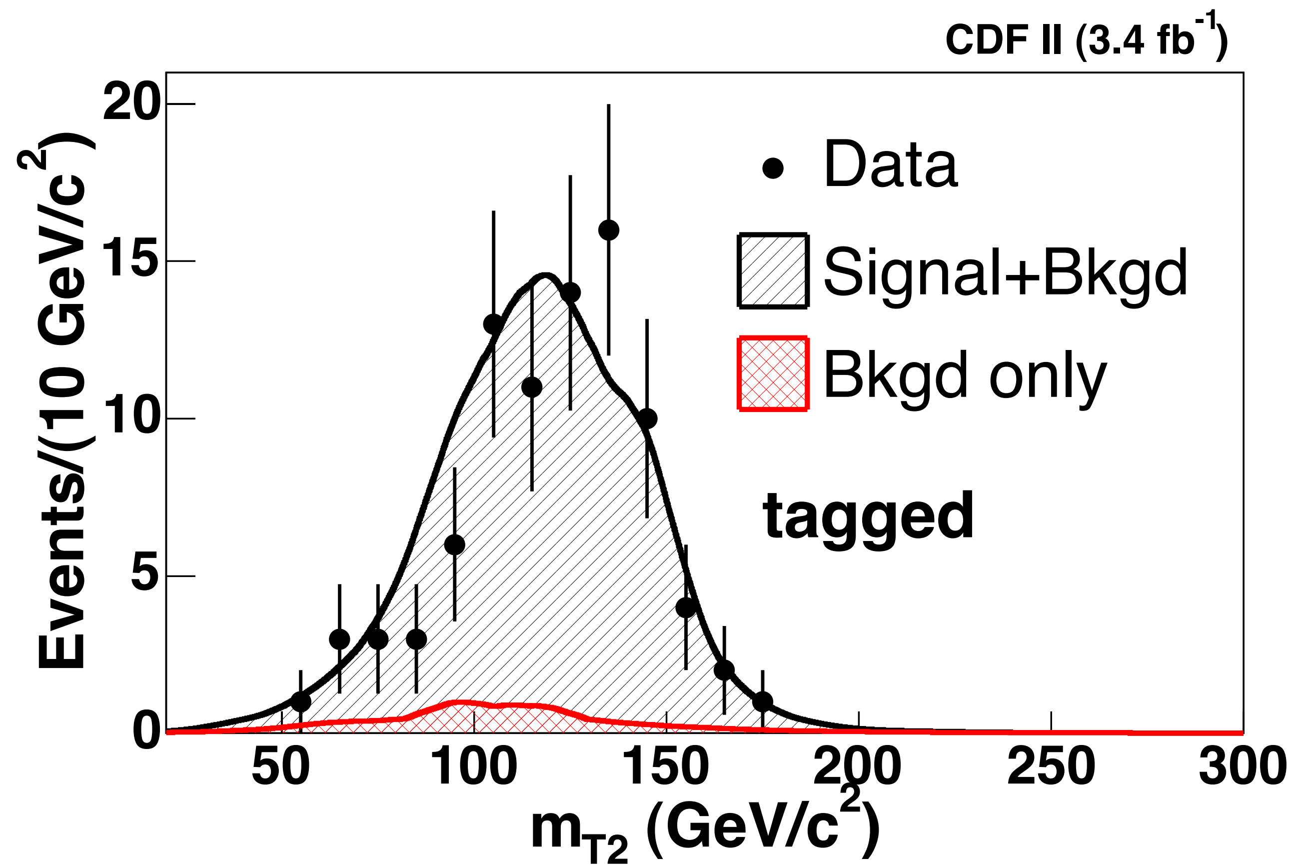
$$\leq m_Y^2 \text{ when } \mu_N = m_N$$

CDF top mass from M_{T2}

non-tagged



b-tagged

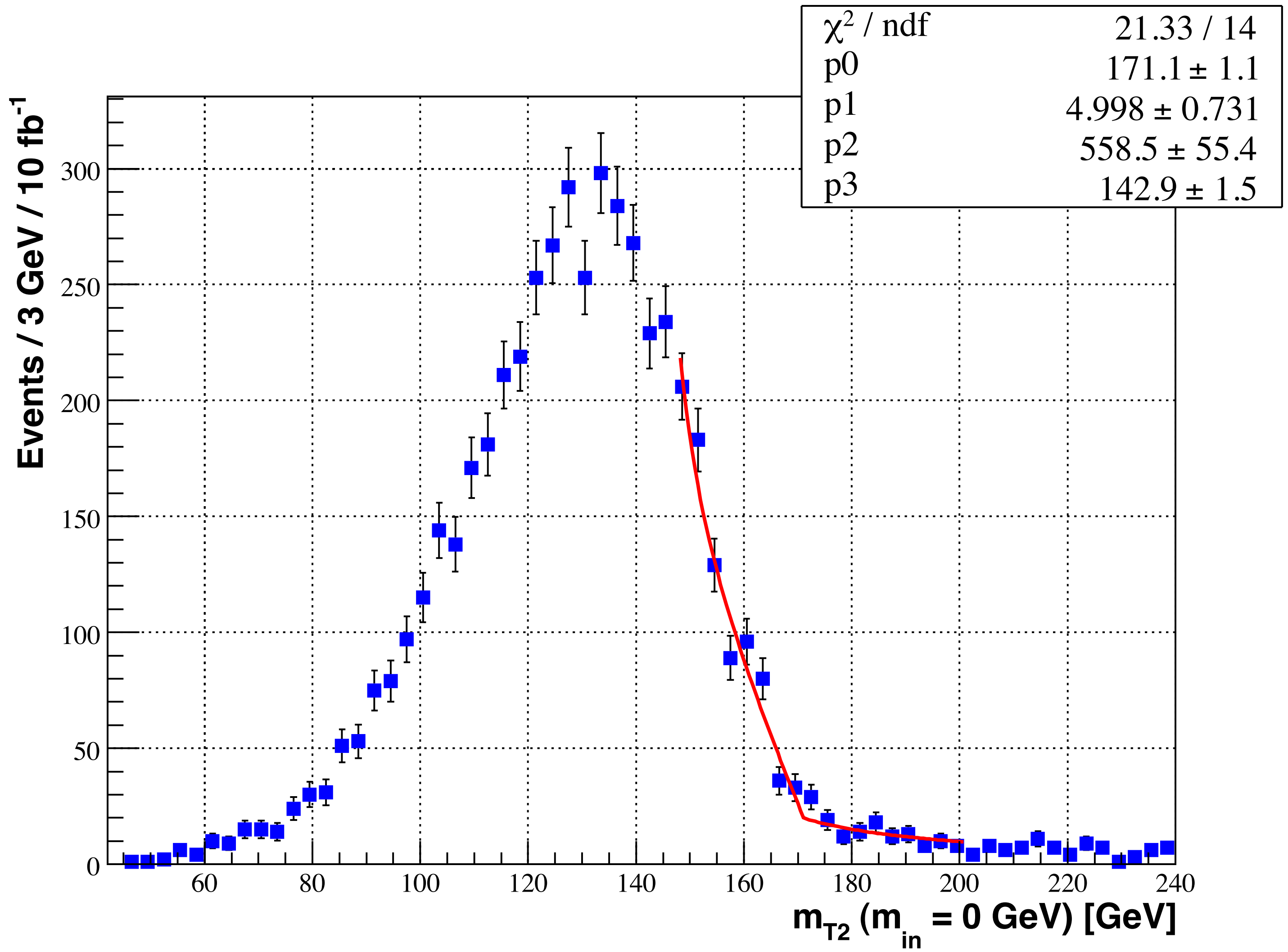


CDF, PRD 81(2010) 031102

- 3.4 fb^{-1} => m_t = 168.0 +5.6/−5.0 GeV (M_{T2} alone)

Top mass from M_{T2} at LHC?

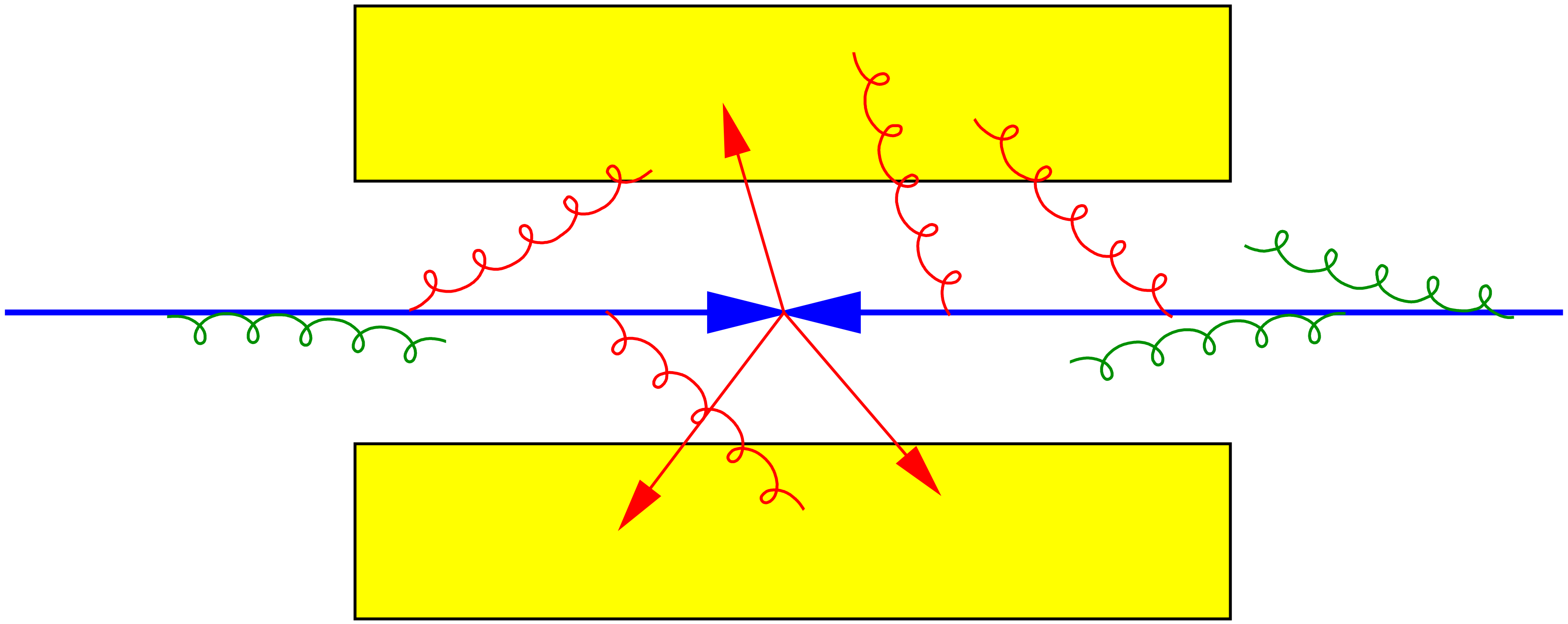
Cho, Choi, Kim & Park, PRD 78(2008)034019



- Input mass 170.9 GeV; PYTHIA+PGS; b-tagging 50%
- 10 fb^{-1} @ LHC (14 TeV) => m_t = 171.1 +/- 1.1 GeV

Jet contamination

Initial-state QCD radiation



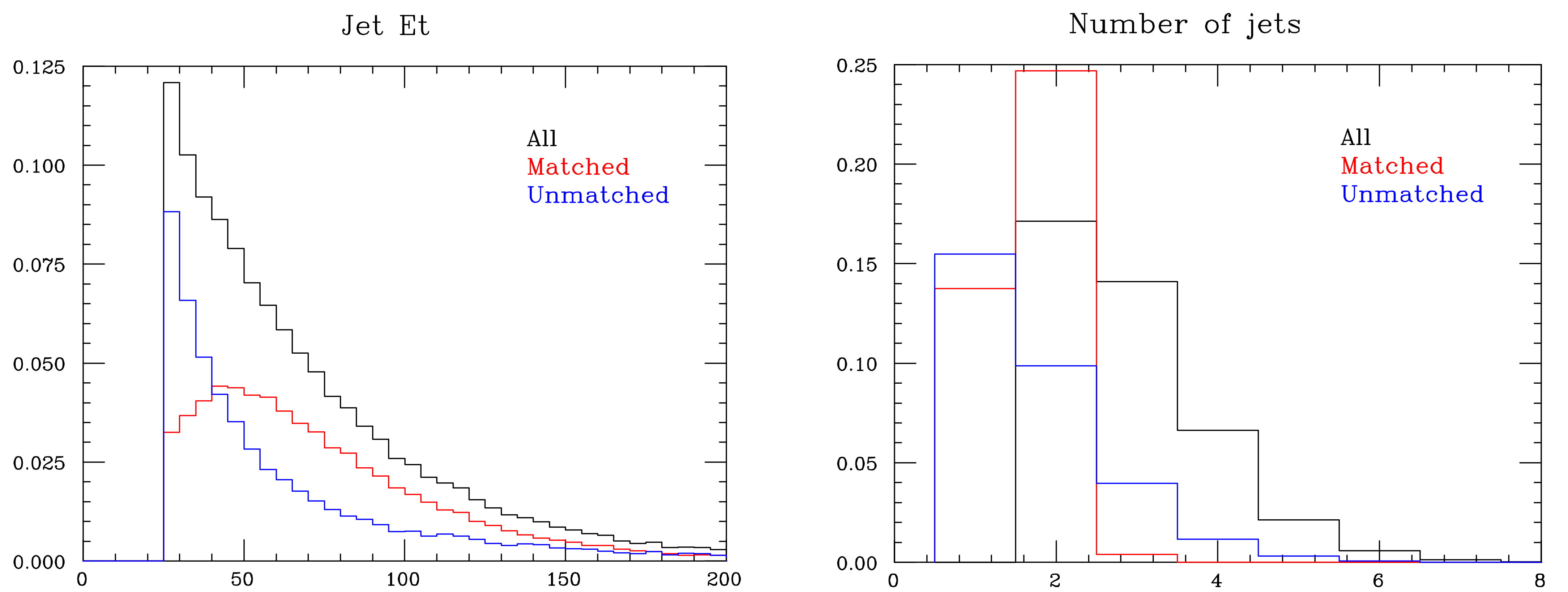
- Irreducible source of "jet contamination"

➡ Misidentification of processes

➡ Combinatorial ambiguities

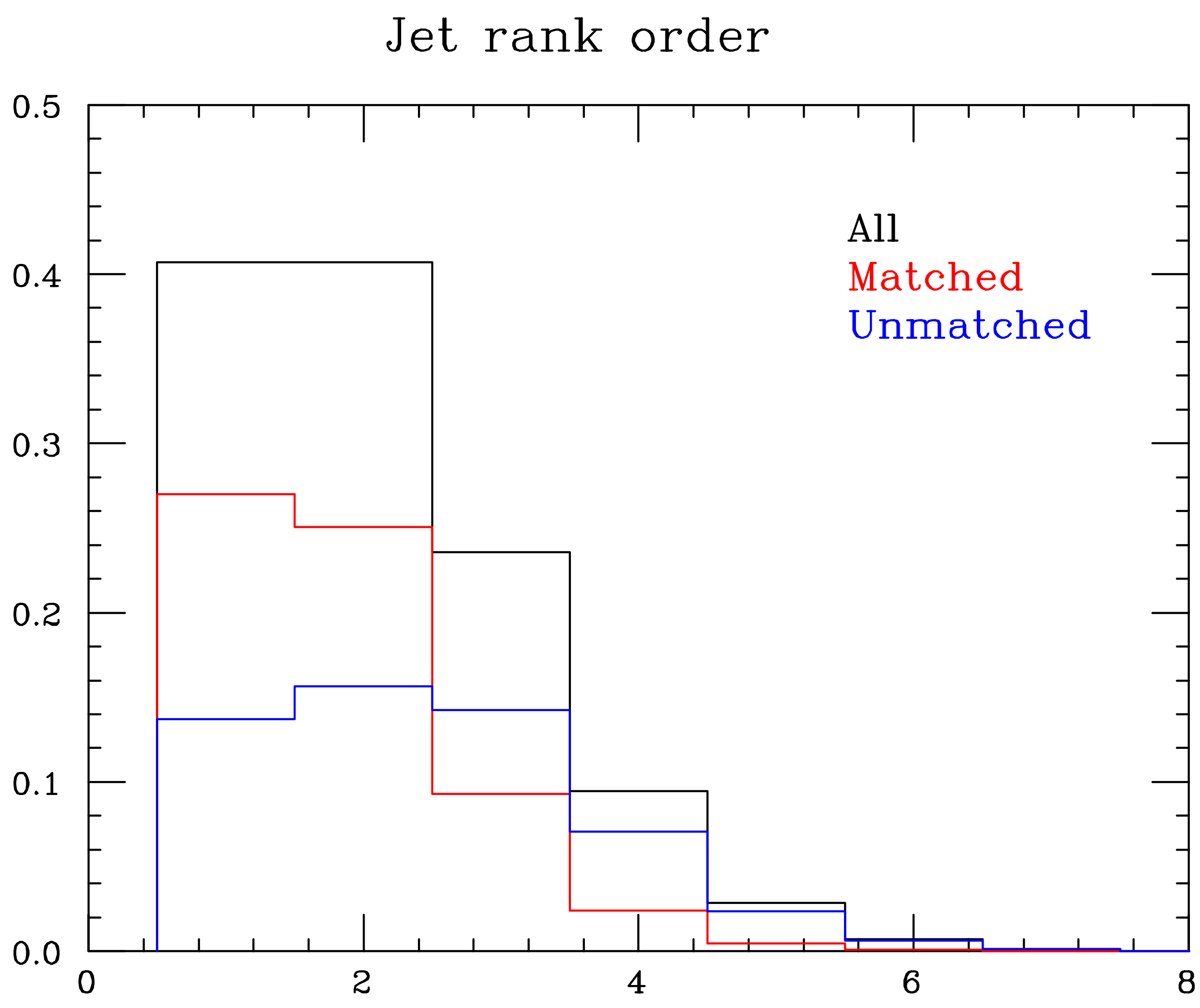
Jet contamination in $t\bar{t}$

- Fully leptonic $t\bar{t}$: 2 jets (+2 leptons + MET)
- Matched = top decay parton within ΔR=0.5 and $\Delta E/E$=0.3
- Generated with MC@NLO (no underlying event)



→ Half of events have an extra jet

E_T ordering of jets



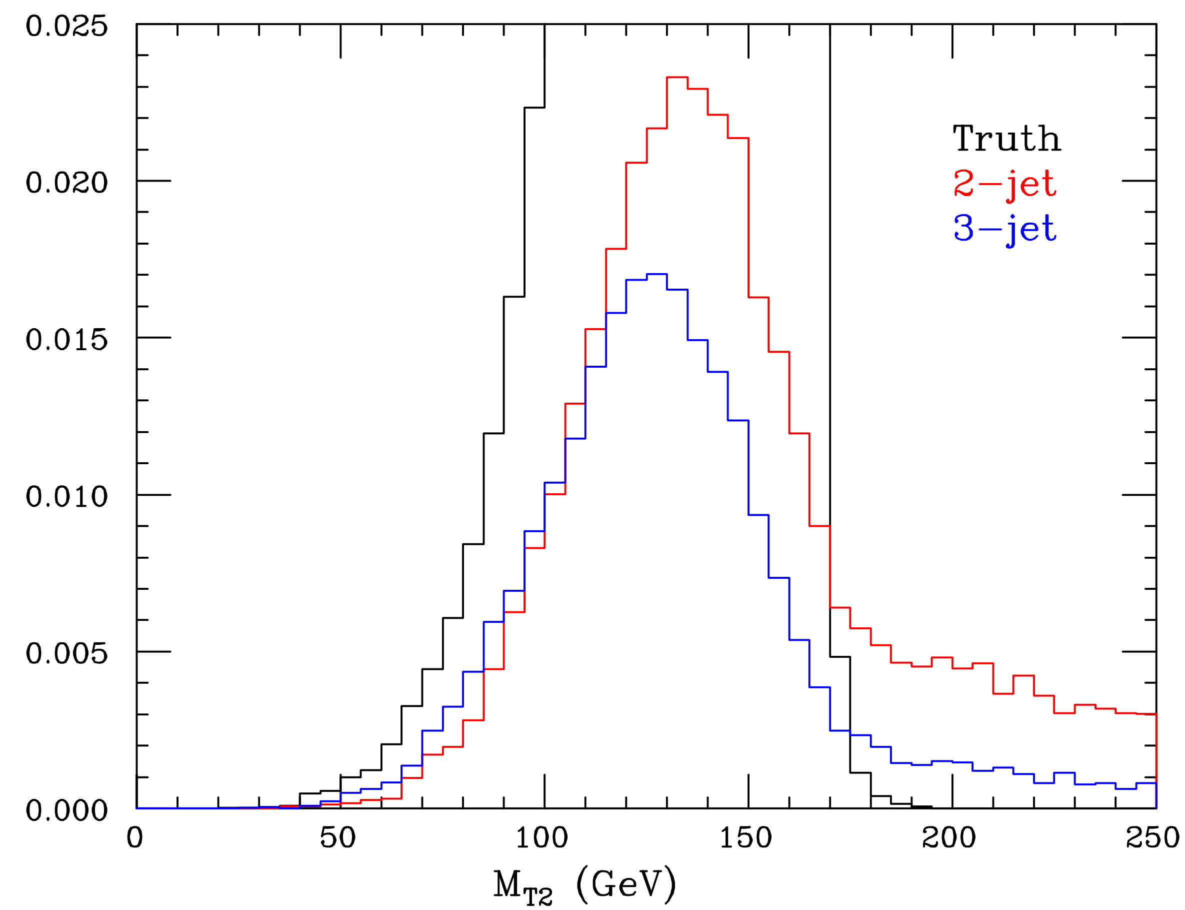
- P(1 or both leading jets unmatched) > 50%

Reducing jet contamination in $t\bar{t}$

- New idea: demand more jets, select lowest M_{T2}
  As long as one is correct, this cannot raise edge

Alwall, Hiramatsu, Nojiri & Shimizu, PRL103(2009)151802

- 7 fb^{-1} MC@NLO, no b-tagging
- > 50% events have extra jets
- Hardest 2 jets (red) => ISR contaminates edge
- Smallest M_{T2} from 3 hardest (blue) => less contamination

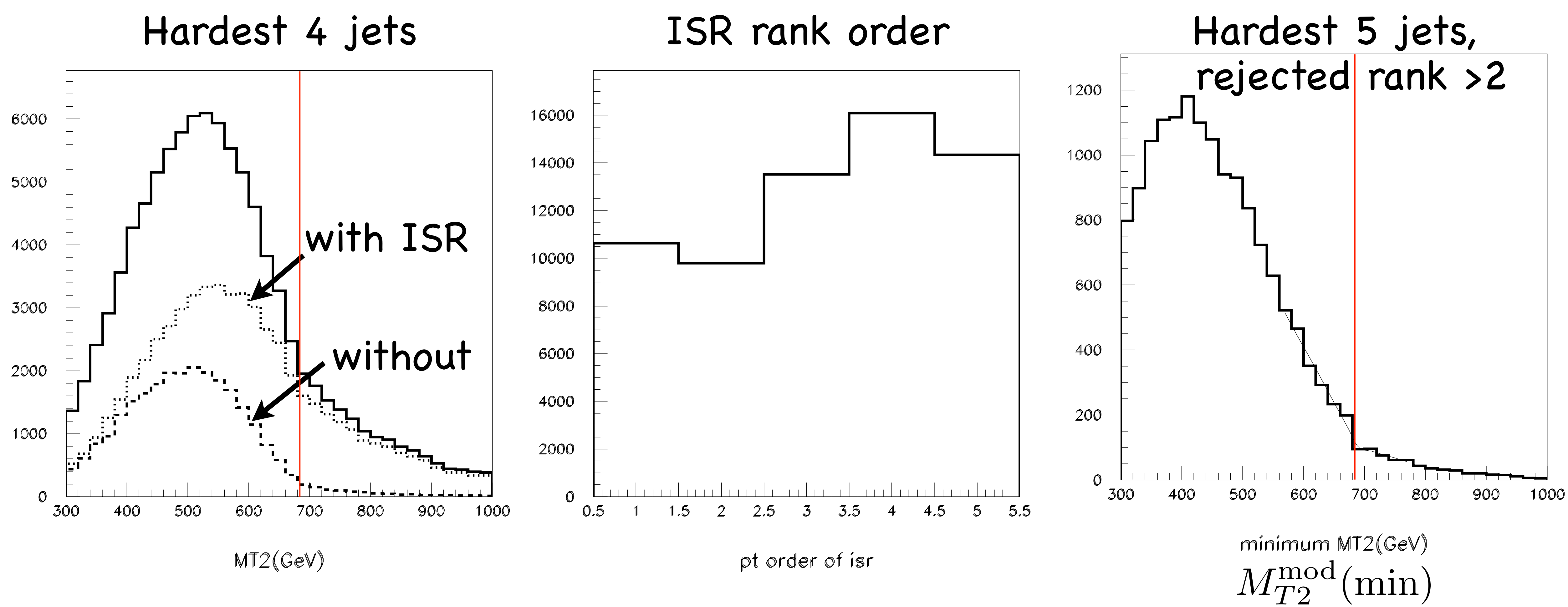


Reducing jet contamination in SUSY

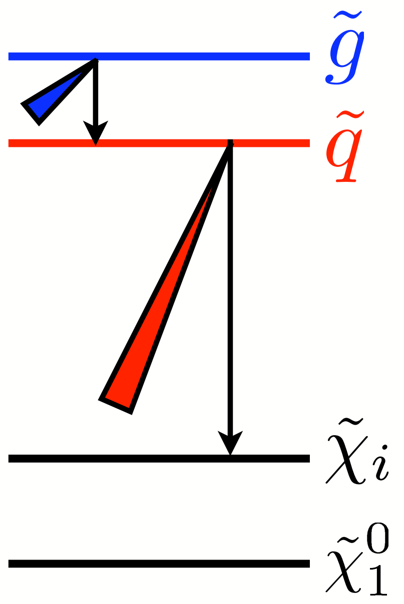
Alwall, Hiramatsu, Nojiri & Shimizu, PRL103(2009)151802

- Consider $gg \to \tilde{g}\tilde{g}\,,\quad \tilde{g} \to q\bar{q}\tilde{\chi}_1^0$ at LHC (PYTHIA, 40 fb^{-1})

$$m_{\tilde{g}} = 685\ \mathrm{GeV}\,,\ m_{\tilde{q}} = 1426\ \mathrm{GeV}\,,\ m_{\tilde{\chi}_1^0} = 102\ \mathrm{GeV}$$



- Again, endpoint is clearer for lowest M_{T2} with extra jet



Nojiri & Sakurai, arXiv:1008:1813

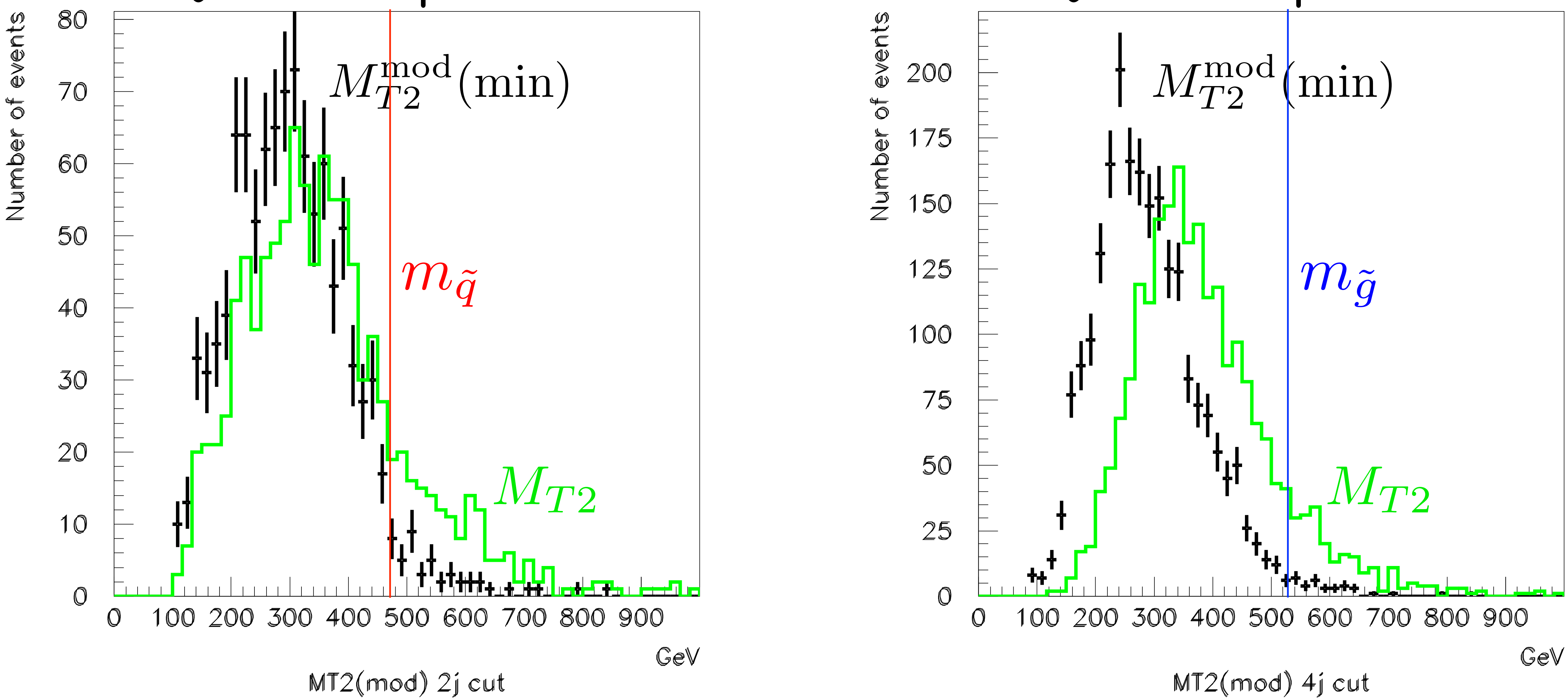
- Squark & gluino production at 7 TeV, 1 fb^{-1}

$$m_{\tilde{g}} = 522\ \mathrm{GeV}\,,\ m_{\tilde{q}} = 472\ \mathrm{GeV}\,,\ m_{\tilde{\chi}_1^0} = 79\ \mathrm{GeV}$$

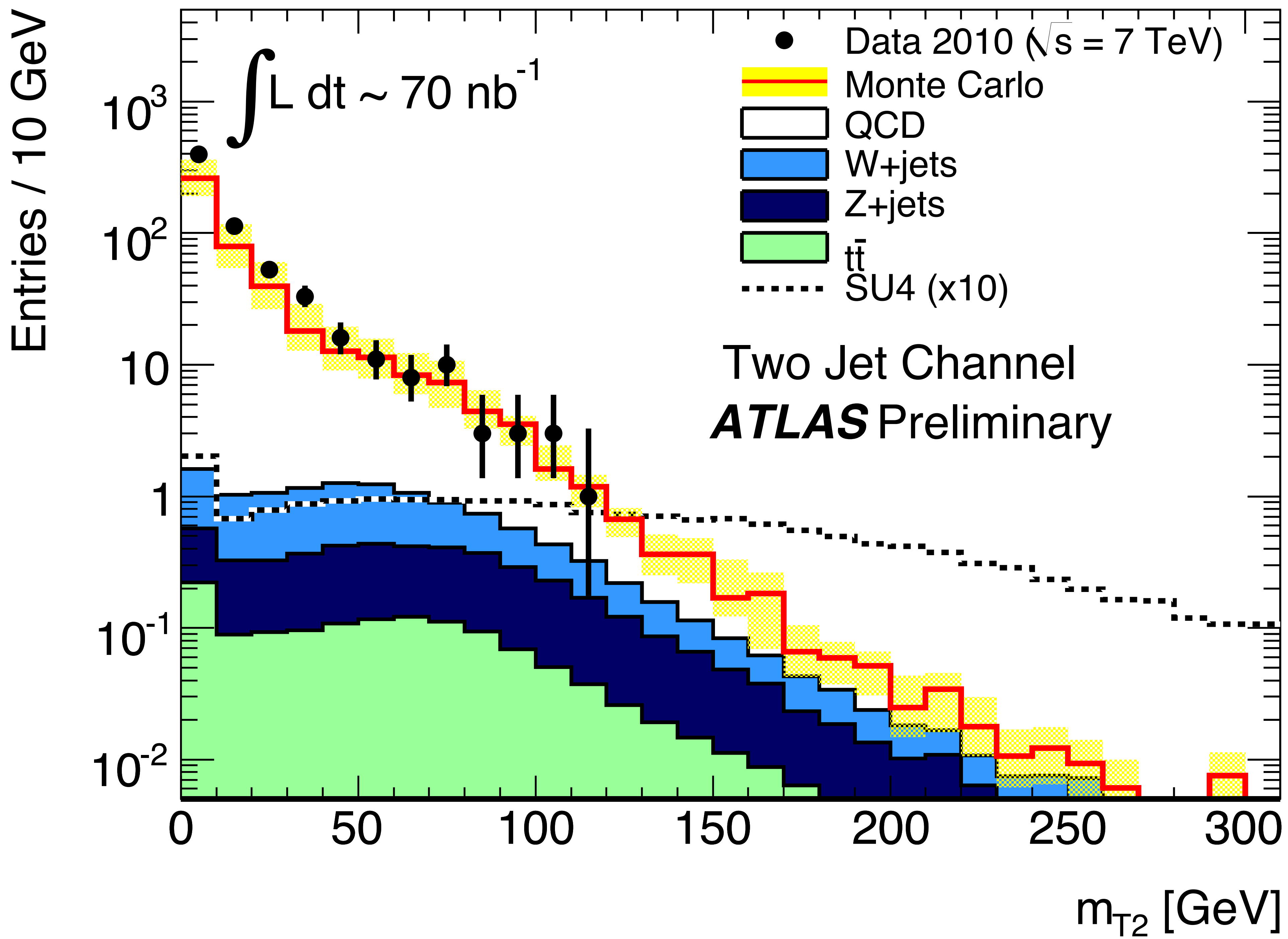
- 2/4 jet cut favours squark/gluino production

2 jets with p_t>200 GeV

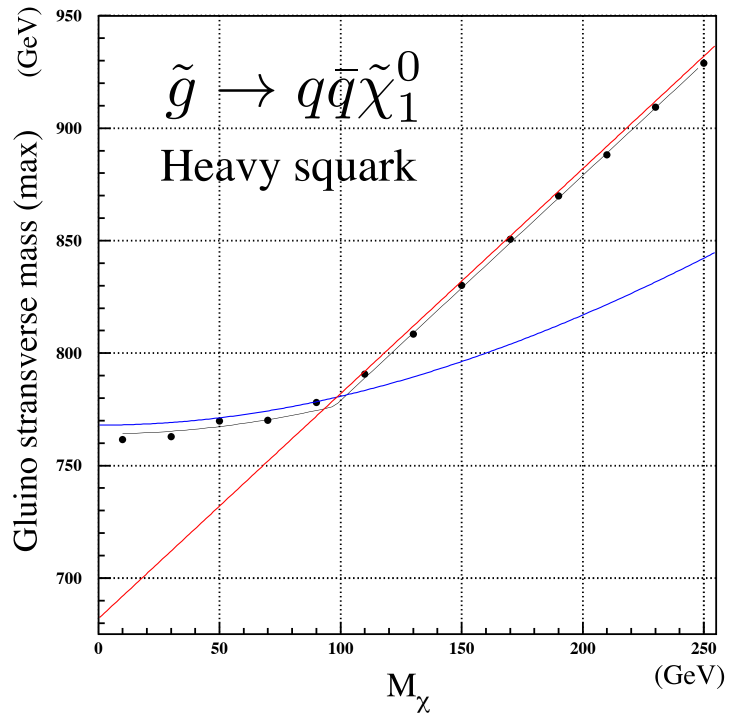
4 jets with p_t>50 GeV



First LHC data



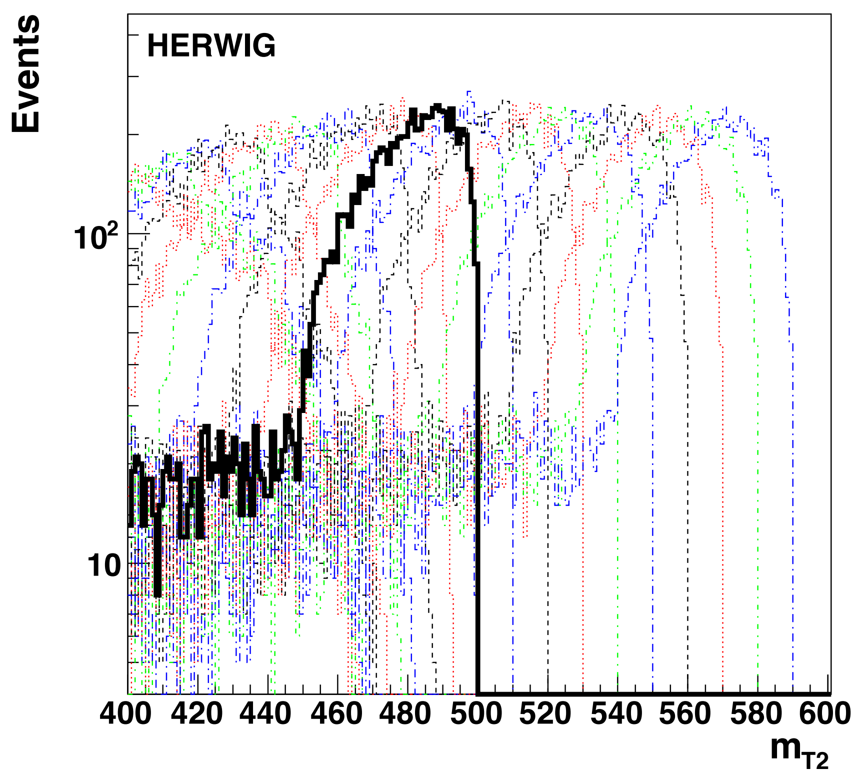
Finding M_{LSP} from M_{T2}?

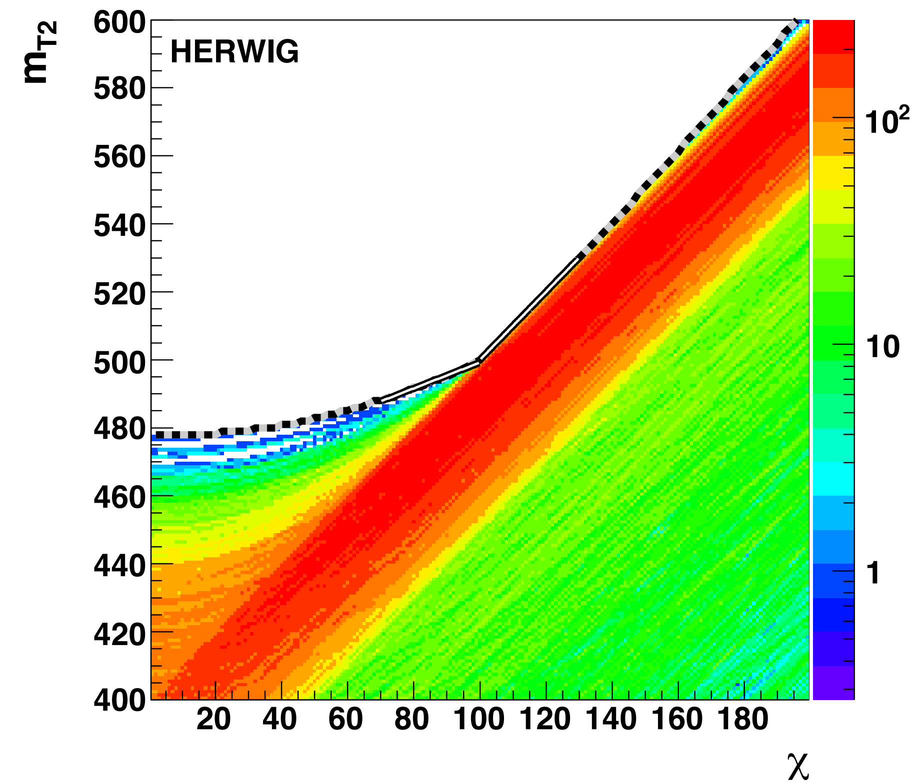


Cho, Choi, Kim, Park, arXiv:1008:1813

- $M_{T2}^{\max}(\mu_N)$ has a kink at $\mu_N = m_{\tilde{\chi}_1^0}$
- Unfortunately endpoint is weak when $\mu_N < m_{\tilde{\chi}_1^0}$

→ Difficult to see kink





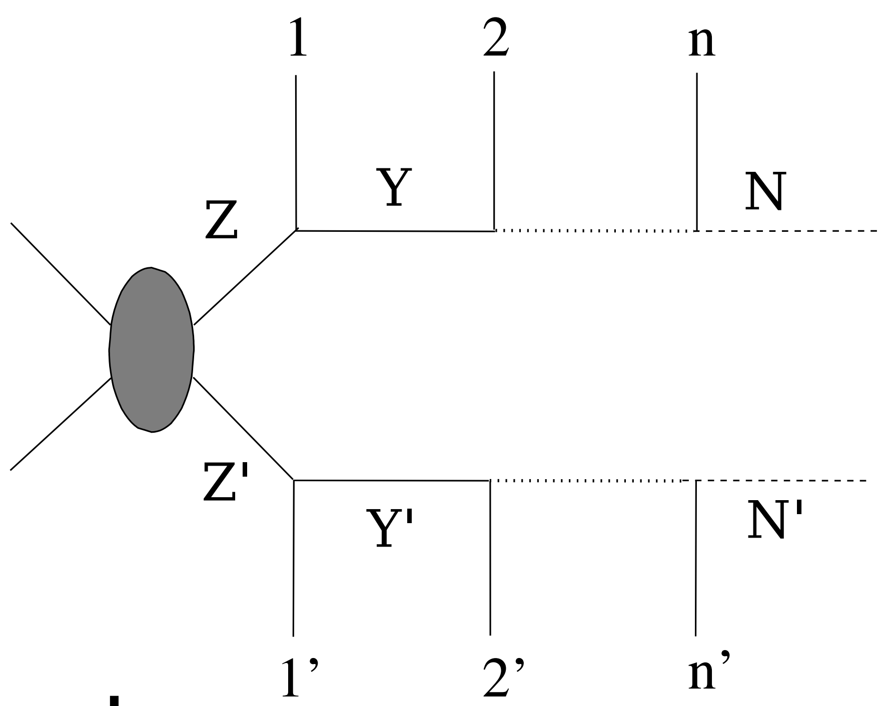
Barr, Gripaios, Lester, JHEP02(2008)014

Solving decay chains

Solving decay chains

- Measure visible momenta 1...n, 1'...n' and missing p_T
  - 6 unknown momentum components per event
  - n+n'+2 on-mass-shell constraints per event
  - N_m unknown masses → we need

    $N_{ev}(n+n'-4) \geqslant N_m$ to solve for masses



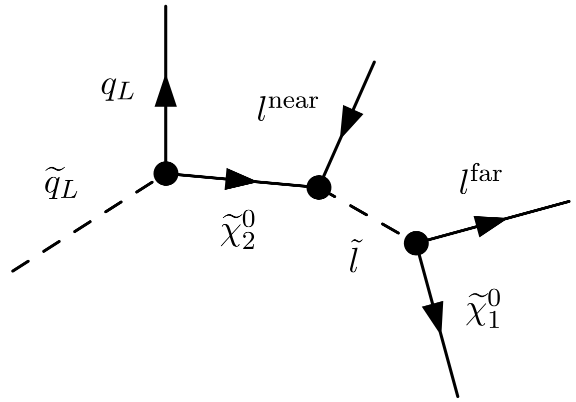
- Identical chains: n=n', N_m = n+1 → need N_{ev} = 2 for n=3,4

Non-identical (N=N'): N_m = n+n'+1 → need N_{ev} = 6 for n+n'=5

Solving pairs of events

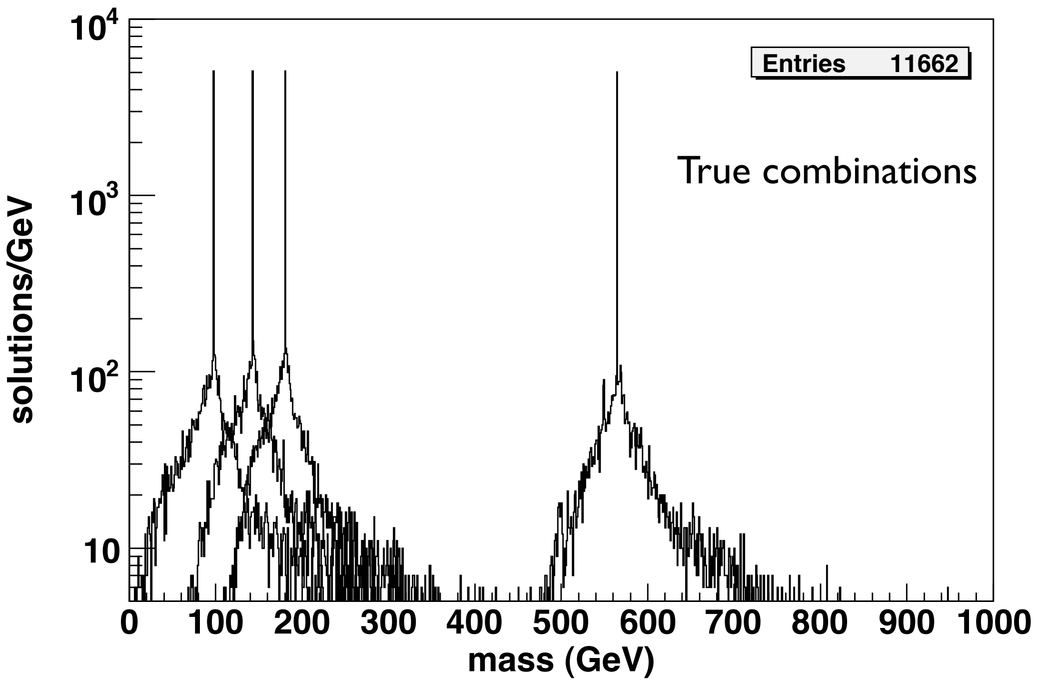
Chen, Gunion, Han, McElrath, PRD 80(2009)035020

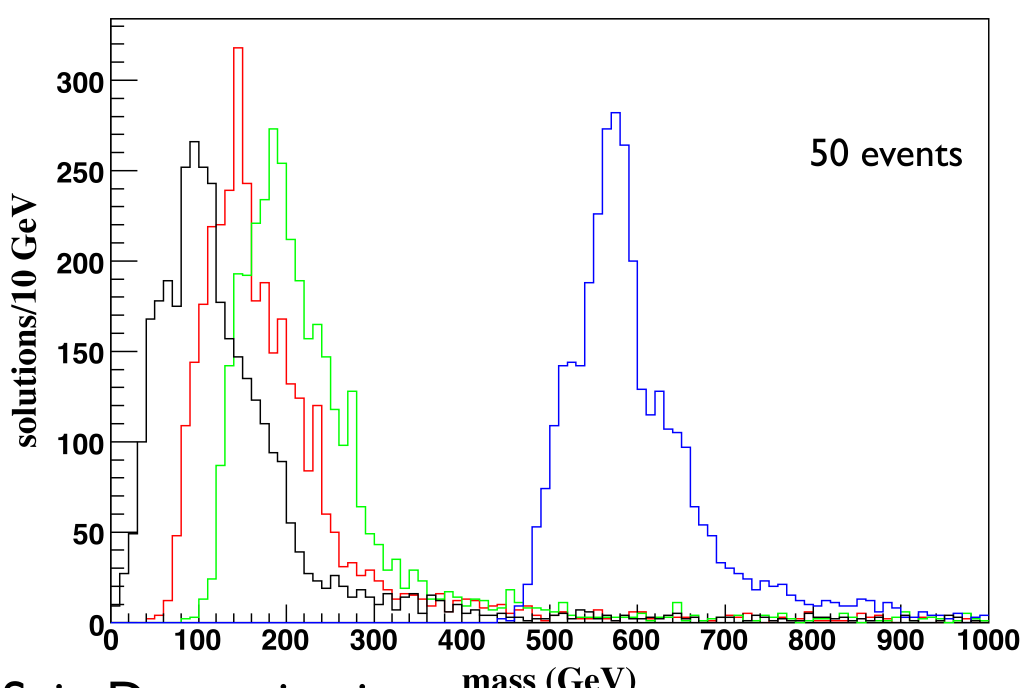
- Two identical chains

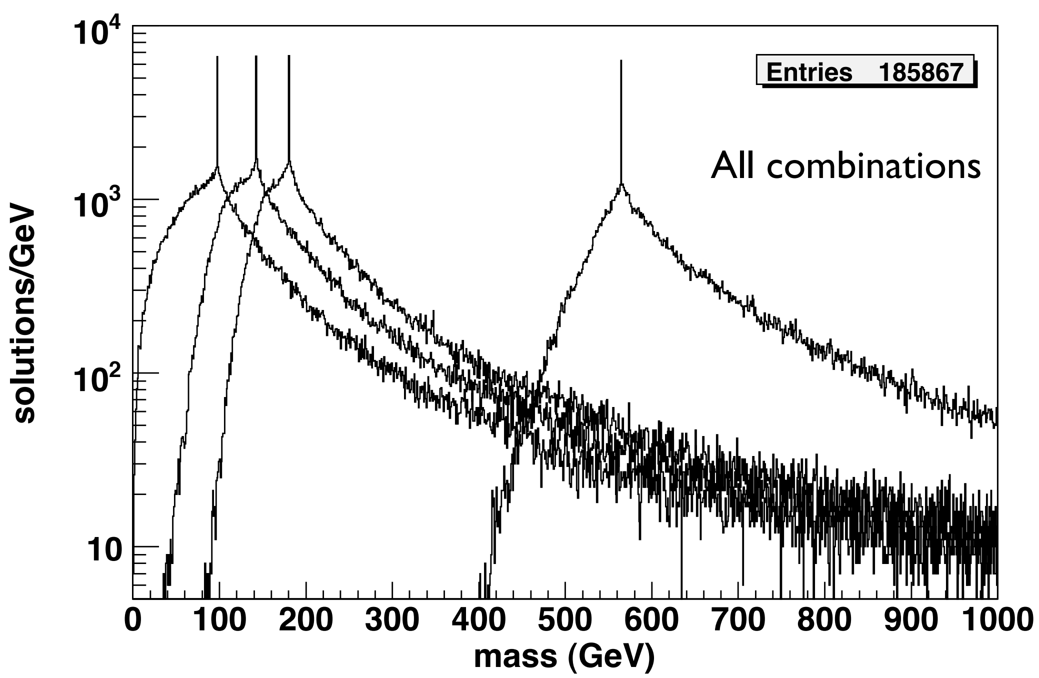


- SPS 1a masses

$\widetilde{\chi}_1^0$	$\widetilde{\chi}_2^0$	$\widetilde{u}_L$	$\widetilde{e}_R$
96	177	537	143







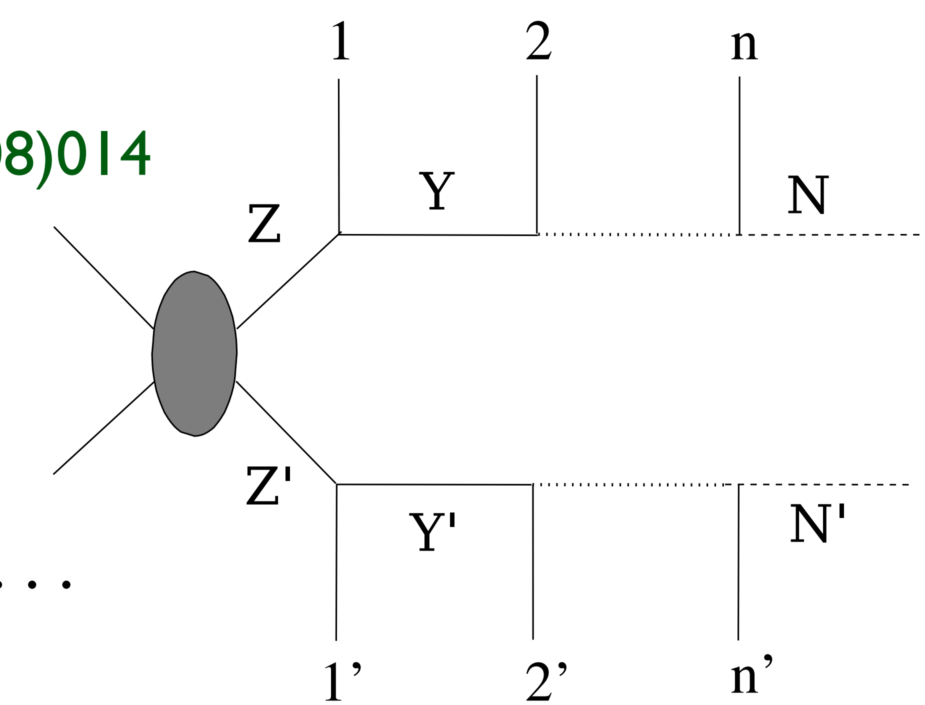
Fitting decay chains

- Assume a mass hypothesis: if n+n' > 4 then each event is over-constrained

Kawagoe et al., PRD 71(2005)035008
BRW, JHEP 09(2009)124

- E.g. if n, n'=3, can solve for p_N, $p_{N'}$

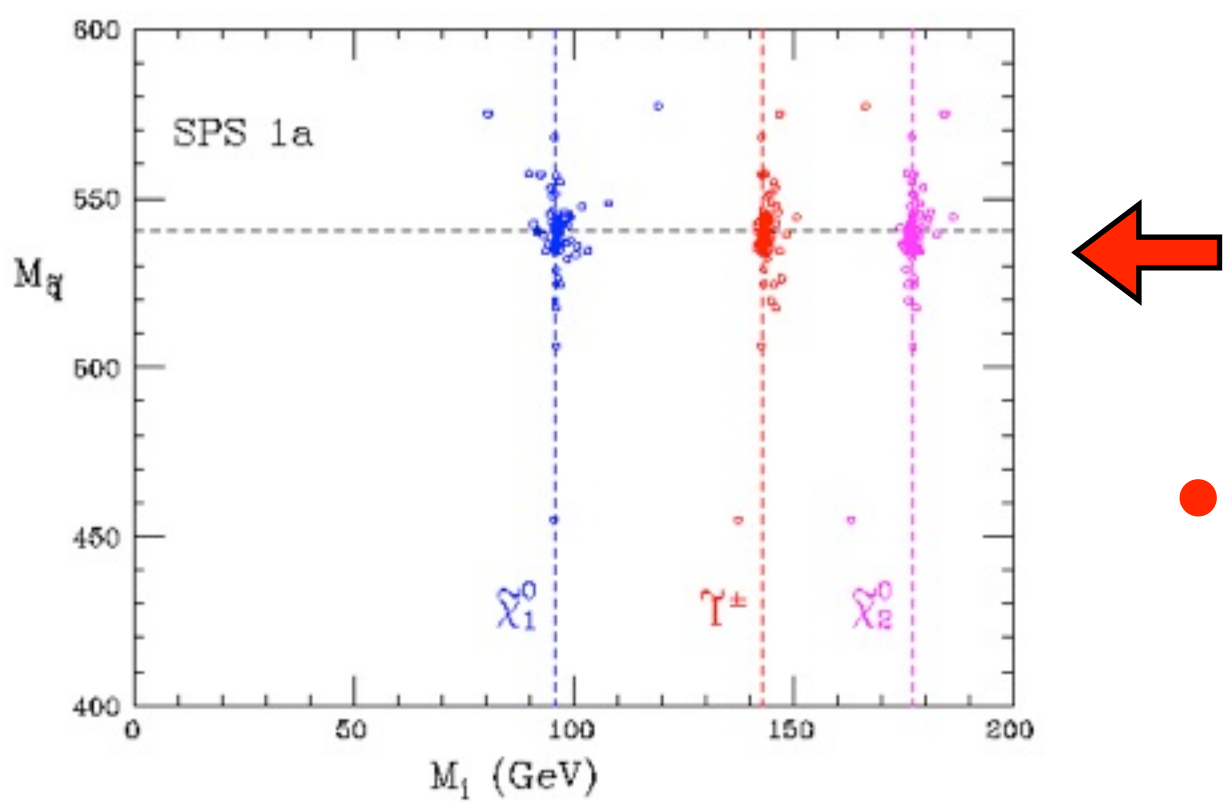
Nojiri, Polesello, Tovey, JHEP05(2008)014



- Measure goodness of fit by

$$\chi^2 = (p_N^2 - M_N^2)^2/\sigma_N^2 + (p_{N'}^2 - M_{N'}^2)^2/\sigma_{N'}^2$$

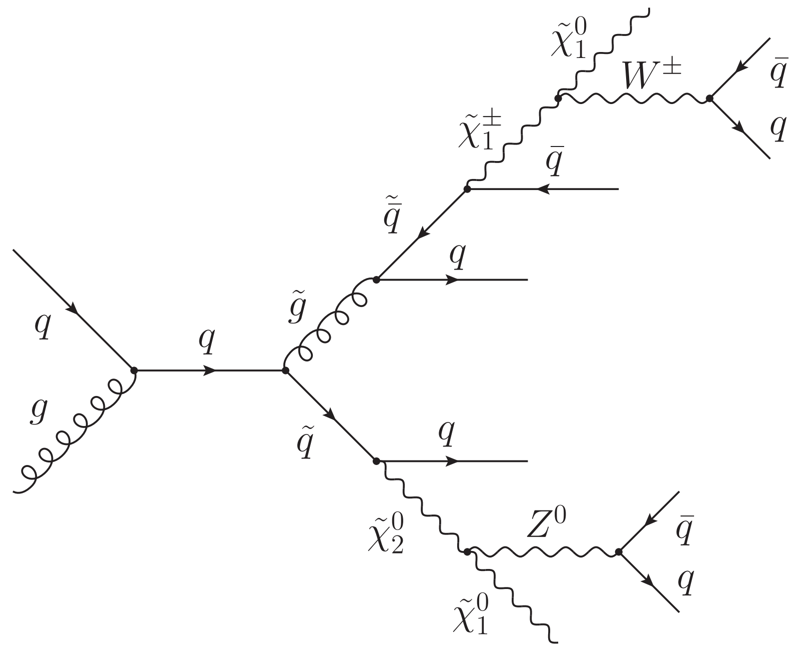
  - N.B. $p_N^2 - M_N^2 = p_Z^2 - M_Z^2 = p_Y^2 - M_Y^2 = \ldots$



Best-fit points for 100 samples of 25 events (all combinations)

- Effects of jet contamination and background not included

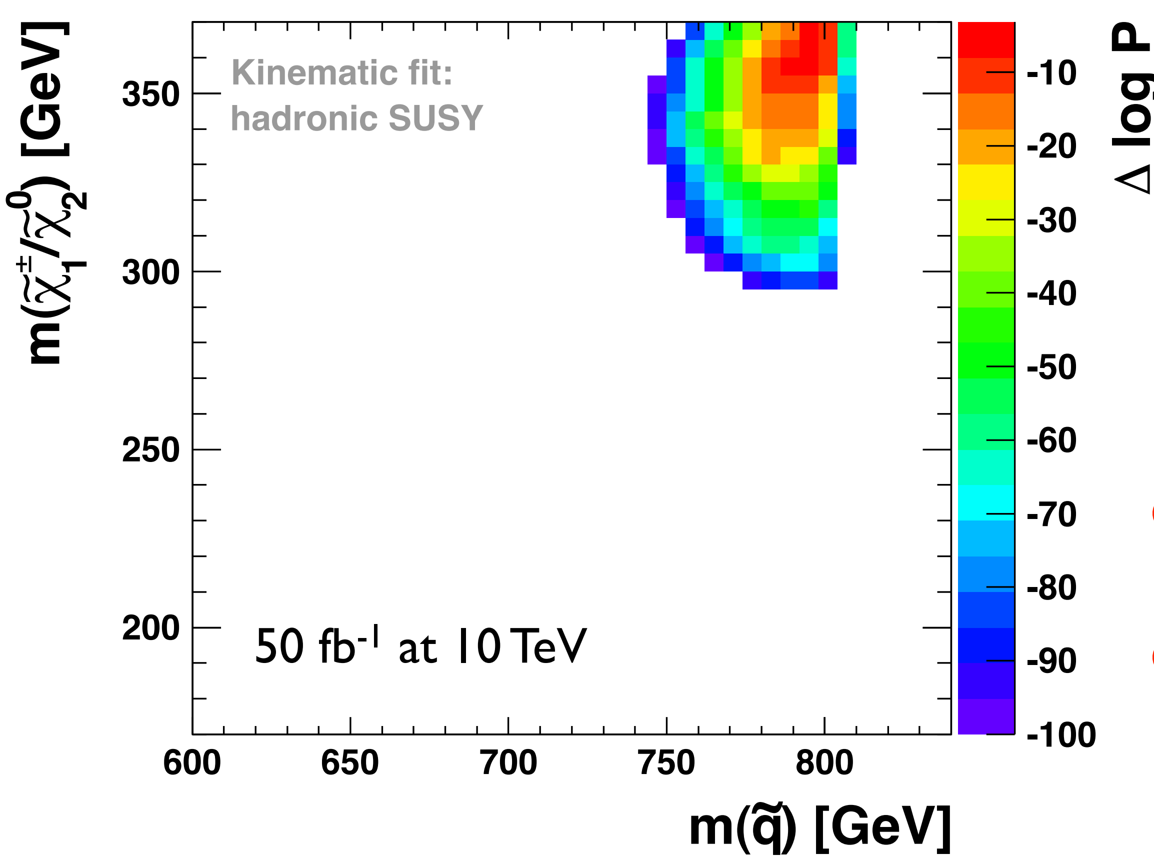
Fully hadronic SUSY decays



Autermann et al., 0911.2607

Parameter	Value	Particle	Mass [GeV]
m_0	230 GeV	$\tilde{q}^L_{ds,uc}$	807, 800
$m_{1/2}$	360 GeV	$\tilde{q}^R_{ds,uc}$	775, 782
$\tan\beta$	10	$\tilde{q}^{1/2}_b$	734, 771
A_0	0 GeV	$\tilde{q}^{1/2}_t$	599, 787
signμ	+	$\tilde{g}$	851
		$\tilde{\chi}^0_{1,2,3,4}$	144, 271, 475, 490
		$\tilde{\chi}^\pm_{1,2}$	273, 487

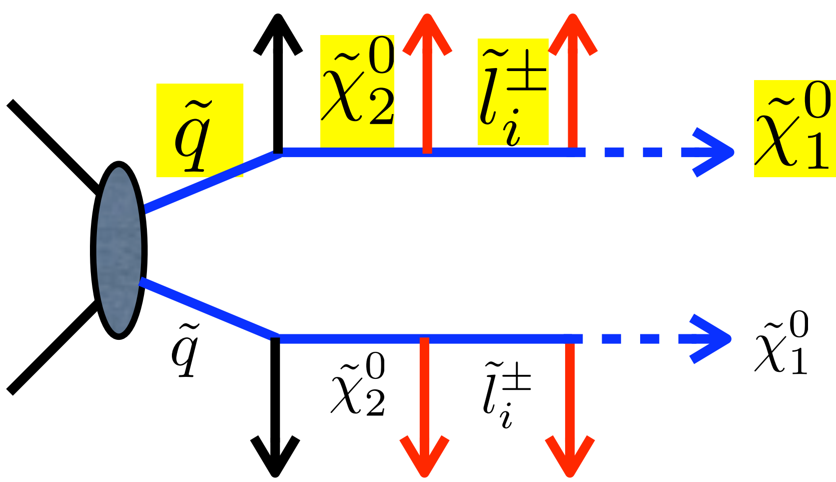
	without ISR & FSR		with ISR & FSR	
	Bg	Sig	Bg	Sig
selection efficiency	4.2%	29%	6.9%	30%
S/B	1/10.9		1/16.4	
S/B (complete)	1/11.3		1/33.4	



- $m(\tilde{g}), m(\tilde{\chi}^0_1)$ held fixed
- wrong combinations shift $m(\tilde{\chi}^\pm_1/\chi^0_2)$

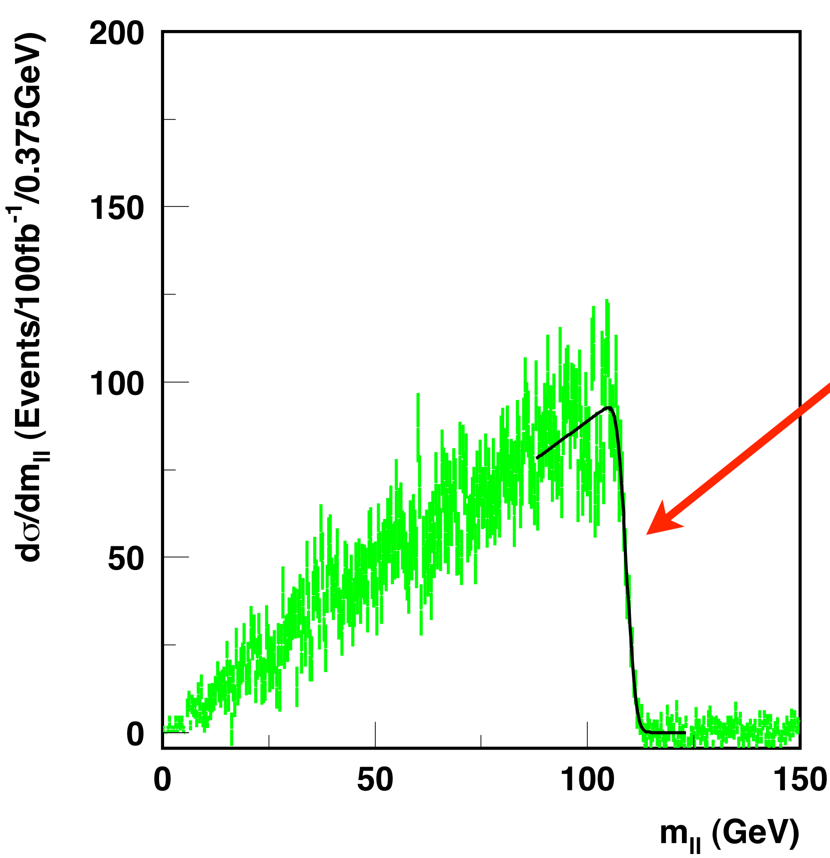
Including dilepton edge

Nojiri, Sakurai, BRW, JHEP 06(2010)069



$$M_1 = m_{\tilde{l}}^2 - m_{\tilde{\chi}_1^0}^2$$
$$M_2 = m_{\tilde{\chi}_2^0}^2 - m_{\tilde{l}}^2$$
$$M_3 = m_{\tilde{q}}^2 - m_{\tilde{\chi}_2^0}^2$$
$$M_4 = M_{ll}^{\max} = (m_{\tilde{\chi}_2^0}^2 - m_{\tilde{l}}^2)(m_{\tilde{l}}^2 - m_{\tilde{\chi}_1^0}^2)/m_{\tilde{l}}^2$$

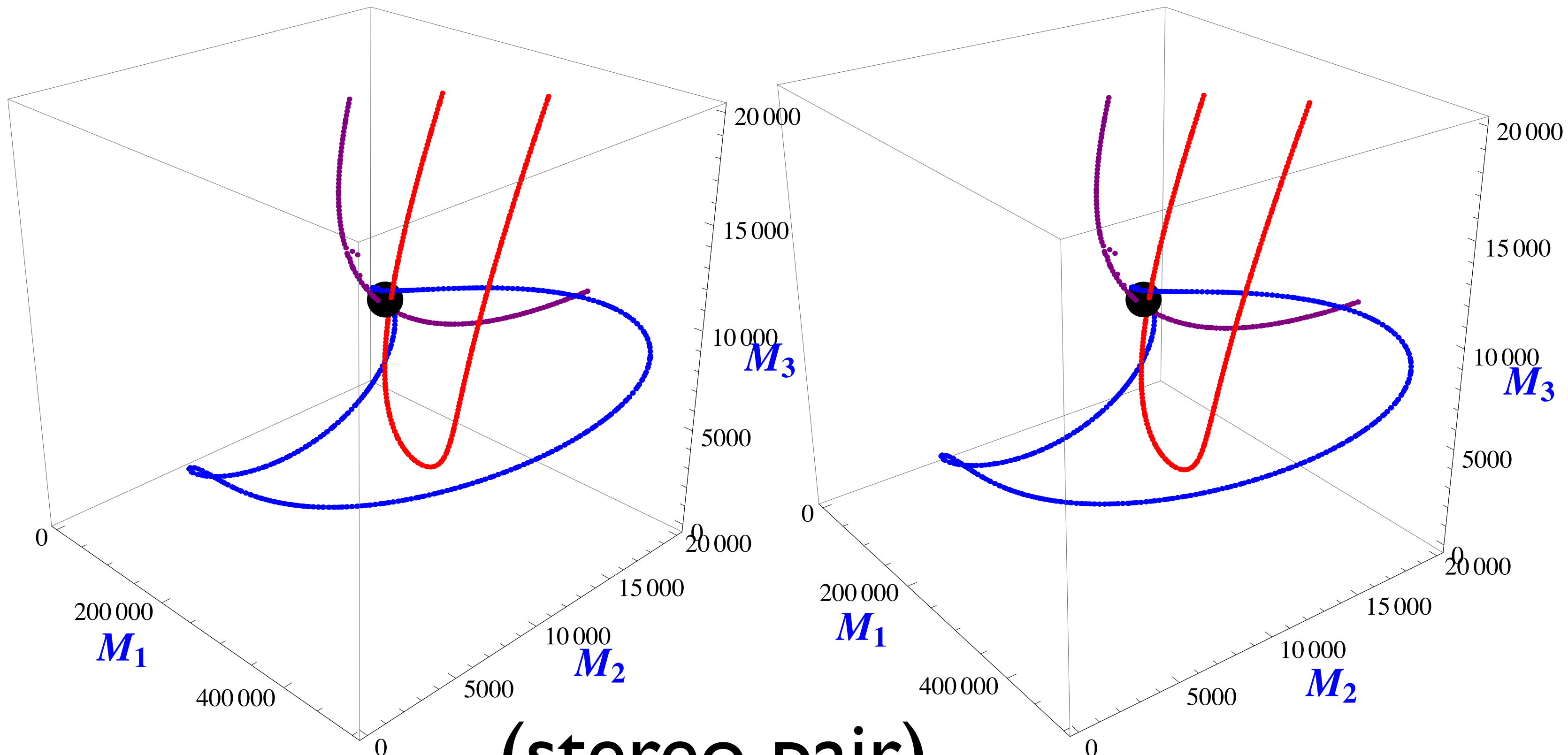
fix M_4 by dilepton mass measurement



- Number of unknowns reduced to 3

➡ Visualize solution curves in 3D

Mass solution curves

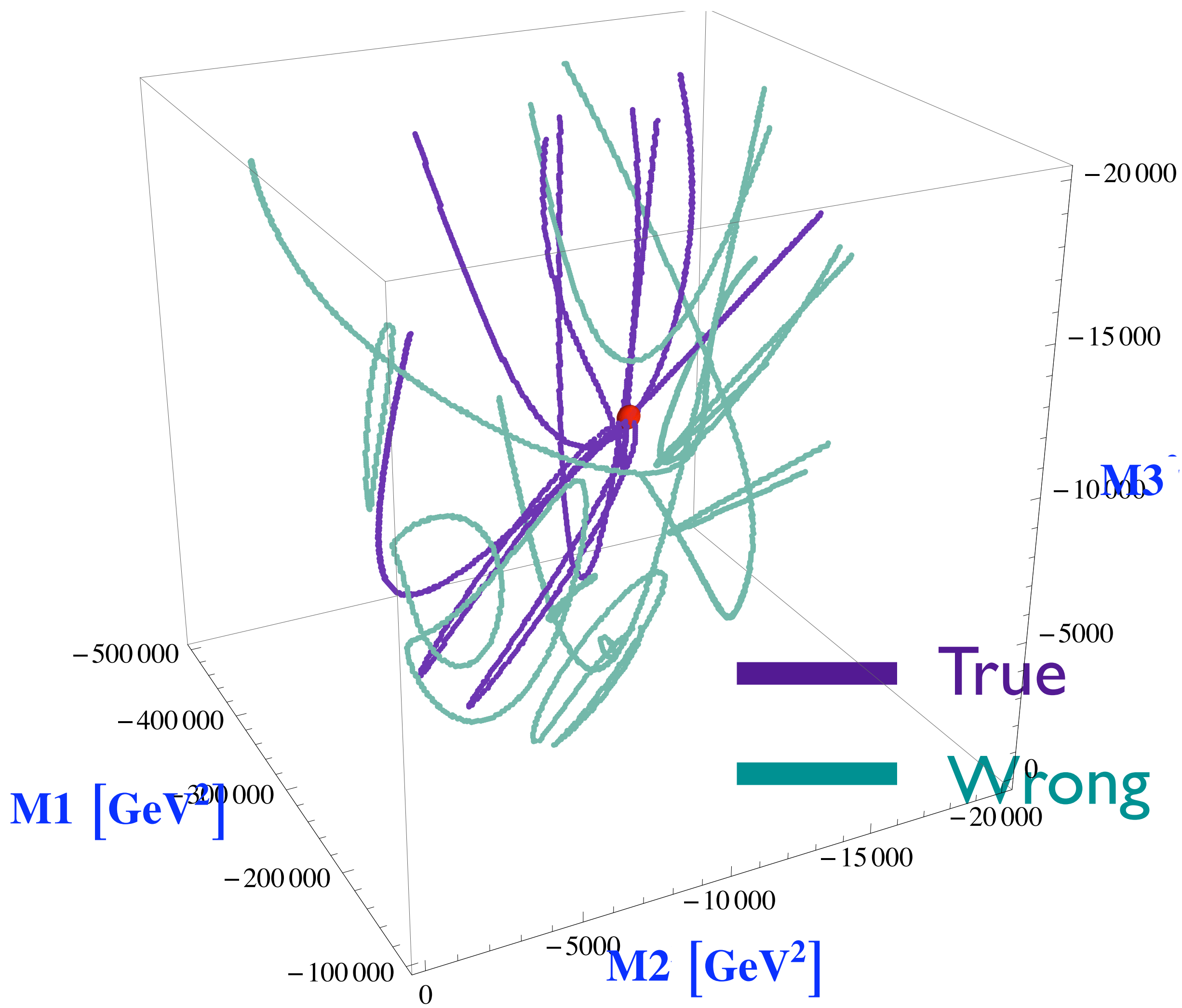


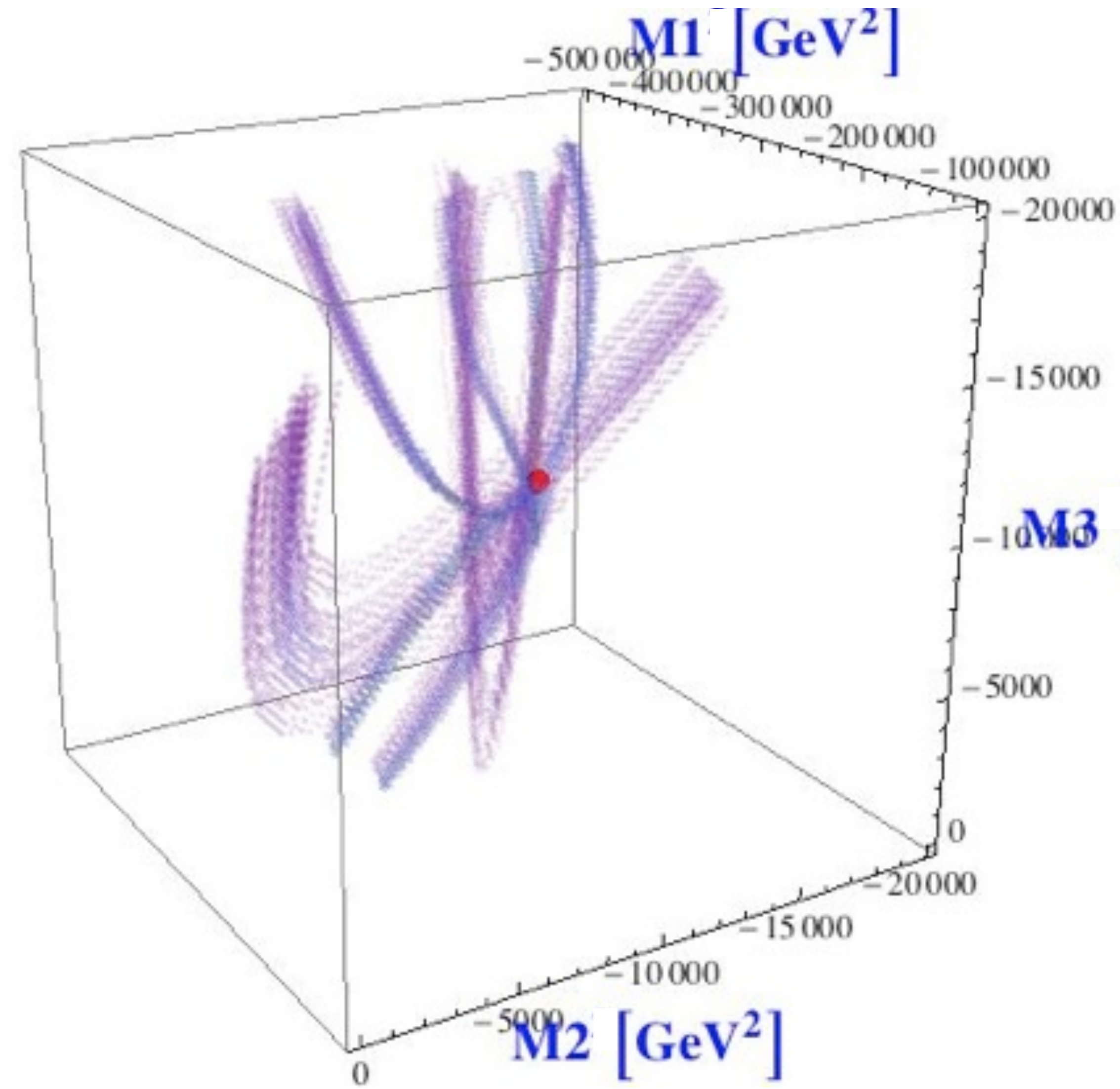
(stereo pair)

- 3 events, parton level, correct combinations

➡ Curves intersect at correct values

Mass solution curves (2)





- Wrong combinations don't intersect
- Resolution smearing (right combinations)

Herwig MC study

	m_0	$m_{1/2}$	A_0	$\tilde{\chi}_1^0$	$\tilde{e}_R$	$\tilde{\chi}_2^0$	$\tilde{u}_L$
Point A	110	220	0	86	142	161	504
Point B	100	250	-100	99	141	186	563
Point C	140	260	0	103	174	193	592

Table 2. Parameters and mass spectra in GeV for non-CMSSM model points A, B and C. Parameters common to all points are $m_0^{\text{3rd gen.}} = 300\,\text{GeV}$, $\tan\beta = 10$, $\text{sign}(\mu) = +$.

The following cuts are applied in order to select signal events:

(i) $M_{\text{eff}} \equiv \sum_{i=1}^{4} p_T^{\text{jet},i} + \sum_{i=1}^{4} p_T^{\text{lep},i} + E_T^{\text{miss}} > 400\,\text{GeV}$;

(ii) $E_T^{\text{miss}} > \max(200\,\text{GeV},\ 0.2 M_{\text{eff}})$;

(iii) At least two jets with $p_T^{\text{jet},1} > 100\,\text{GeV}$ and $p_T^{\text{jet},2} > 50\,\text{GeV}$ within $|\eta| < 2.5$;

(iv) Two pairs of opposite sign same flavour leptons with $p_T > 20\,\text{GeV}$ and $|\eta| < 3$;

(v) No b jet with $p_T > 30\,\text{GeV}$ and $|\eta| < 3$.

→ ~250 events for 20 fb^{-1} at 14 TeV

MC results

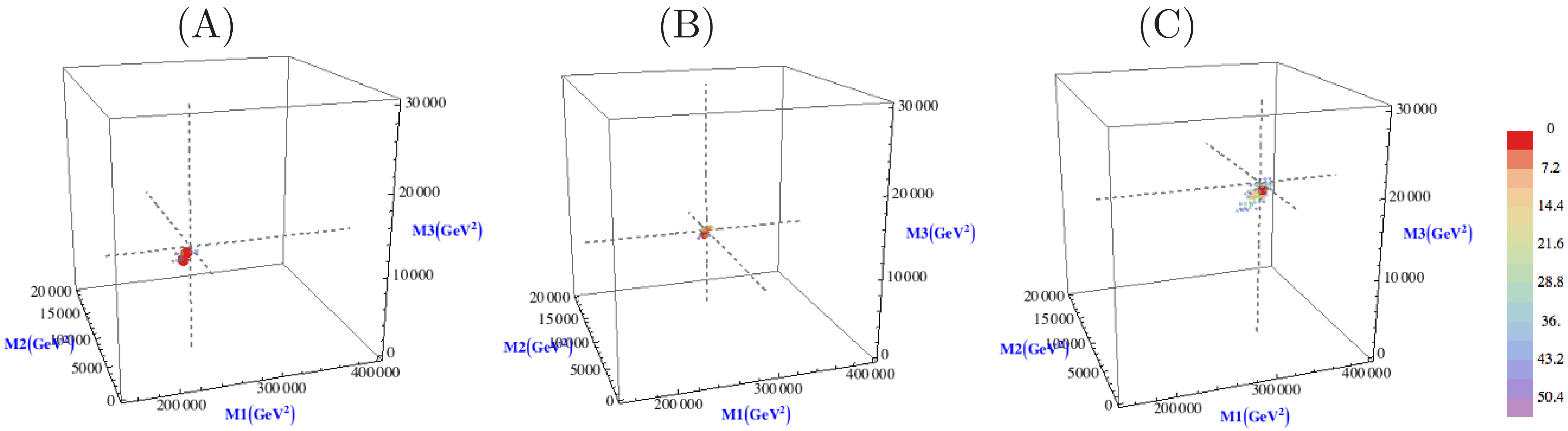


Figure 4. Distribution of $\Delta\chi^2(\mathbf{M})$ for each model point at detector level. The true mass point is at the intersection of the three dashed lines.

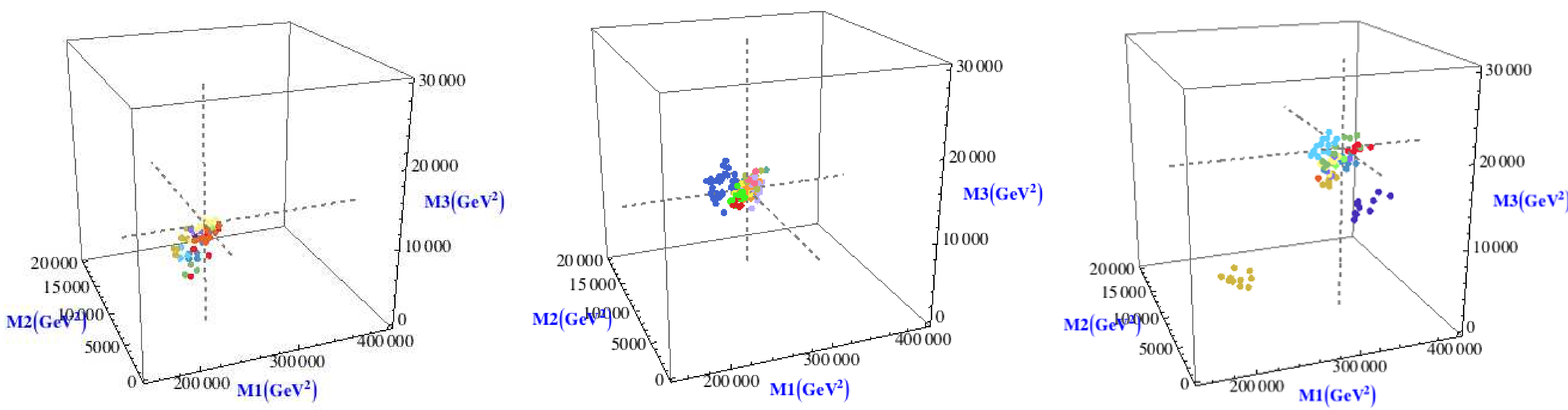


Figure 5. One-sigma regions of 10 sub-samples, distinguished by their colours. Each sub-sample contains 25 events.

Global Inclusive Observables

Inclusive observables

- How can jets from hard subprocess be distinguished from ISR jets?
- In principle, there is no way! So let's look at "global inclusive" observables
- Consider e.g. the total invariant mass M visible in the detector:

$$M = \sqrt{E^2 - P_z^2 - \not{E}_T^2}$$

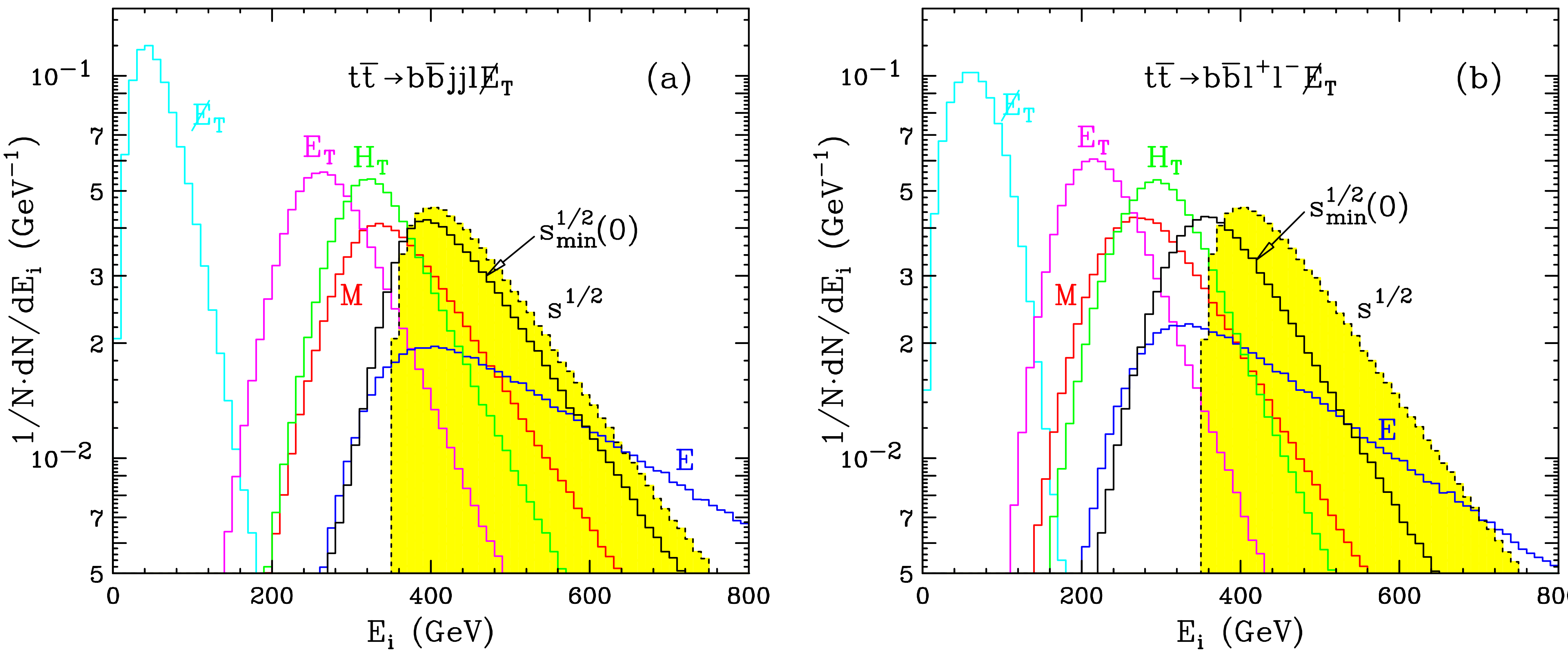
or (Konar, Kong & Matchev, JHEP 03(2009)085)

$$\hat{s}^{1/2}_{\min}(M_{\rm inv}) = \sqrt{M^2 + \not{E}_T^2} + \sqrt{M_{\rm inv}^2 + \not{E}_T^2}$$

Inclusive observables: MC results

$$\hat{s}^{1/2}_{\min}(M_{\rm inv}) = \sqrt{M^2 + \not{E}_T^2} + \sqrt{M_{\rm inv}^2 + \not{E}_T^2}$$

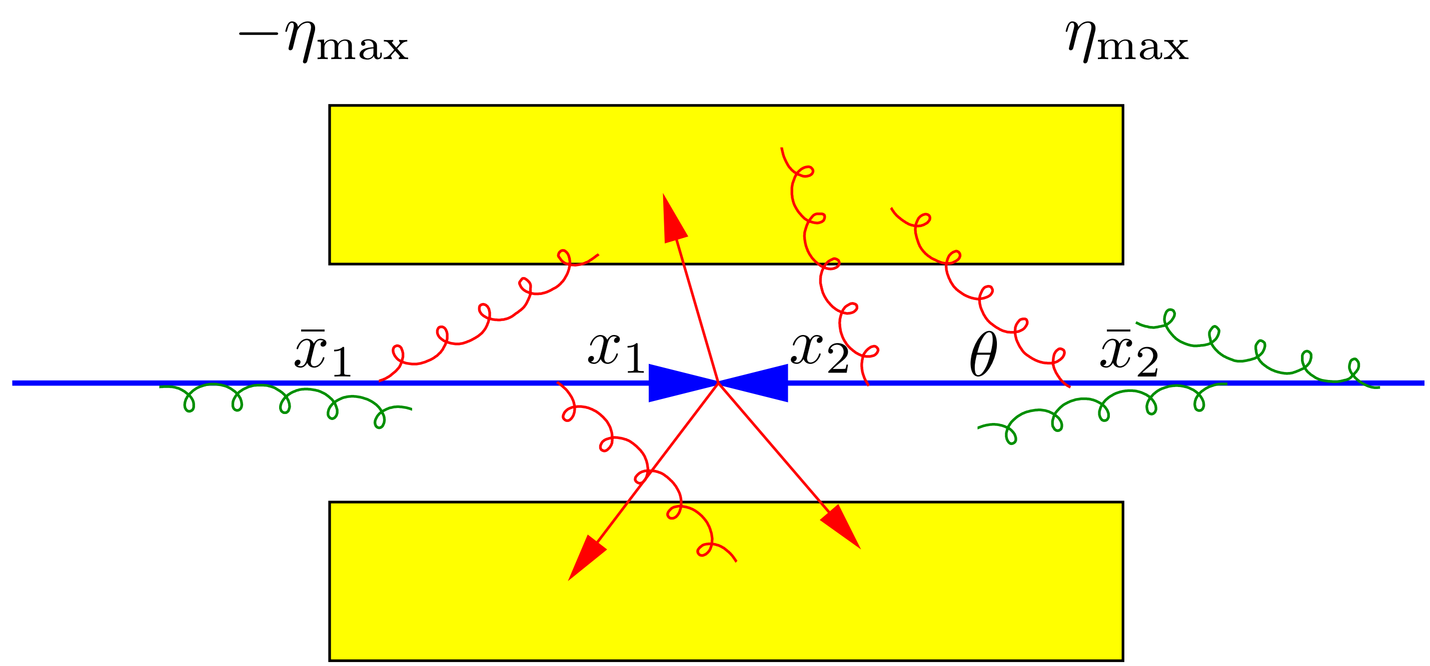
$$M = \sqrt{E^2 - P_z^2 - \not{E}_T^2} \qquad H_T = E_T + \not{E}_T$$



- Pythia MC: ISR turned off!

Konar, Kong, Matchev, JHEP03(2009)085

ISR effects on inclusive observables



$$\frac{d\sigma}{dM^2} = \int \frac{d\bar{x}_1}{\bar{x}_1}\frac{d\bar{x}_2}{\bar{x}_2} dx_1\, dx_2 f(\bar{x}_1, Q_c) f(\bar{x}_2, Q_c) K\left(\frac{x_1}{\bar{x}_1}; Q_c, Q\right) K\left(\frac{x_2}{\bar{x}_2}; Q_c, Q\right) \hat{\sigma}(x_1 x_2 S)\delta(M^2 - \bar{x}_1\bar{x}_2 S)$$

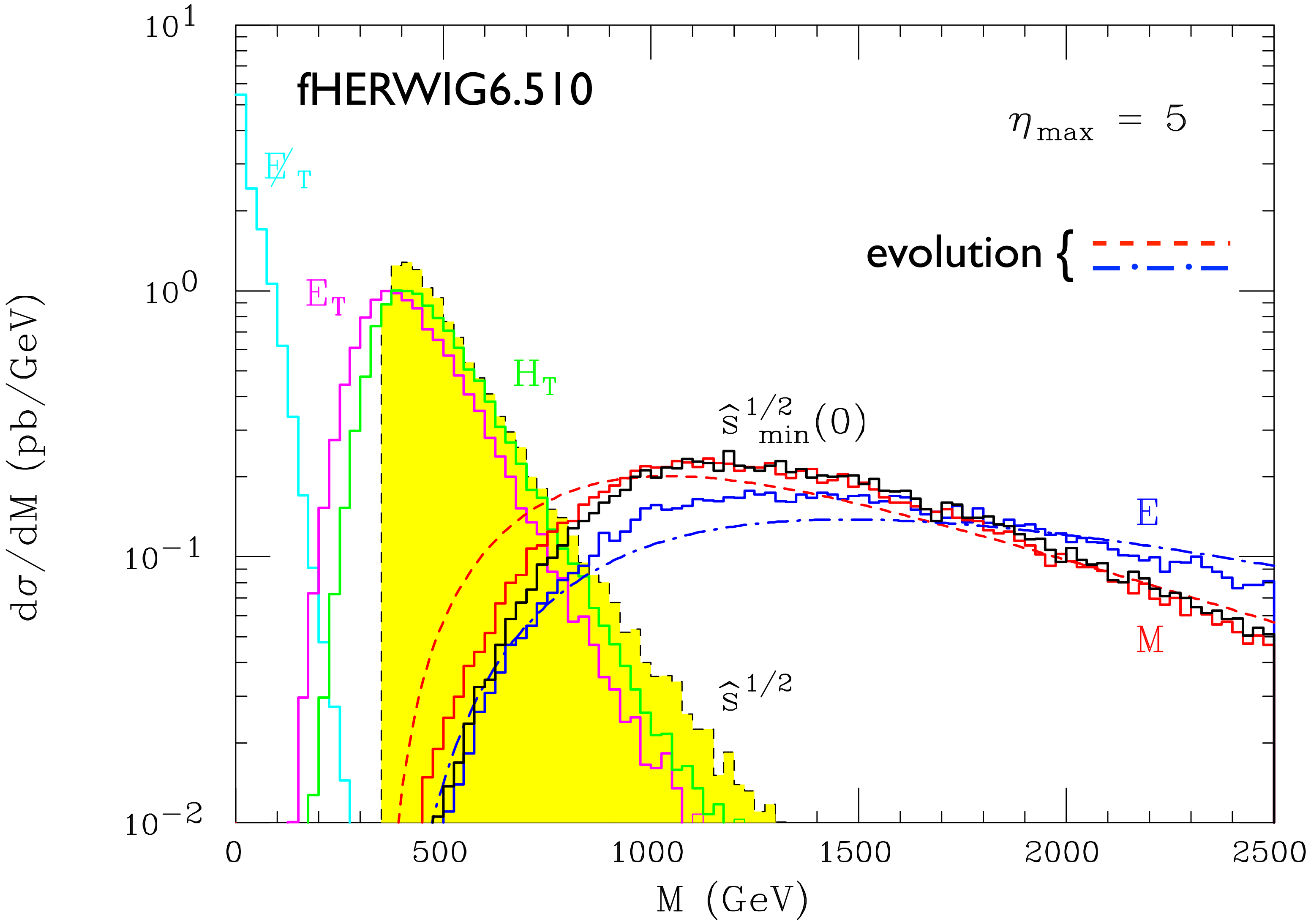
- ISR at $\theta > \theta_c \sim \exp(-\eta_{\rm max})$ enters detector
- Hard scale $Q^2 \sim \hat{s} = x_1 x_2 S$ but $M^2 = \bar{x}_1\bar{x}_2 S$
- PDFs sampled at $Q_c \sim \theta_c Q$

A Papaefstathiou & BW, JHEP 04(2010)084

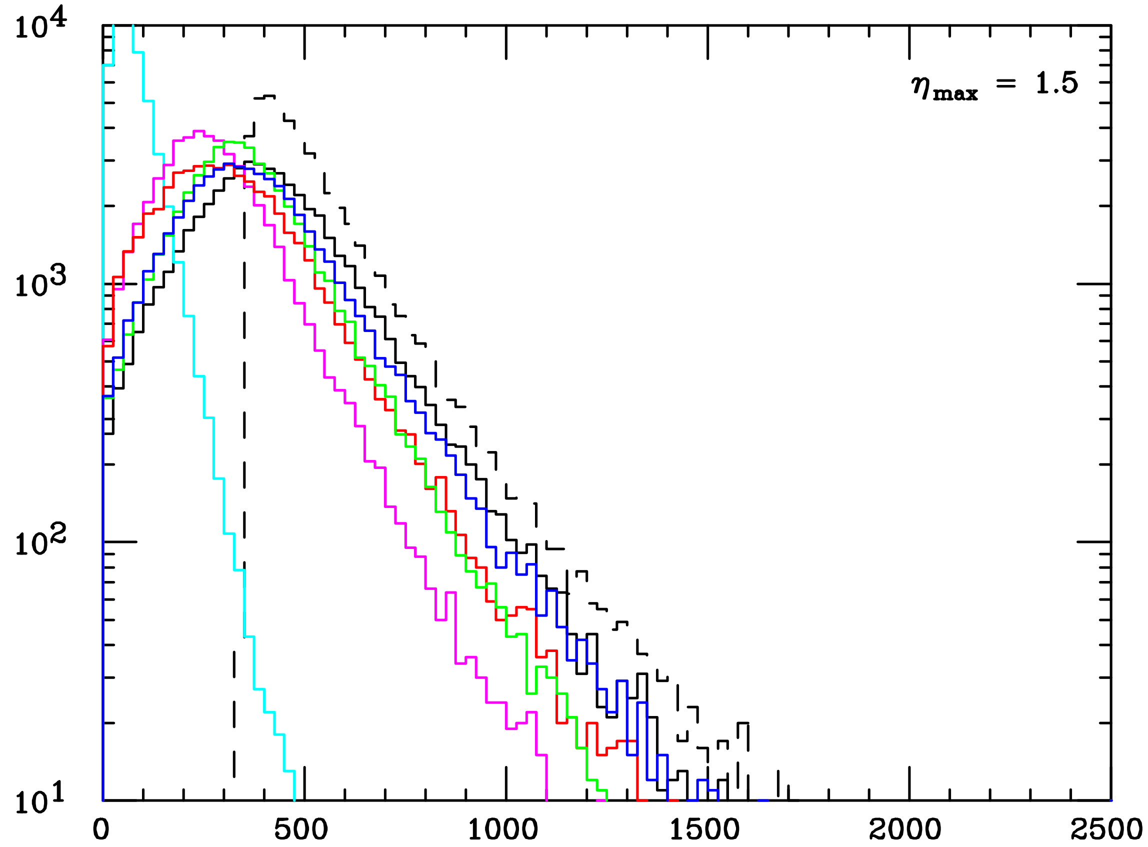
ISR Effects: MC Results

$$\hat{s}^{1/2}_{\min}(M_{\rm inv}) = \sqrt{M^2 + \not{E}_T^2} + \sqrt{M_{\rm inv}^2 + \not{E}_T^2}$$

$$M = \sqrt{E^2 - P_z^2 - \not{E}_T^2} \qquad H_T = E_T + \not{E}_T$$

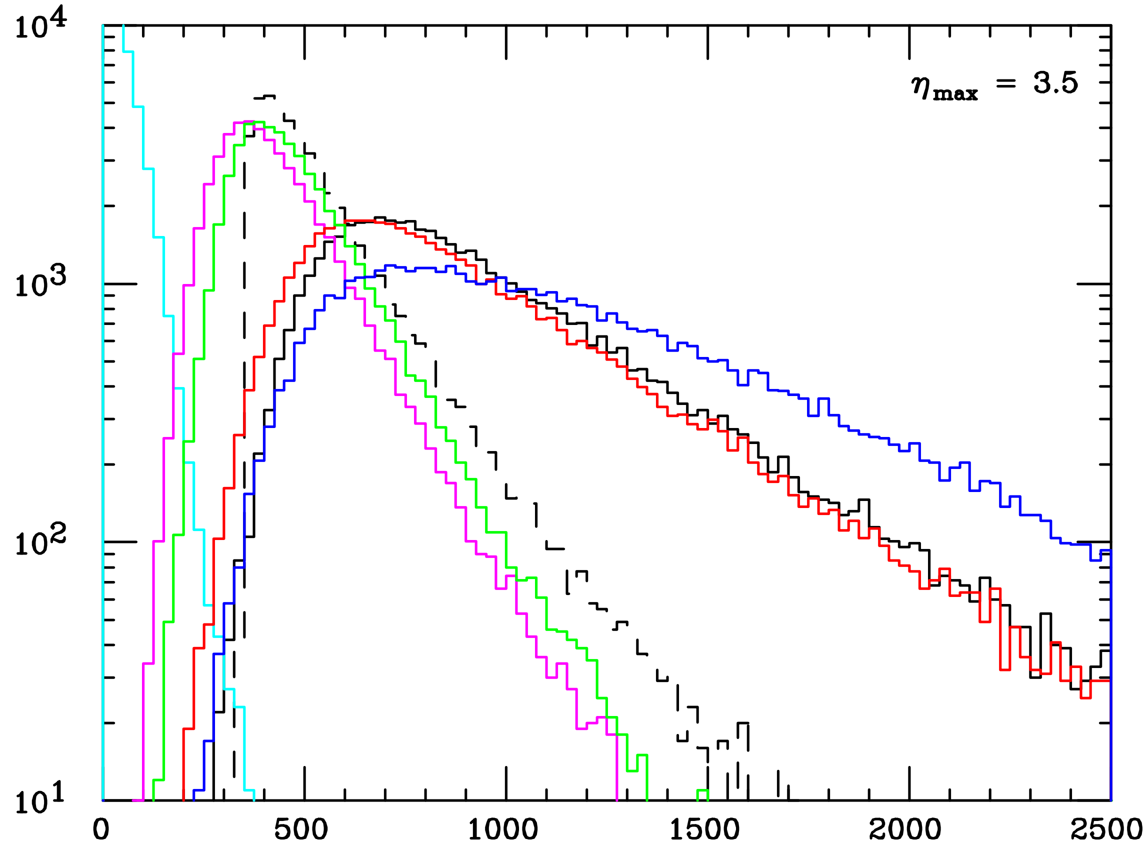


Dependence on $\eta_{\max}$



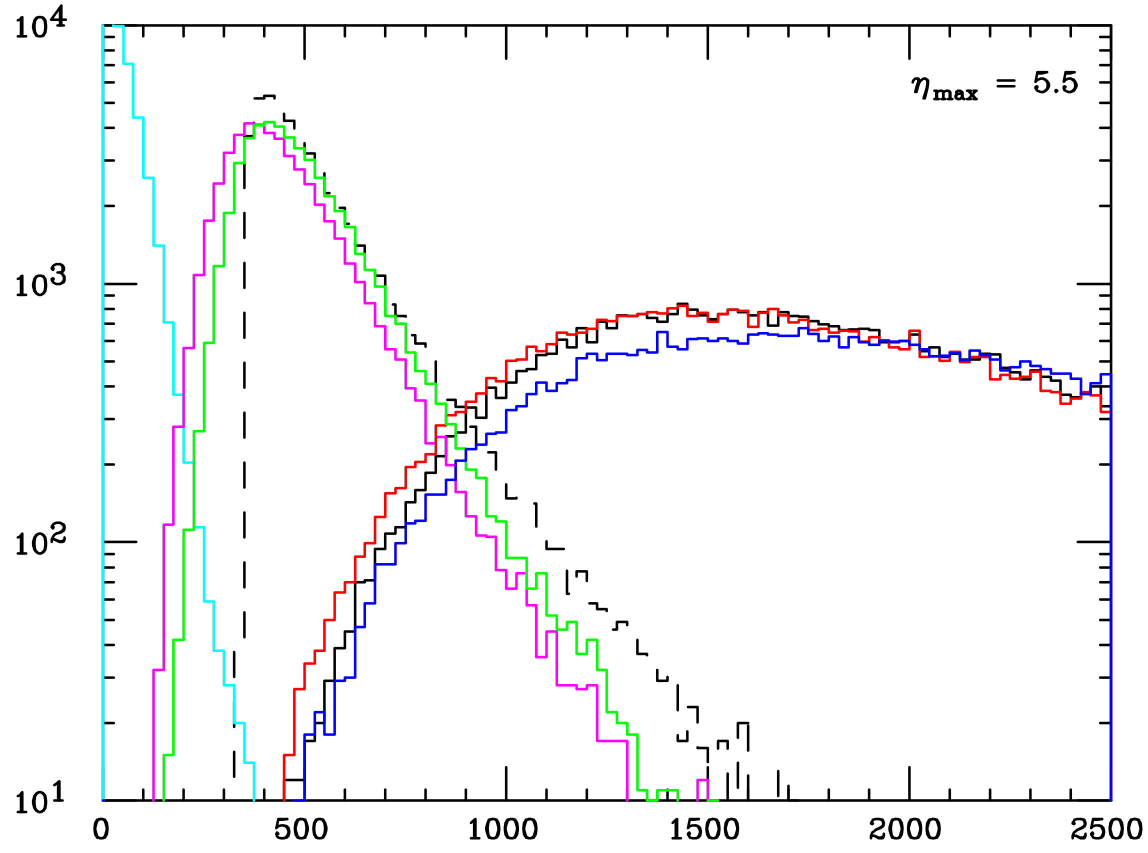
- E, M, $\hat{s}_{\min}$ strongly dependent; $\not{E}_T$, E_T, H_T not

Dependence on $\eta_{\rm max}$



- E, M, $\hat{s}_{min}$ strongly dependent; $\not{E}_T$, E_T, H_T not

Dependence on $\eta_{\max}$



- E, M, $\hat{s}_{\min}$ strongly dependent; $\not{E}_T$, E_T, H_T not

Conclusions on Masses

- M_{T2} will be an important observable
  - New ideas on reducing ISR jet contamination
- Decay chains: solving and fitting
  - Include edge information when solving
- Global inclusive observables
  - Only transverse observables are robust
  - Scale information from others?

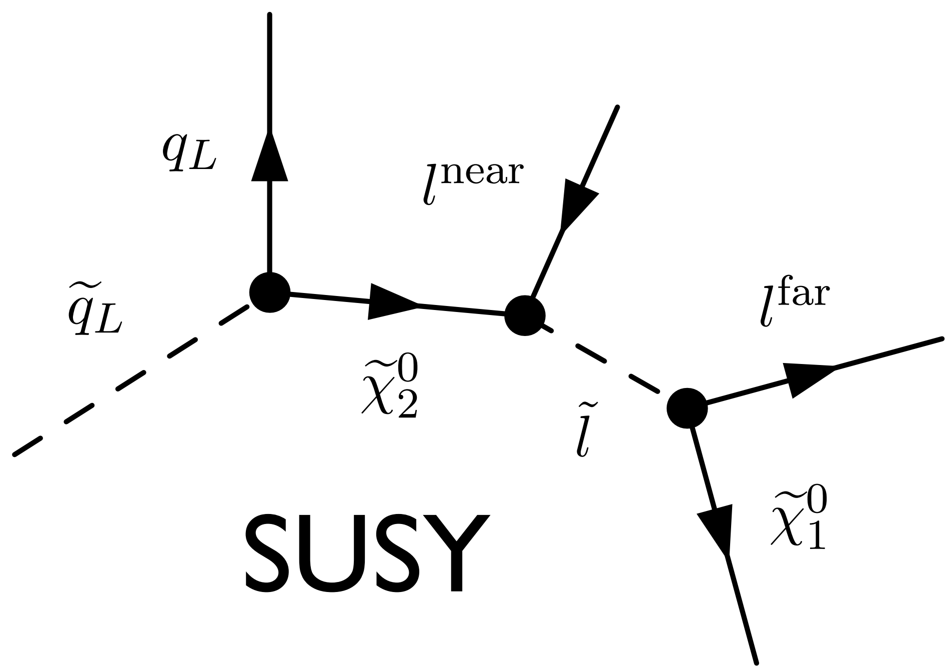
Spin Determination with ...

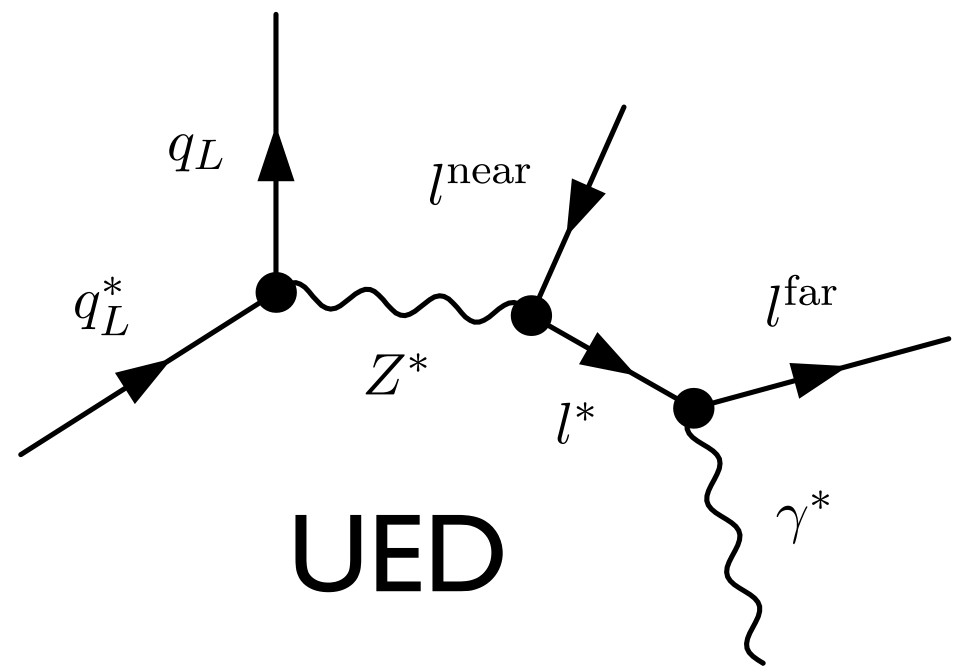
- Sequential decay chains
- Dileptons
- Three-body decays
- Cross sections

See also: review by Wang & Yavin,
Int.J.Mod.Phys. A23(2008)4647

Decay chains

"Classic" decay chain again

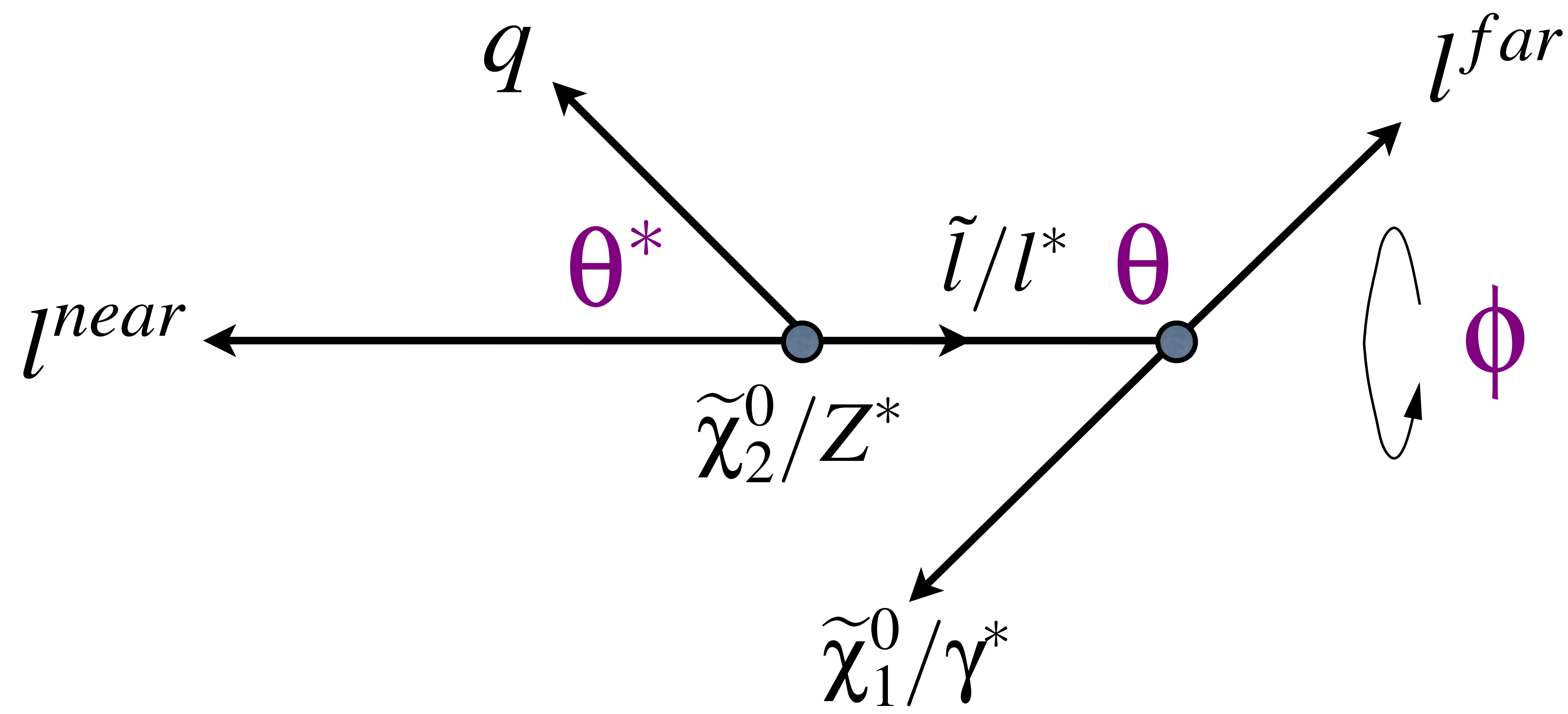




- Two distinct helicity structures, with different spin correlations:
  - Process 1: $\{q, l^{\rm near}, l^{\rm far}\} = \{q_L, l_L^-, l_L^+\}$ or $\{\bar{q}_L, l_L^+, l_L^-\}$ or $\{q_L, l_R^+, l_R^-\}$ or $\{\bar{q}_L, l_R^-, l_R^+\}$;
  - Process 2: $\{q, l^{\rm near}, l^{\rm far}\} = \{q_L, l_L^+, l_L^-\}$ or $\{\bar{q}_L, l_L^-, l_L^+\}$ or $\{q_L, l_R^-, l_R^+\}$ or $\{\bar{q}_L, l_R^+, l_R^-\}$.

Smillie & BW, JHEP 10(2005)069
Datta, Kong, Matchev, PR D72(2005)096006

Angular variables



- θ^* defined in $\tilde{\chi}_2^0/Z^*$ rest frame
- θ, ϕ defined in $\tilde{l}/l^*$ rest frame

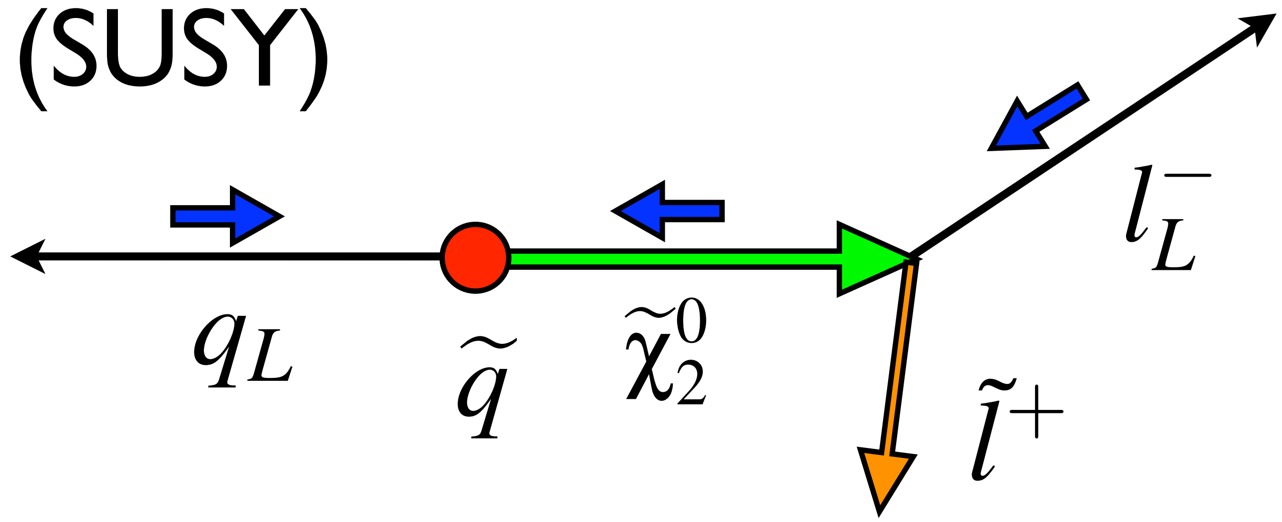
Invariant masses

- ql^{near}: $m_{ql}/(m_{ql})_{max} = \sin(\theta^*/2)$
- $l^{near}l^{far}$: $m_{ll}/(m_{ll})_{max} = \sin(\theta/2)$
- ql^{far}: $m_{ql}/(m_{ql})_{max} = \frac{1}{2}\Big[(1-y)(1-\cos\theta^*\cos\theta)+$
  $+(1-y)(\cos\theta^* - \cos\theta) - 2\sqrt{y}\sin\theta^*\sin\theta\cos\phi\Big]^{\frac{1}{2}}$

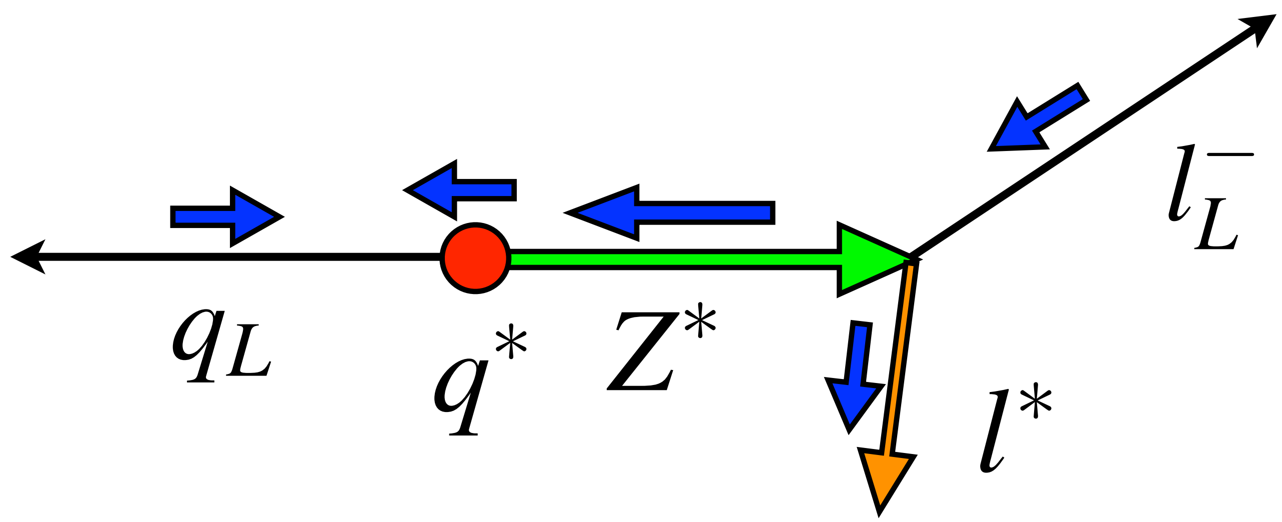
where $x = m_{Z^*}^2/m_{q^*}^2,\ y = m_{l^*}^2/m_{Z^*}^2,\ z = m_{\gamma^*}^2/m_{l^*}^2$

Helicity dependence

- Process I (SUSY)



- Process I (UED, transverse Z*: $P_T/P_L = 2x$)



➡ Both prefer high $(ql^-)^{near}$ invariant mass

UED and SUSY mass spectra

- UED models tend to have quasi-degenerate spectra

γ^*	Z^*	q_L^*	l_R^*	l_L^*
501	536	598	505	515

Table 1: UED masses in GeV, for $R^{-1} = 500\text{GeV}$, $\Lambda R = 20$, $m_h = 120\text{GeV}$, $\overline{m}_h^2 = 0$ and vanishing boundary terms at cut-off scale Λ.

($M_n \sim n/R$ broken by boundary terms and loops, with low cutoff)

- SUSY spectra typically more hierarchical

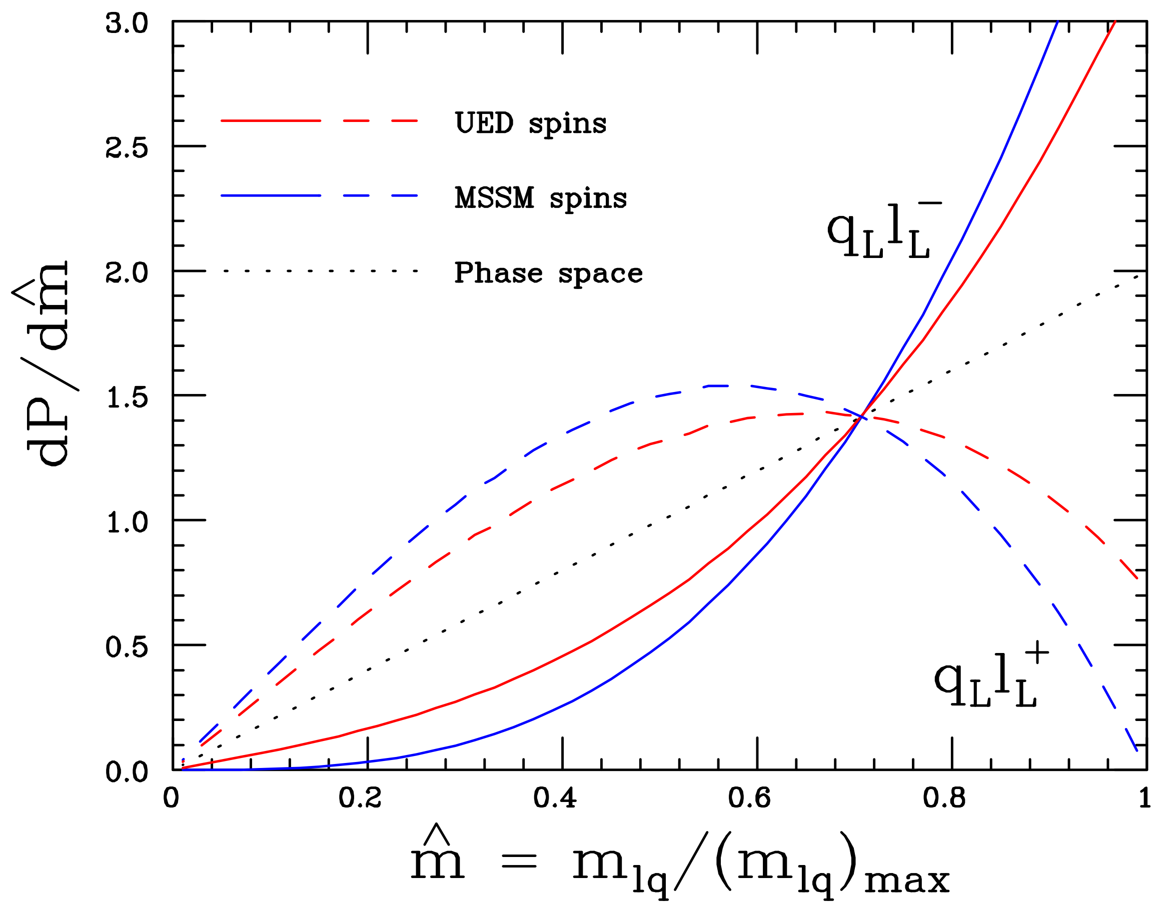
$\widetilde{\chi}_1^0$	$\widetilde{\chi}_2^0$	$\widetilde{u}_L$	$\widetilde{e}_R$	$\widetilde{e}_L$
96	177	537	143	202

Table 2: SUSY masses in GeV, for SPS point 1a.

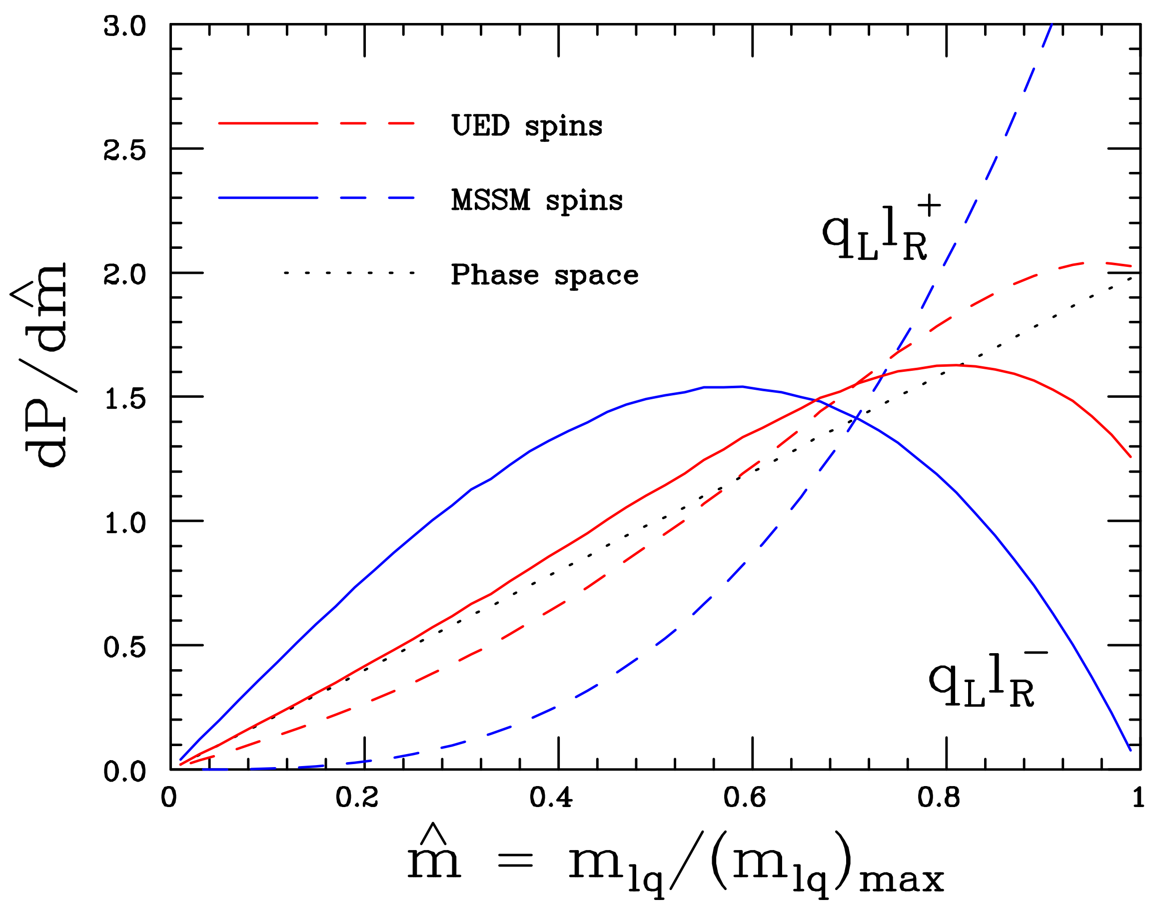
(high-scale universality)

ql^{near} mass distribution

UED masses



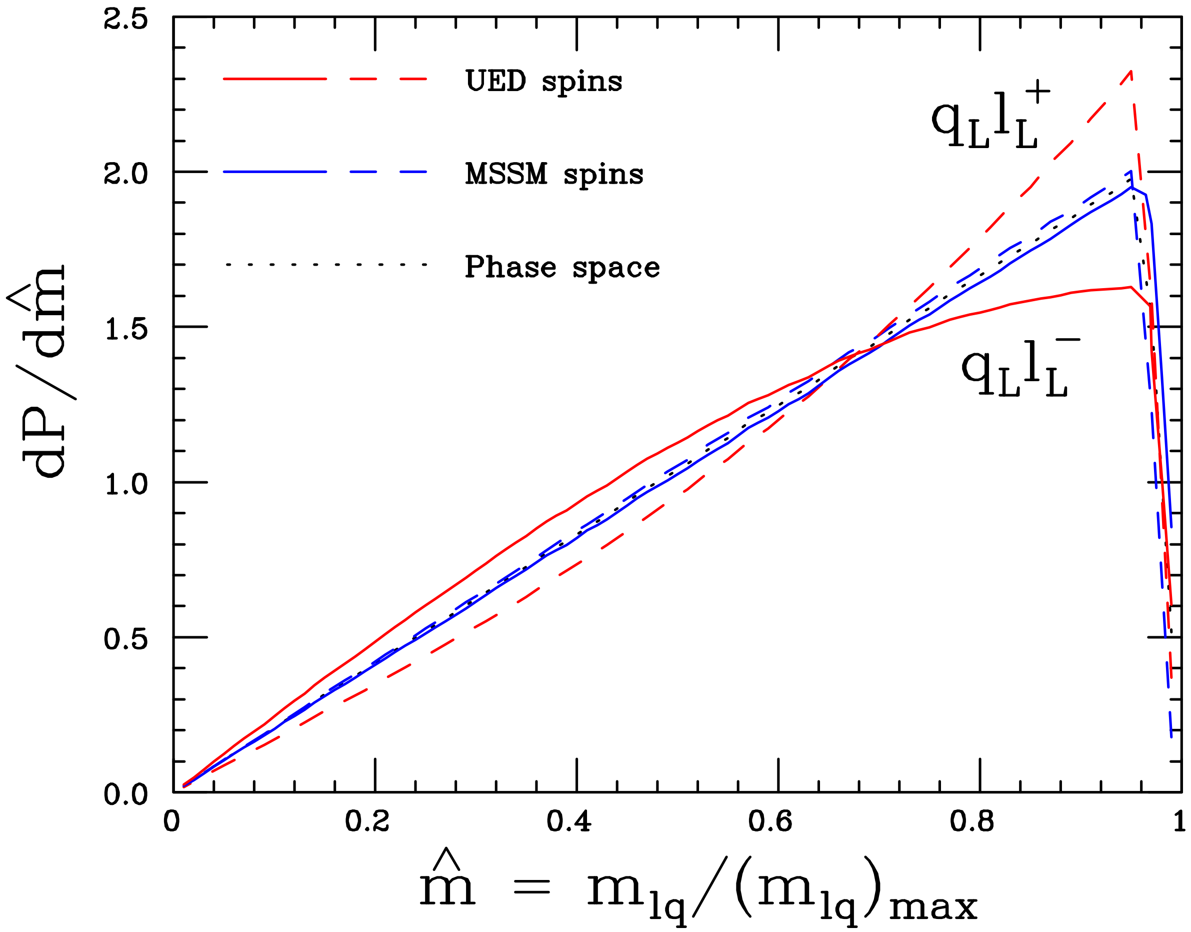
SPS 1a masses



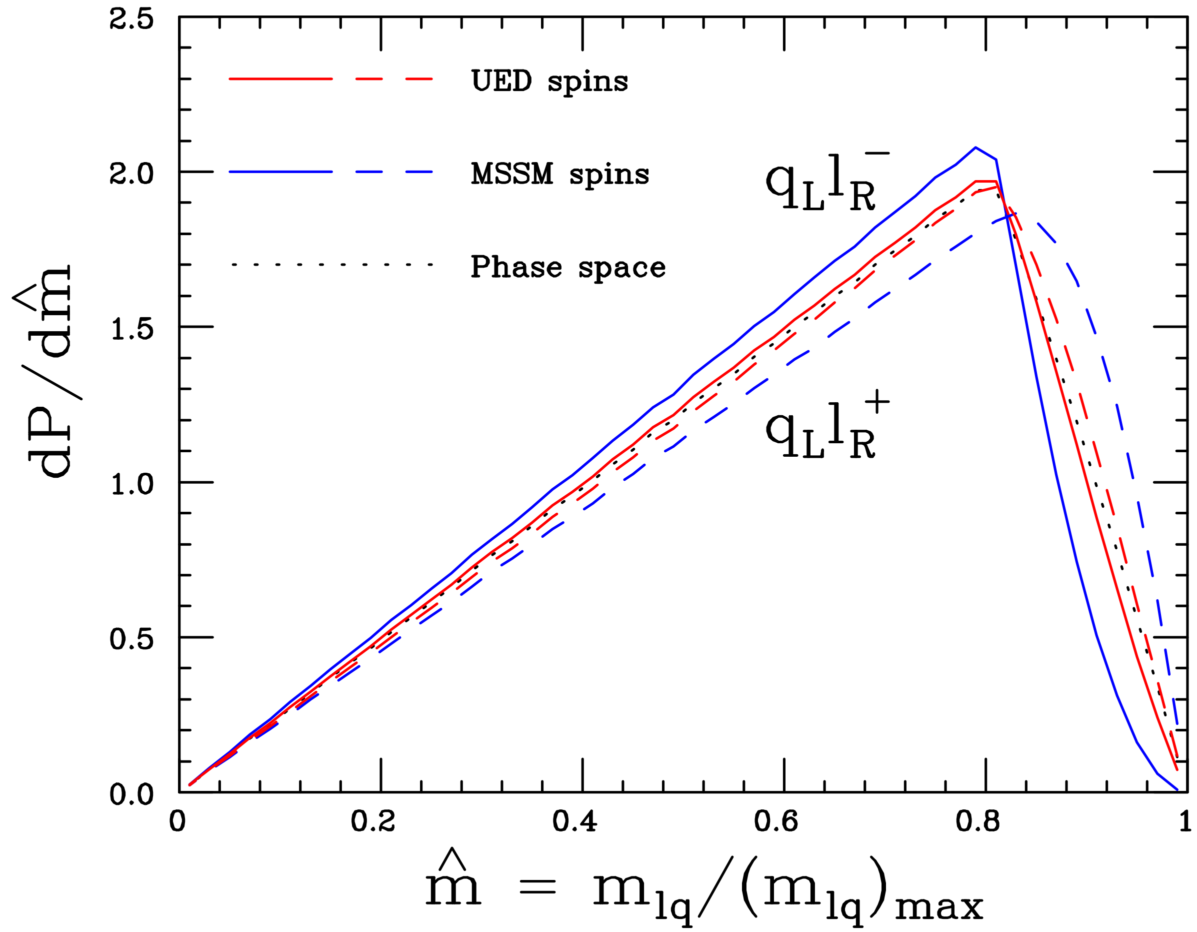
➡ UED and SUSY not distinguishable for UED masses

ql^{far} mass distribution

UED masses

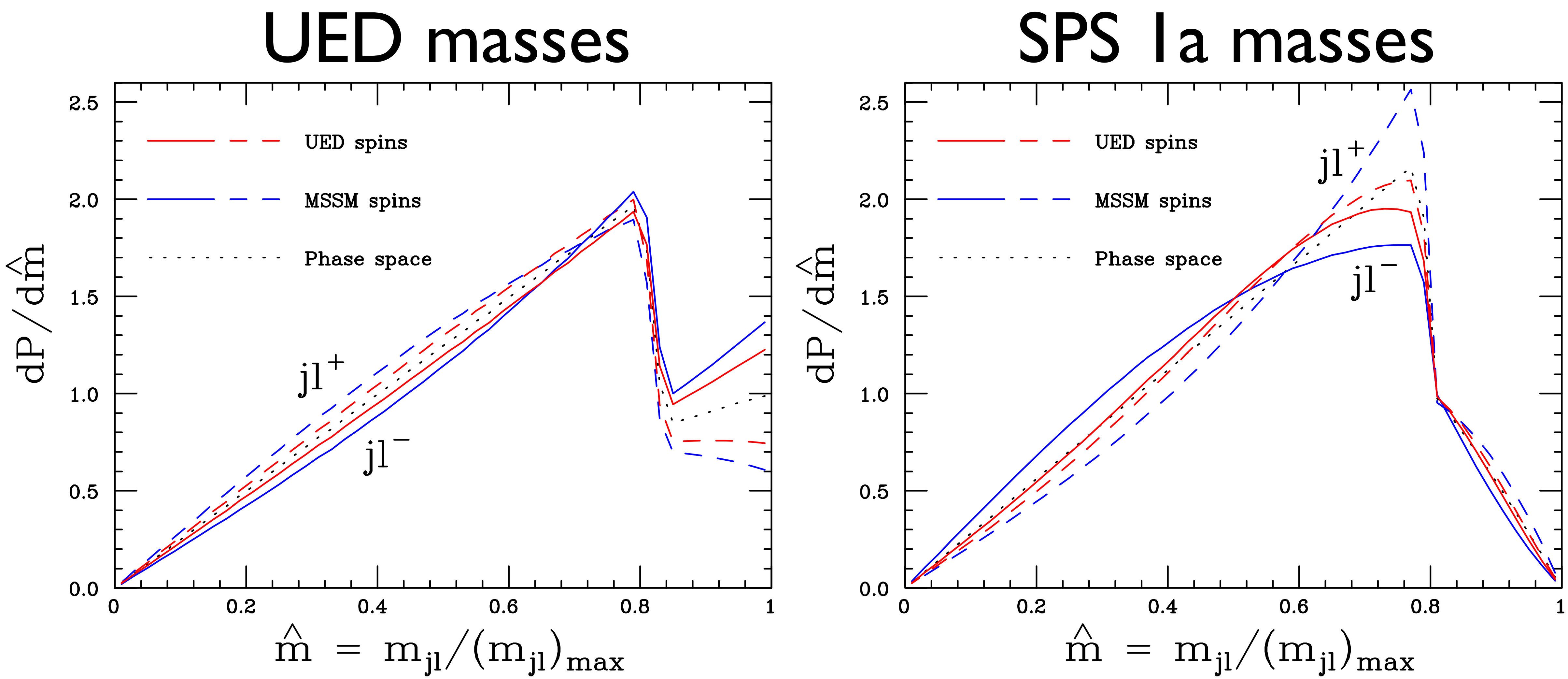


SPS 1a masses



➡ Correlation weak but slightly enhances UED-SUSY difference

Jet + lepton mass distribution



- Not resolvable for UED masses, maybe for SUSY masses
- Charge asymmetry due to quark vs antiquark excess

Production cross sections (pb)

Masses	Model	σ_{all}	σ_{q^*}	$\sigma_{\bar{q}^*}$	f_q
UED	UED	253	163	84	0.66
UED	SUSY	28	18	9	0.65
SPS 1a	UED	433	224	80	0.74
SPS 1a	SUSY	55	26	11	0.70

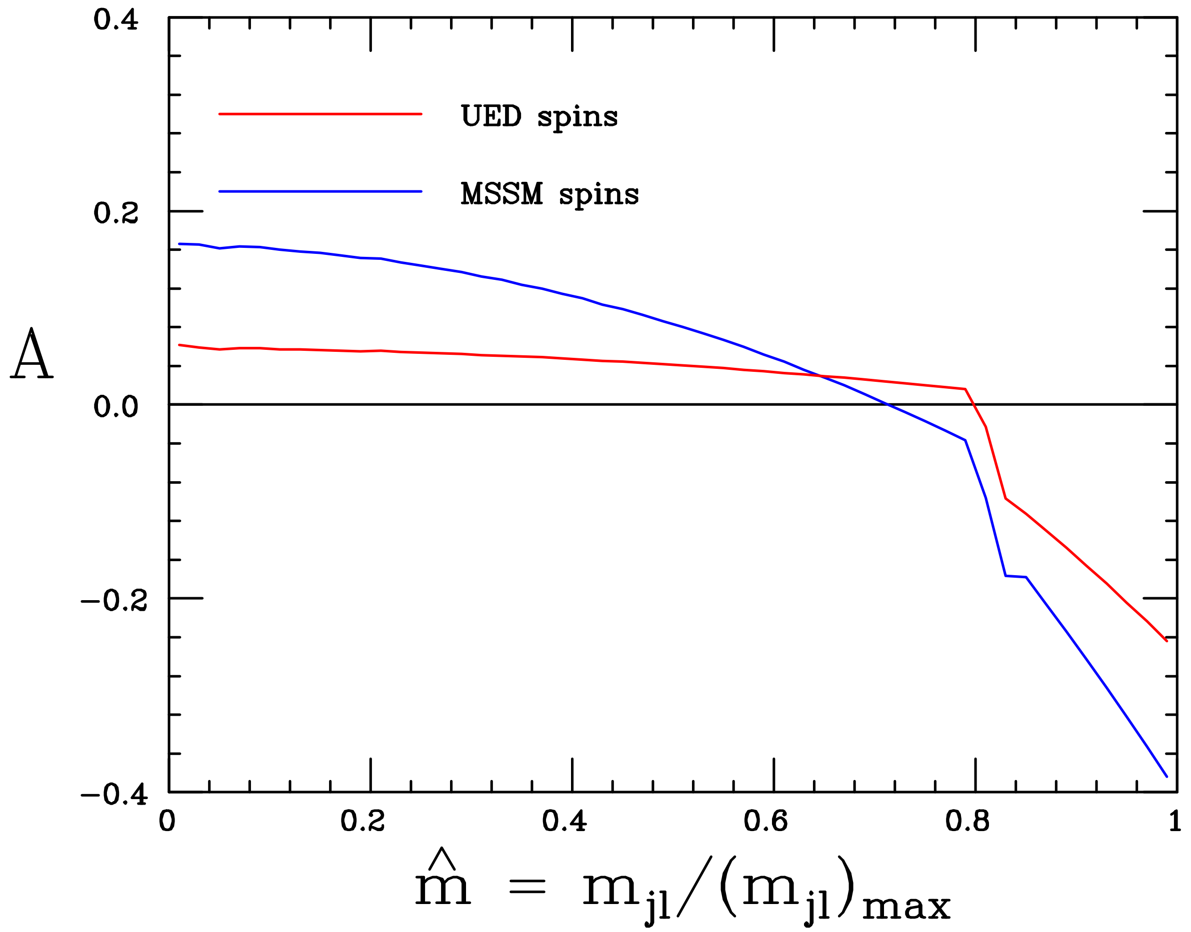
➡ $\sigma_{\text{UED}} \gg \sigma_{\text{SUSY}}$ for same masses (100 pb = 1/sec)

➡ $q^*/\bar{q}^* \sim 2 \Rightarrow$ charge asymmetry

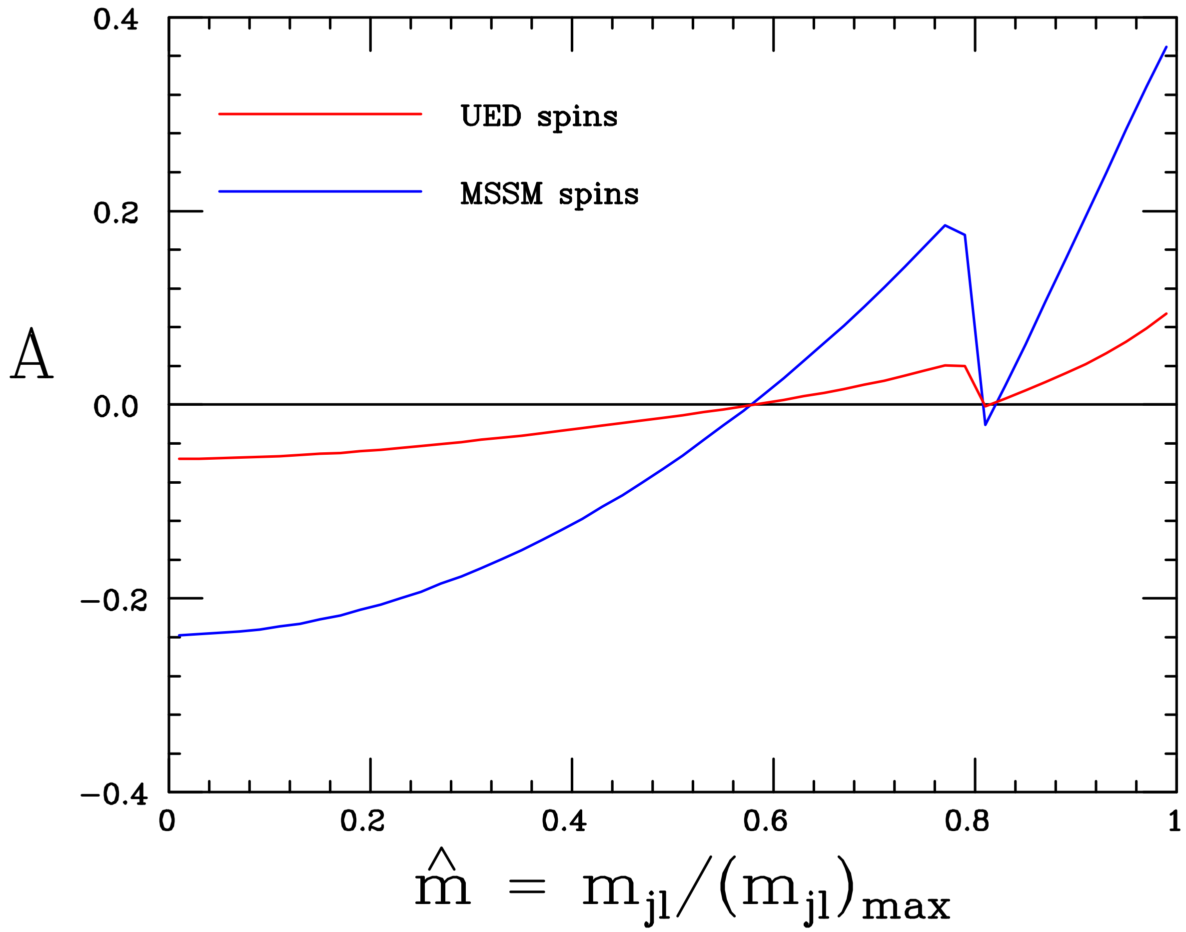
Charge asymmetry

$$A = \frac{(jl^+) - (jl^-)}{(jl^+) + (jl^-)}$$

UED masses



SPS 1a masses

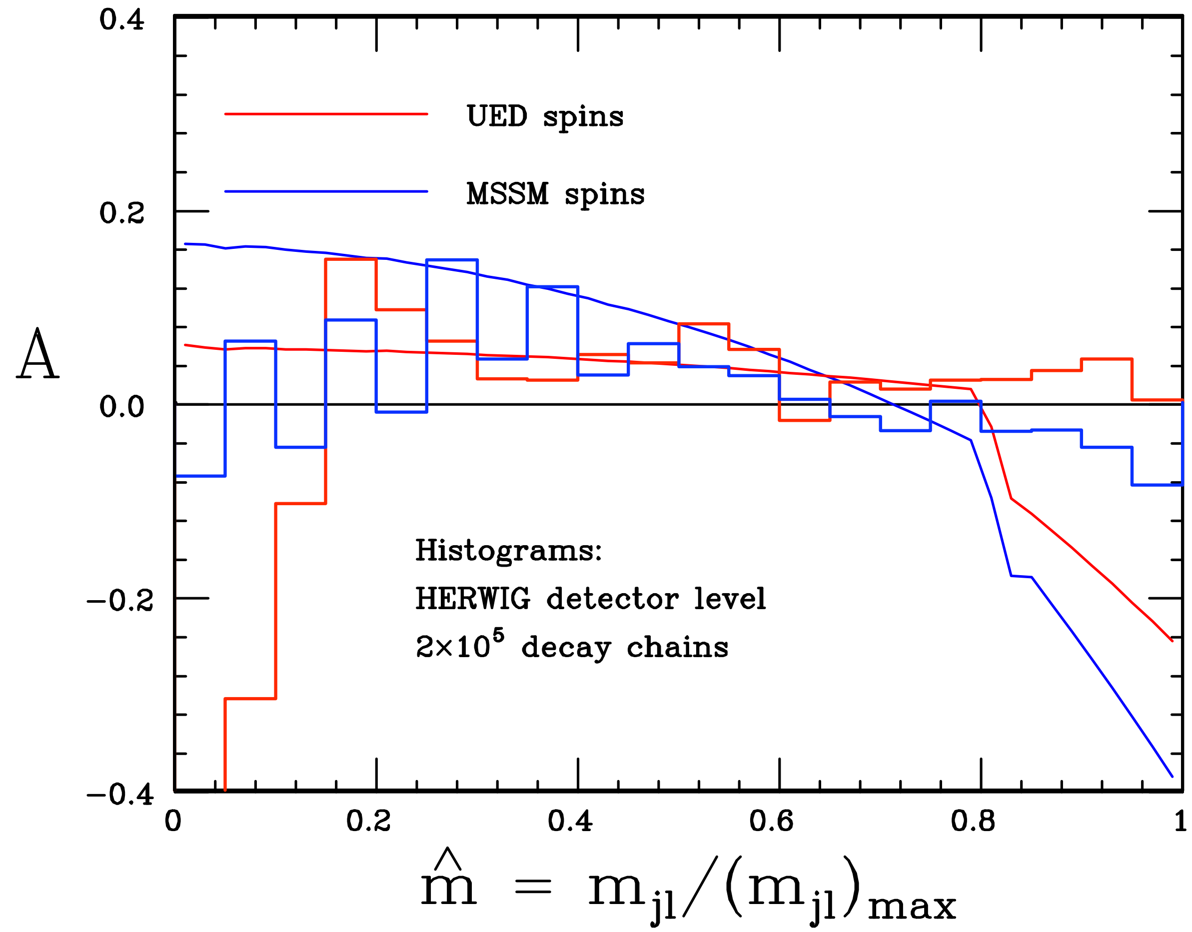


➡ Similar form, different magnitude

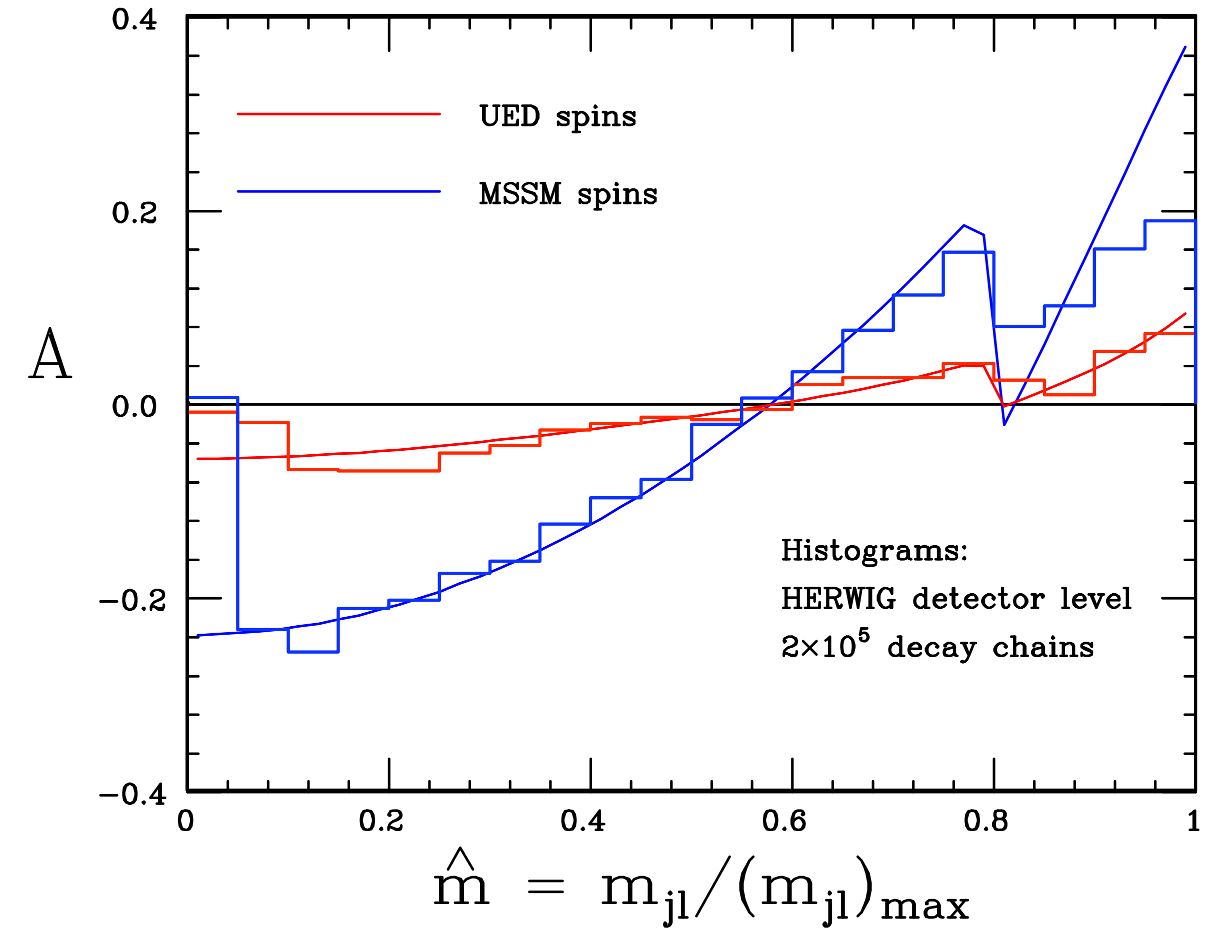
Charge asymmetry

$$A = \frac{(jl^+) - (jl^-)}{(jl^+) + (jl^-)}$$

UED masses



SPS 1a masses

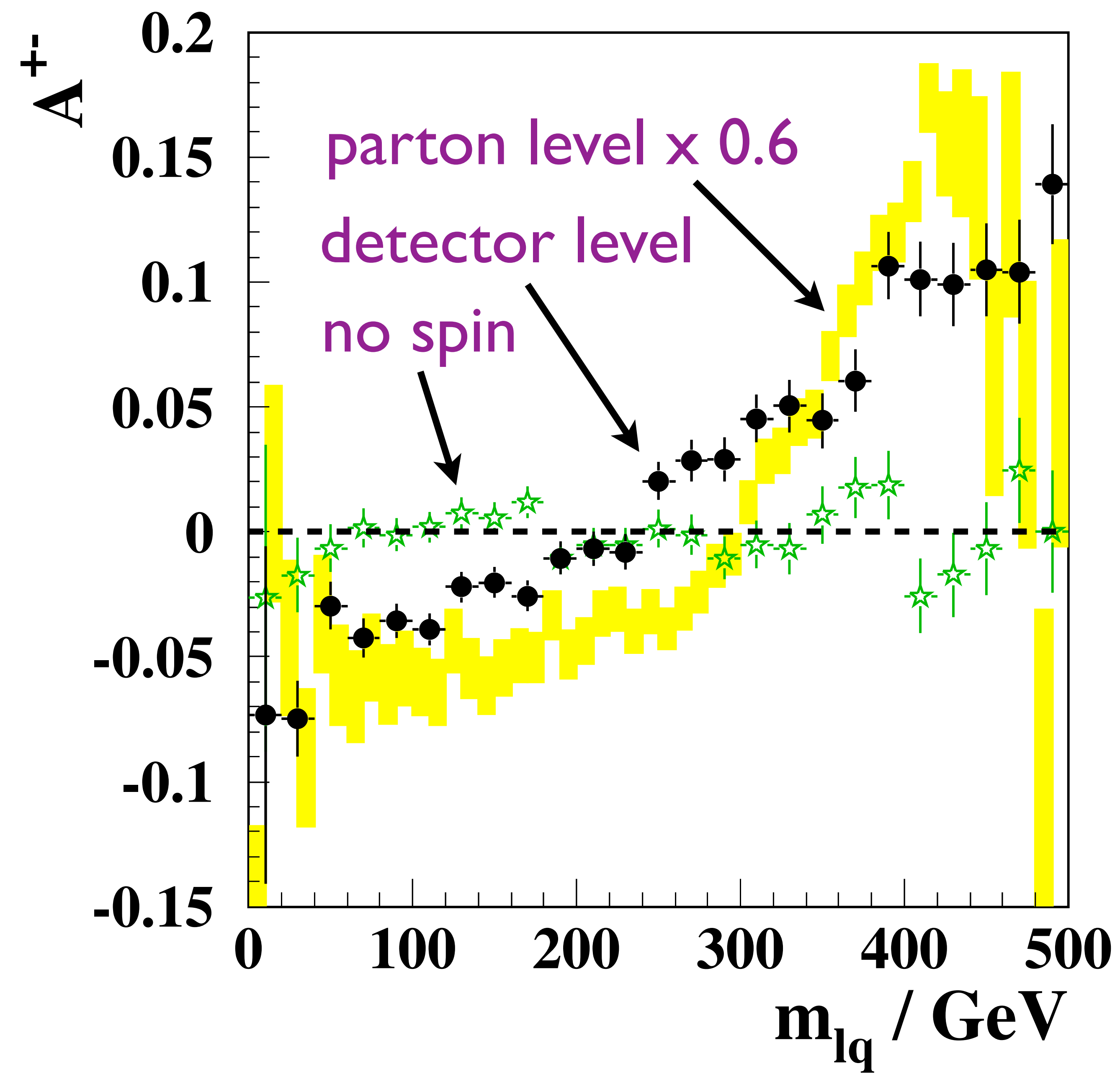


- Similar form, different magnitude
- Not detectable for UED masses

Charge asymmetry at detector level

A Barr, hep-ph/0405052

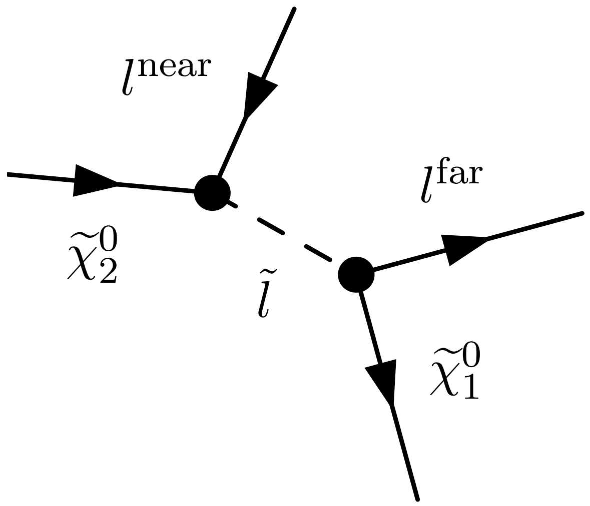
- Same decay chain:
  $\tilde{q}_L \to \tilde{\chi}_2^0 q_L \to \tilde{l}_R^{\pm} l^{\mp} q_L$
- Different MSSM point (now excluded)
- Compared with no spin (i.e. phase space) only
- More careful study of background and detector effects
- Points are for 500 fb^{-1}
- Used HERWIG

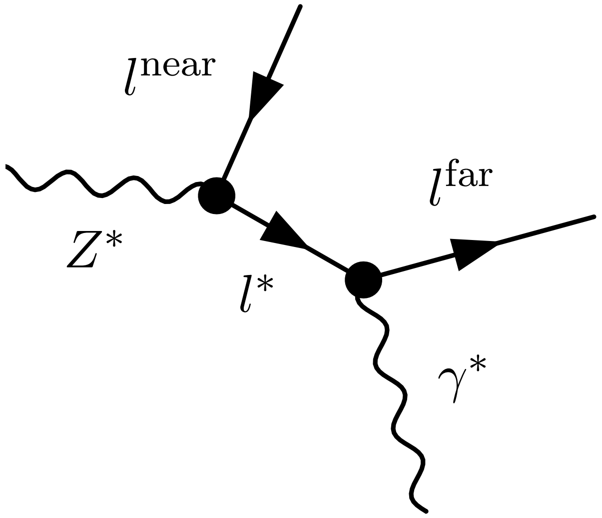


See also: Goto, Kawagoe, Nojiri, PR D70(2004)075016

Dileptons

Dileptons in “classic” chain



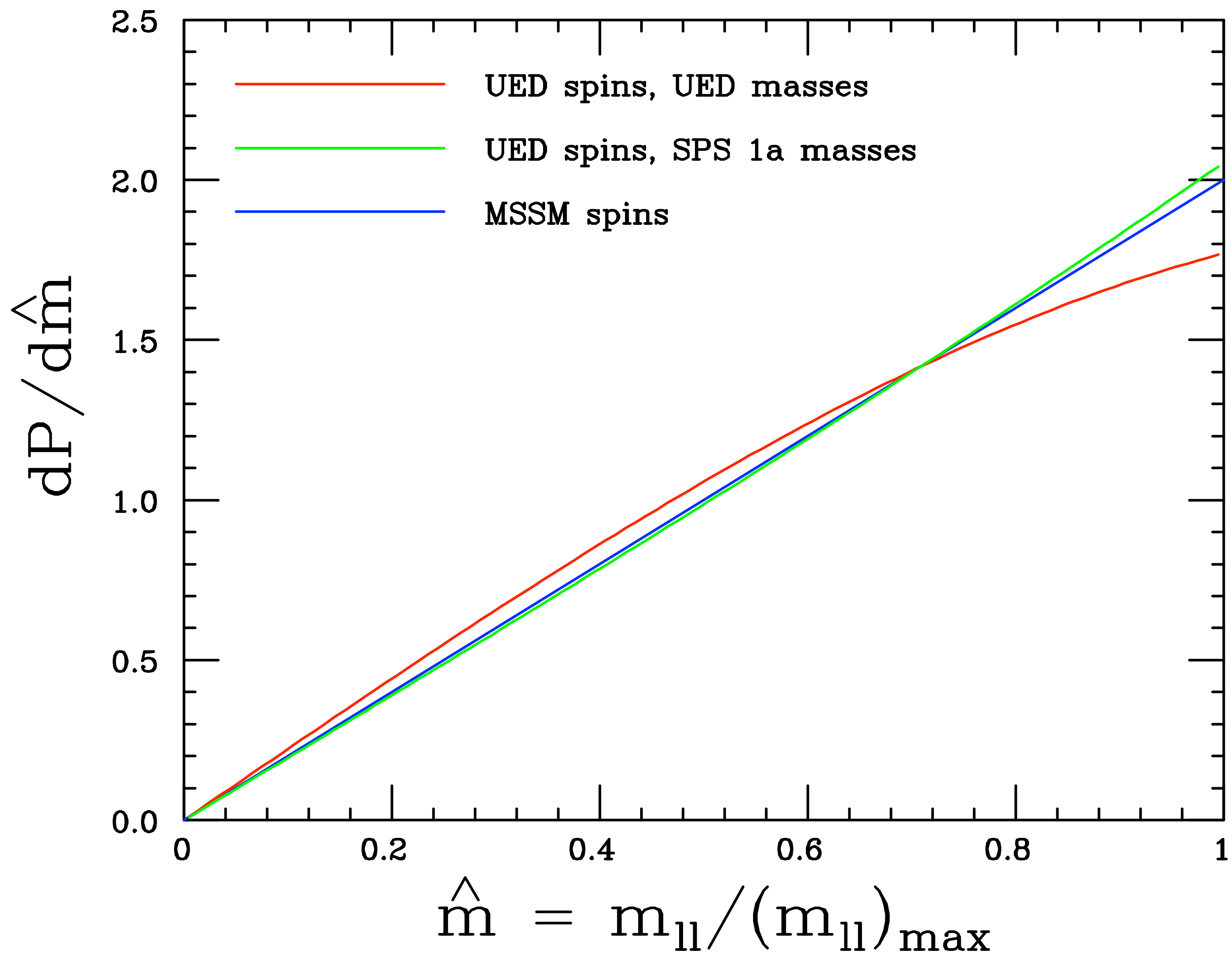


$$\frac{dP^{UED}}{d\widehat{m}_{ll}} = \frac{4\widehat{m}_{ll}}{(2+y)(1+2z)}\left[y+4z+(2-y)(1-2z)\widehat{m}_{ll}^2\right]$$

- $y = m_{l^*}^2/m_{Z^*}^2$ and $z = m_{\gamma^*}^2/m_{l^*}^2$
- UED: $y = 0.92 \quad z = 0.95$
- SPS 1a: $y = 0.65 \quad z = 0.45$

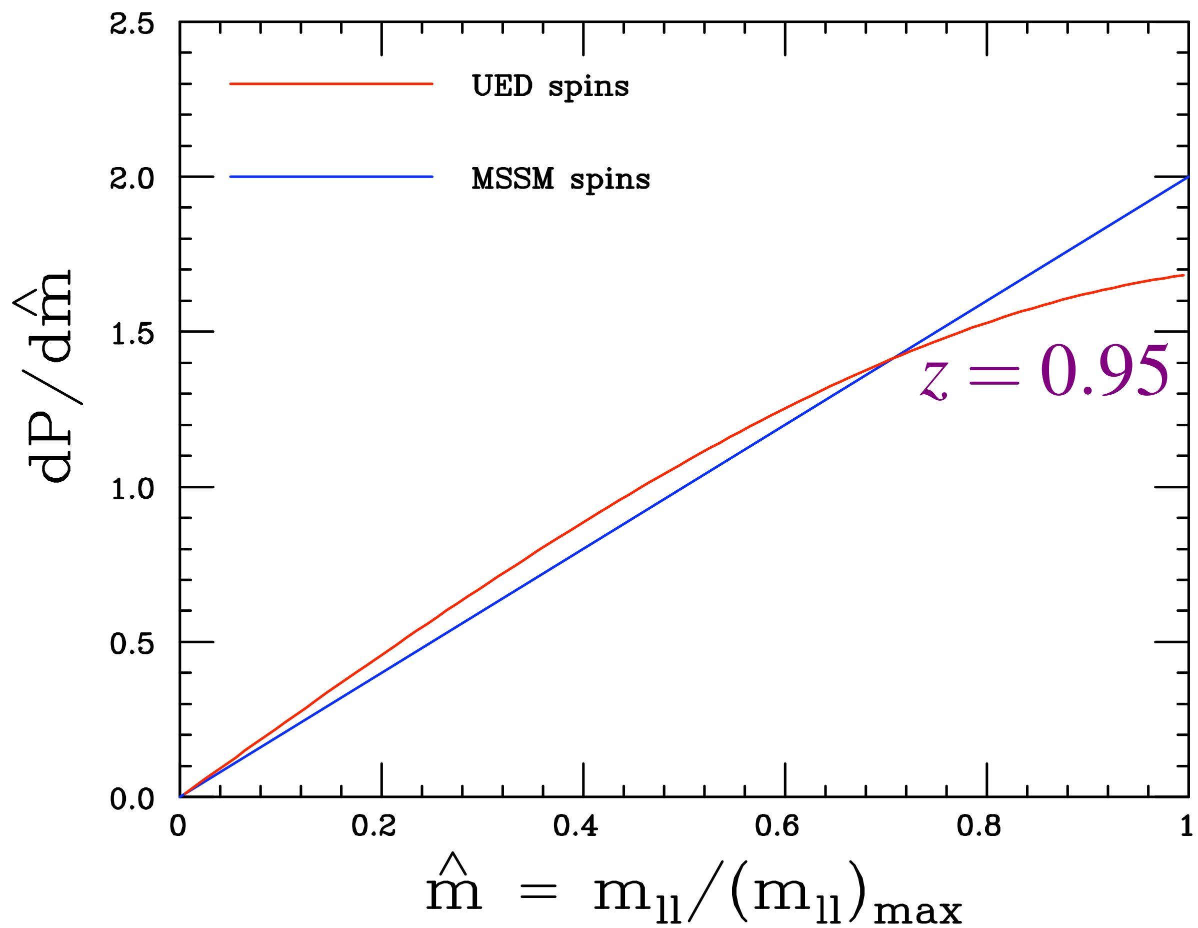
➡ Sensitivity greatest at small y and z

Dilepton mass distribution



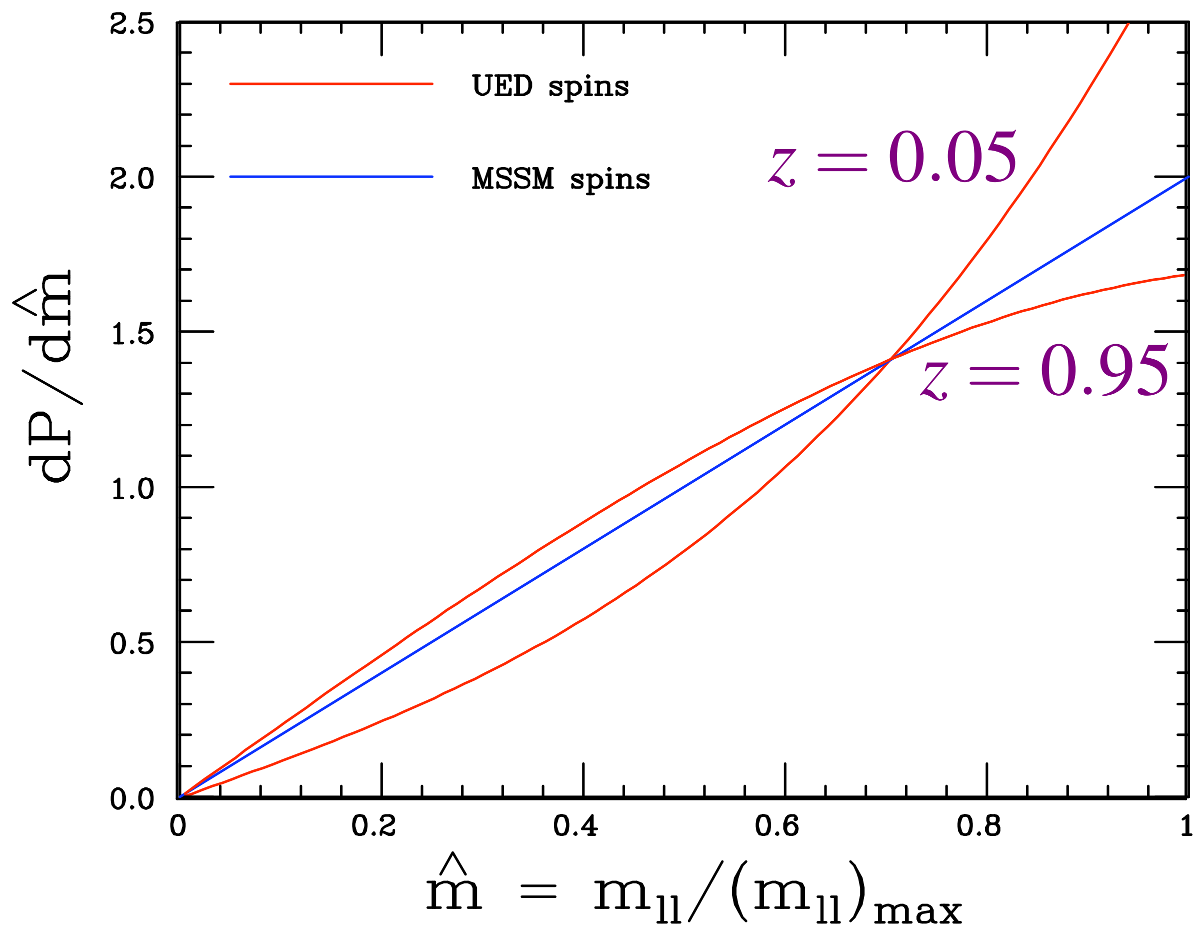
➡ No sensitivity for these masses!

Dilepton mass distribution (2)



$$y = m_{l^*}^2/m_{Z^*}^2 = 0.65\,,\;\; z = m_{\gamma^*}^2/m_{l^*}^2 = 0.95 - 0.05$$

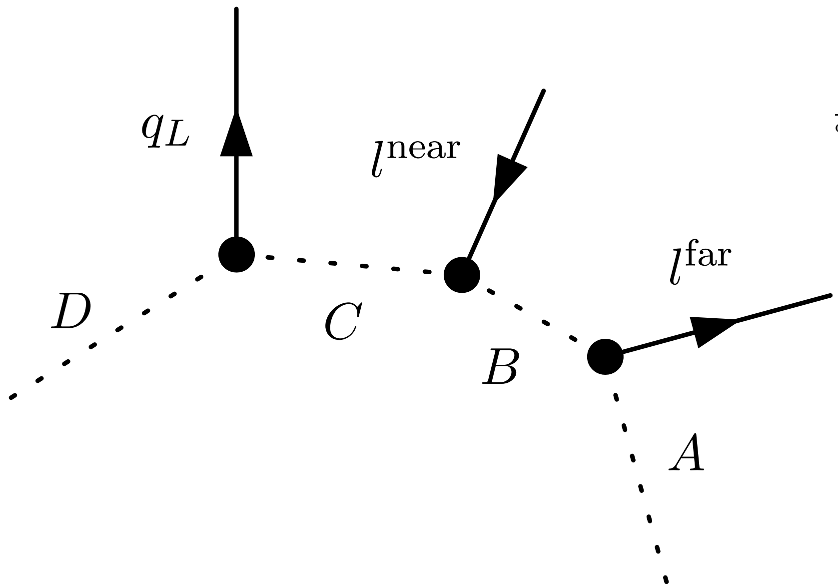
Dilepton mass distribution (2)



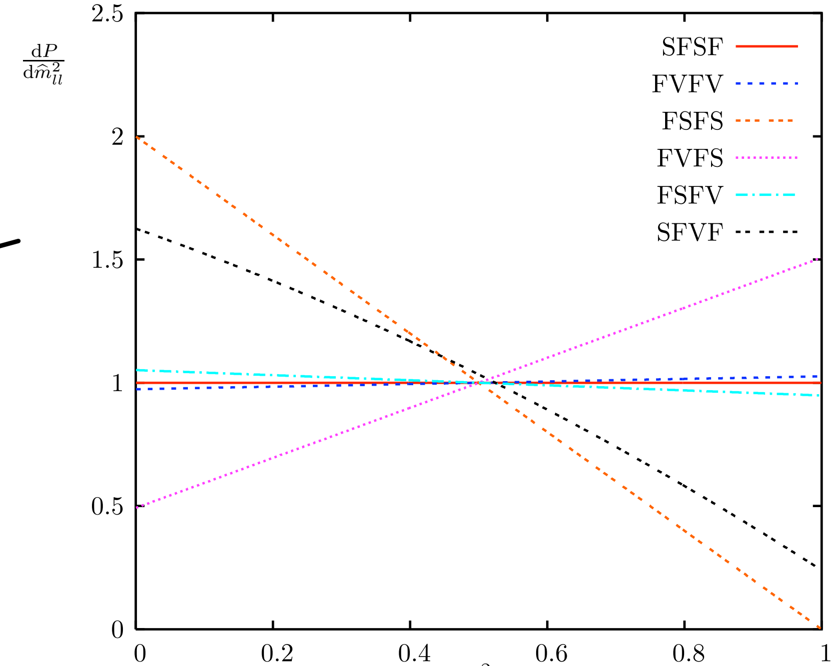
$$y = m_{l^*}^2/m_{Z^*}^2 = 0.65\,,\;\; z = m_{\gamma^*}^2/m_{l^*}^2 = 0.95 - 0.05$$

➡ Independent of masses and spins at $\widehat{m} = 1/\sqrt{2}$ $(\theta = \pi/2)$

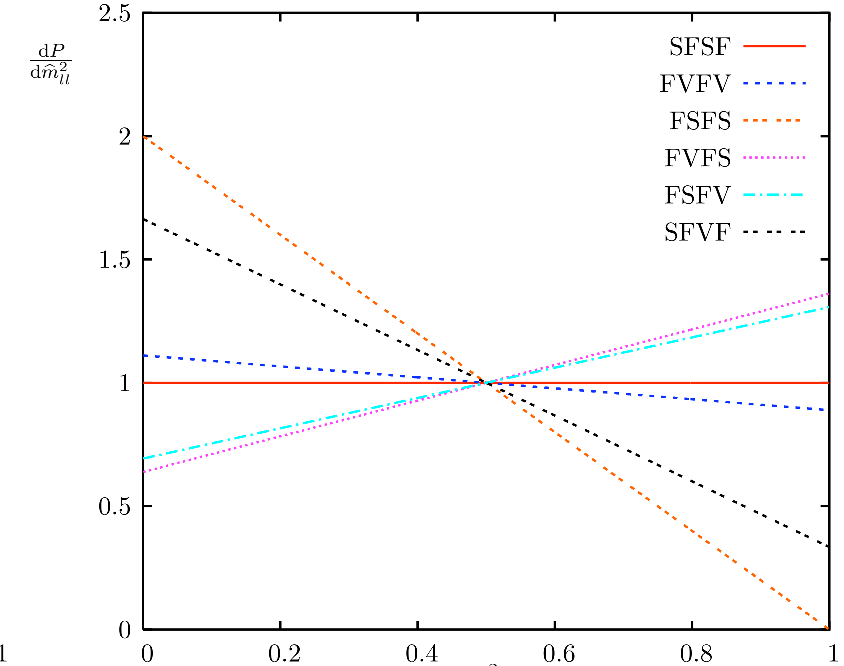
All possible spin assignments



A	B	C	D
$\tilde{\chi}_1^0$	$\tilde{e}_R$	$\tilde{\chi}_2^0$	$\tilde{u}_L$
96	143	177	537



A	B	C	D
γ^*	l_L^*	Z^*	q_L^*
800	824	851	956



Dilepton invariant mass-squared

D	C	B	A
Scalar	Fermion	Scalar	Fermion
Fermion	Vector	Fermion	Vector
Fermion	Scalar	Fermion	Scalar
Fermion	Vector	Fermion	Scalar
Fermion	Scalar	Fermion	Vector
Scalar	Fermion	Vector	Fermion

← SUSY
← UED } not distinguishable

... but some others are.

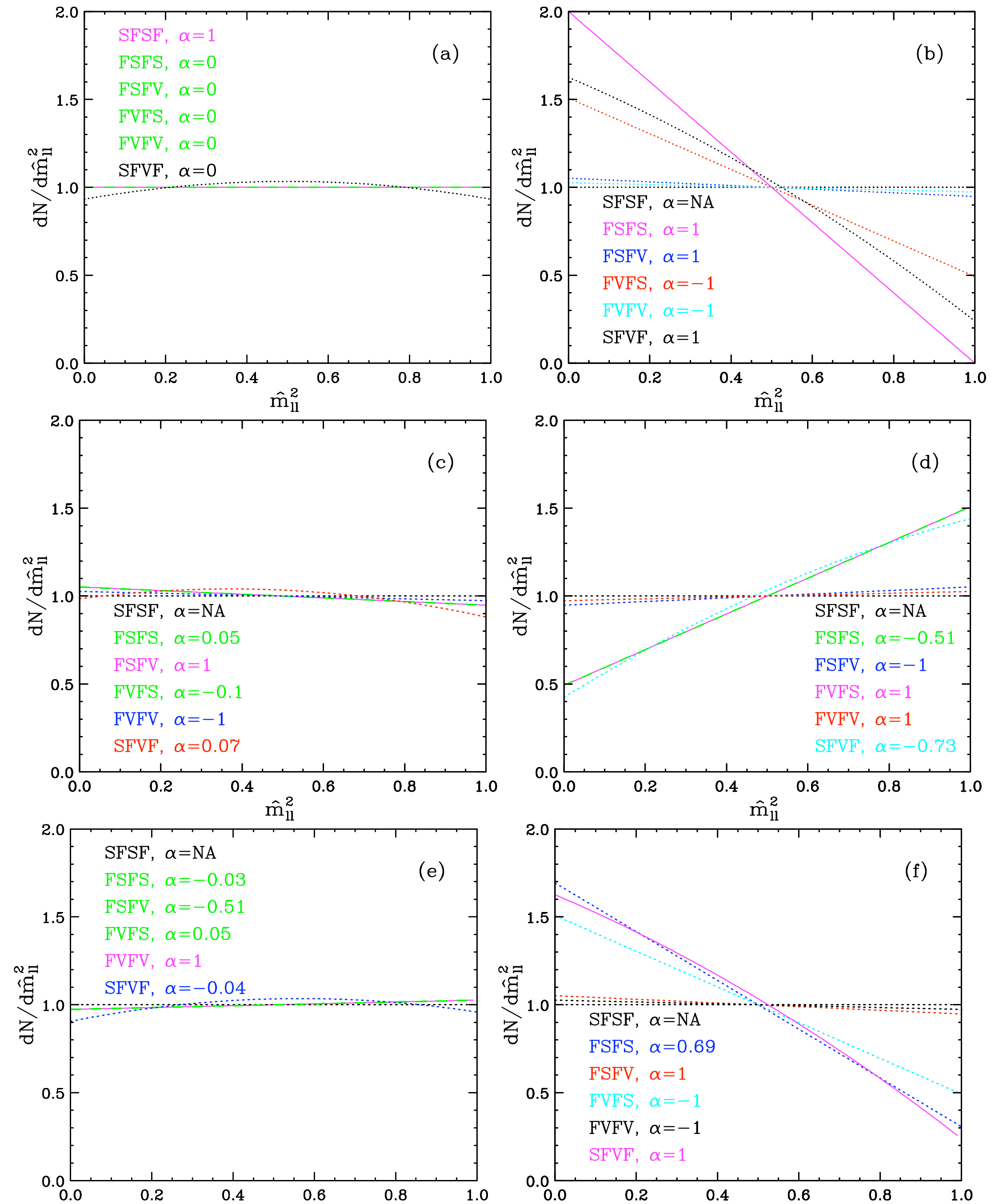
Athanasiou, Lester, Smillie, BW, JHEP 08(2006)055

All possible assignments (2)

Allowing arbitrary mixtures of L and R couplings:

Processes P_{11}		Processes P_{12}	
$\{q_L, \ell_L^-, \ell_L^+\}$ $f\lvert c_L\rvert^2\lvert b_L\rvert^2\lvert a_L\rvert^2$	$\{\bar{q}_L, \ell_L^+, \ell_L^-\}$ $\bar{f}\lvert c_L\rvert^2\lvert b_L\rvert^2\lvert a_L\rvert^2$	$\{q_L, \ell_L^-, \ell_R^+\}$ $f\lvert c_L\rvert^2\lvert b_L\rvert^2\lvert a_R\rvert^2$	$\{\bar{q}_L, \ell_L^+, \ell_R^-\}$ $\bar{f}\lvert c_L\rvert^2\lvert b_L\rvert^2\lvert a_R\rvert^2$
$\{\bar{q}_L, \ell_R^-, \ell_R^+\}$ $\bar{f}\lvert c_L\rvert^2\lvert b_R\rvert^2\lvert a_R\rvert^2$	$\{q_L, \ell_R^+, \ell_R^-\}$ $f\lvert c_L\rvert^2\lvert b_R\rvert^2\lvert a_R\rvert^2$	$\{\bar{q}_L, \ell_R^-, \ell_L^+\}$ $\bar{f}\lvert c_L\rvert^2\lvert b_R\rvert^2\lvert a_L\rvert^2$	$\{q_L, \ell_R^+, \ell_L^-\}$ $f\lvert c_L\rvert^2\lvert b_R\rvert^2\lvert a_L\rvert^2$
$\{q_R, \ell_R^-, \ell_R^+\}$ $f\lvert c_R\rvert^2\lvert b_R\rvert^2\lvert a_R\rvert^2$	$\{\bar{q}_R, \ell_R^+, \ell_R^-\}$ $\bar{f}\lvert c_R\rvert^2\lvert b_R\rvert^2\lvert a_R\rvert^2$	$\{q_R, \ell_R^-, \ell_L^+\}$ $f\lvert c_R\rvert^2\lvert b_R\rvert^2\lvert a_L\rvert^2$	$\{\bar{q}_R, \ell_R^+, \ell_L^-\}$ $\bar{f}\lvert c_R\rvert^2\lvert b_R\rvert^2\lvert a_L\rvert^2$
$\{\bar{q}_R, \ell_L^-, \ell_L^+\}$ $\bar{f}\lvert c_R\rvert^2\lvert b_L\rvert^2\lvert a_L\rvert^2$	$\{q_R, \ell_L^+, \ell_L^-\}$ $f\lvert c_R\rvert^2\lvert b_L\rvert^2\lvert a_L\rvert^2$	$\{\bar{q}_R, \ell_L^-, \ell_R^+\}$ $\bar{f}\lvert c_R\rvert^2\lvert b_L\rvert^2\lvert a_R\rvert^2$	$\{q_R, \ell_L^+, \ell_R^-\}$ $f\lvert c_R\rvert^2\lvert b_L\rvert^2\lvert a_R\rvert^2$
$\{\bar{q}_L, \ell_L^-, \ell_L^+\}$ $\bar{f}\lvert c_L\rvert^2\lvert b_L\rvert^2\lvert a_L\rvert^2$	$\{q_L, \ell_L^+, \ell_L^-\}$ $f\lvert c_L\rvert^2\lvert b_L\rvert^2\lvert a_L\rvert^2$	$\{\bar{q}_L, \ell_L^-, \ell_R^+\}$ $\bar{f}\lvert c_L\rvert^2\lvert b_L\rvert^2\lvert a_R\rvert^2$	$\{q_L, \ell_L^+, \ell_R^-\}$ $f\lvert c_L\rvert^2\lvert b_L\rvert^2\lvert a_R\rvert^2$
$\{q_L, \ell_R^-, \ell_R^+\}$ $f\lvert c_L\rvert^2\lvert b_R\rvert^2\lvert a_R\rvert^2$	$\{\bar{q}_L, \ell_R^+, \ell_R^-\}$ $\bar{f}\lvert c_L\rvert^2\lvert b_R\rvert^2\lvert a_R\rvert^2$	$\{q_L, \ell_R^-, \ell_L^+\}$ $f\lvert c_L\rvert^2\lvert b_R\rvert^2\lvert a_L\rvert^2$	$\{\bar{q}_L, \ell_R^+, \ell_L^-\}$ $\bar{f}\lvert c_L\rvert^2\lvert b_R\rvert^2\lvert a_L\rvert^2$
$\{\bar{q}_R, \ell_R^-, \ell_R^+\}$ $\bar{f}\lvert c_R\rvert^2\lvert b_R\rvert^2\lvert a_R\rvert^2$	$\{q_R, \ell_R^+, \ell_R^-\}$ $f\lvert c_R\rvert^2\lvert b_R\rvert^2\lvert a_R\rvert^2$	$\{\bar{q}_R, \ell_R^-, \ell_L^+\}$ $\bar{f}\lvert c_R\rvert^2\lvert b_R\rvert^2\lvert a_L\rvert^2$	$\{q_R, \ell_R^+, \ell_L^-\}$ $f\lvert c_R\rvert^2\lvert b_R\rvert^2\lvert a_L\rvert^2$
$\{q_R, \ell_L^-, \ell_L^+\}$ $f\lvert c_R\rvert^2\lvert b_L\rvert^2\lvert a_L\rvert^2$	$\{\bar{q}_R, \ell_L^+, \ell_L^-\}$ $\bar{f}\lvert c_R\rvert^2\lvert b_L\rvert^2\lvert a_L\rvert^2$	$\{q_R, \ell_L^-, \ell_R^+\}$ $f\lvert c_R\rvert^2\lvert b_L\rvert^2\lvert a_R\rvert^2$	$\{\bar{q}_R, \ell_L^+, \ell_R^-\}$ $\bar{f}\lvert c_R\rvert^2\lvert b_L\rvert^2\lvert a_R\rvert^2$
Processes P_{21}		Processes P_{22}	

Data from	Can this data be fitted by model SFSF	FSFS	FSFV	FVFS	FVFV	SFVF
SFSF	yes	no	no	no	no	no
FSFS	no	yes	maybe	no	no	no
FSFV	no	yes	yes	no	no	no
FVFS	no	no	no	yes	maybe	no
FVFV	no	no	no	yes	yes	no
SFVF	no	no	no	no	no	yes



Burns, Kong, Matchev, Park, 0808.2472

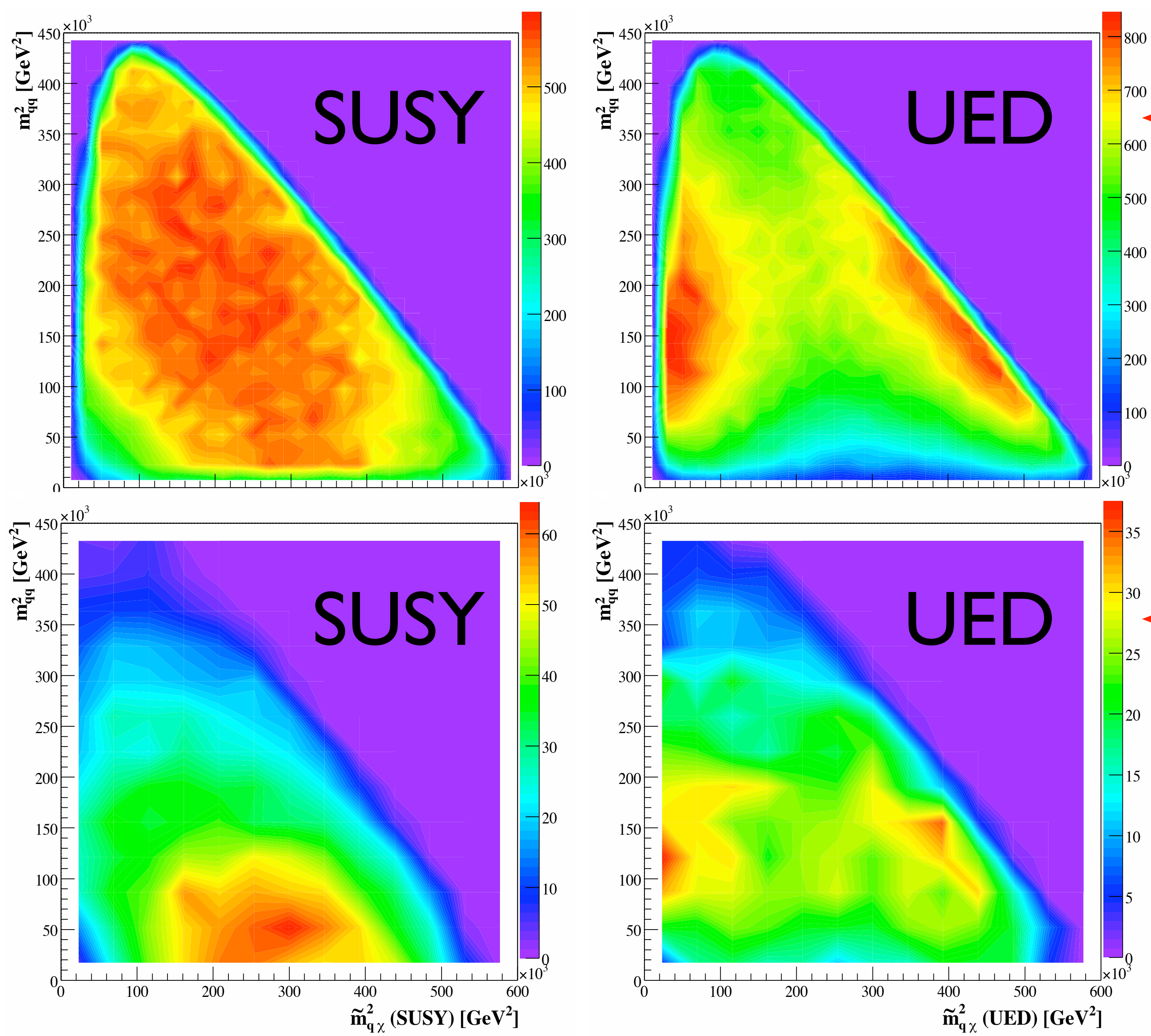
Dilepton invariant mass-squared

Three-body decays

M_{T2}-assisted spin determination

$$pp \to Y(1) + \bar{Y}(2) \to V(p_1)\chi(k_1) + V(p_2)\chi(k_2), \quad Y \to q(p_q)\bar{q}(p_{\bar{q}})\chi(k)$$

$$M_{T2}(p_i, m_\chi) \equiv \min_{\mathbf{k}_{1T}+\mathbf{k}_{2T}=\mathbf{p}_T^{\text{miss}}} \left[\max\{M_T^{(1)}, M_T^{(2)}\}\right]$$ → **assign 4-momenta**



← $m_{\chi,Y} = m_{\chi,Y}^{\text{true}}$

$\mathcal{L} = \infty$

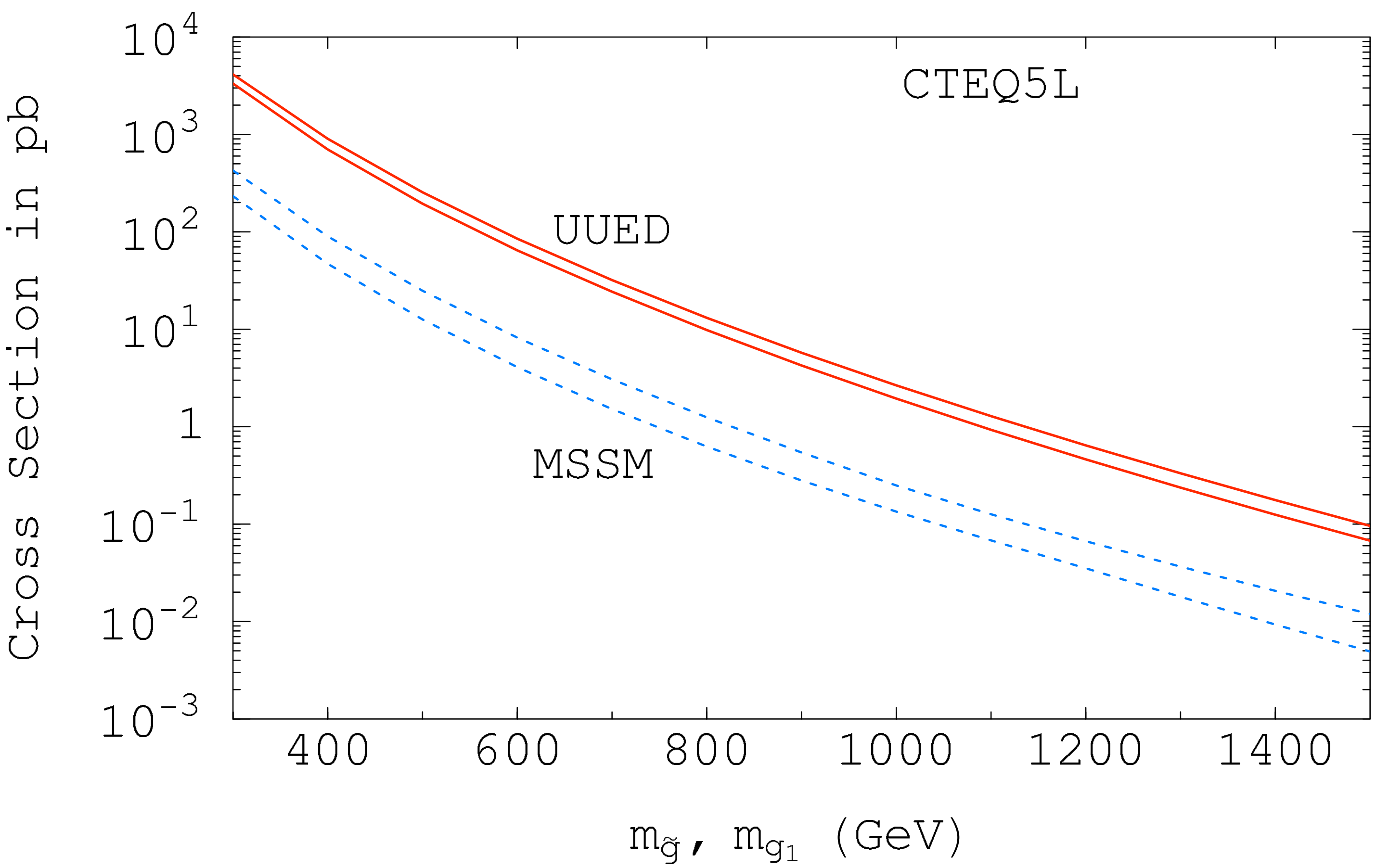
← $m_\chi = 0, \; m_Y = M_{T2}^{\max}(m_\chi = 0)$

$\mathcal{L} = 300\,\text{fb}^{-1}$

Cho, Choi, Kim, Park,
PR D79(2009)031701

Cross sections

Cross sections imply spins

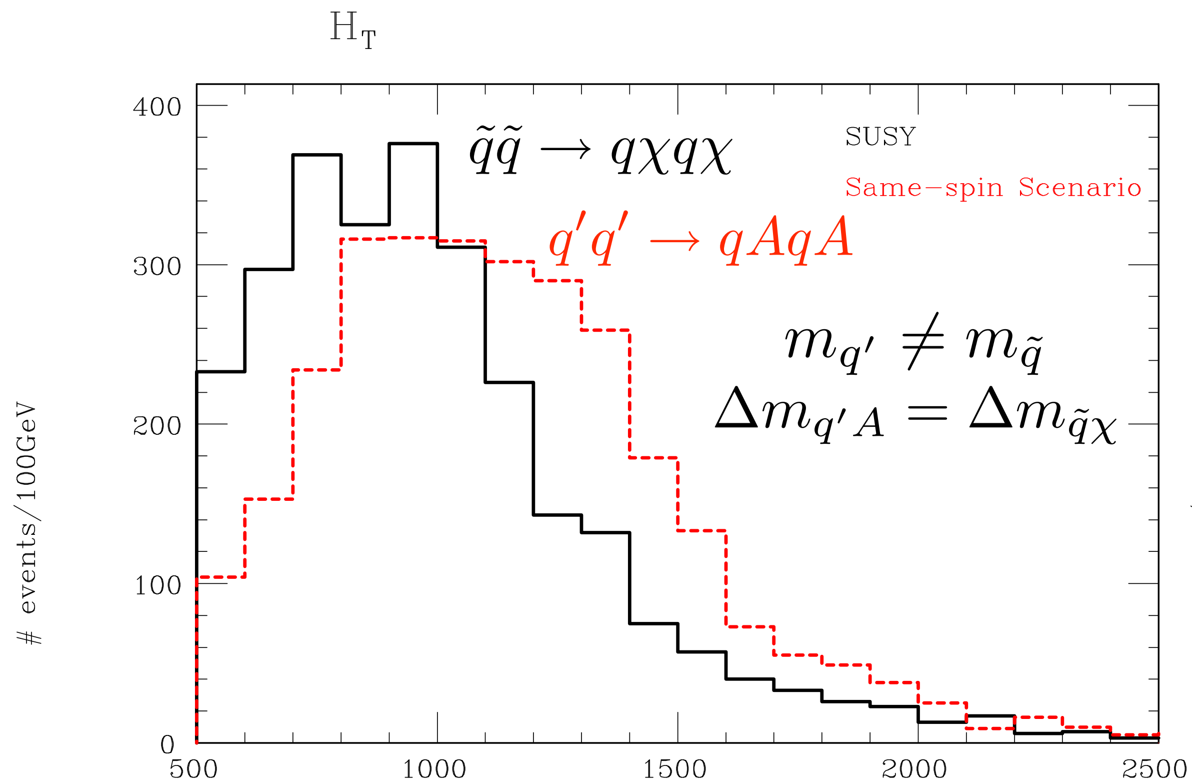


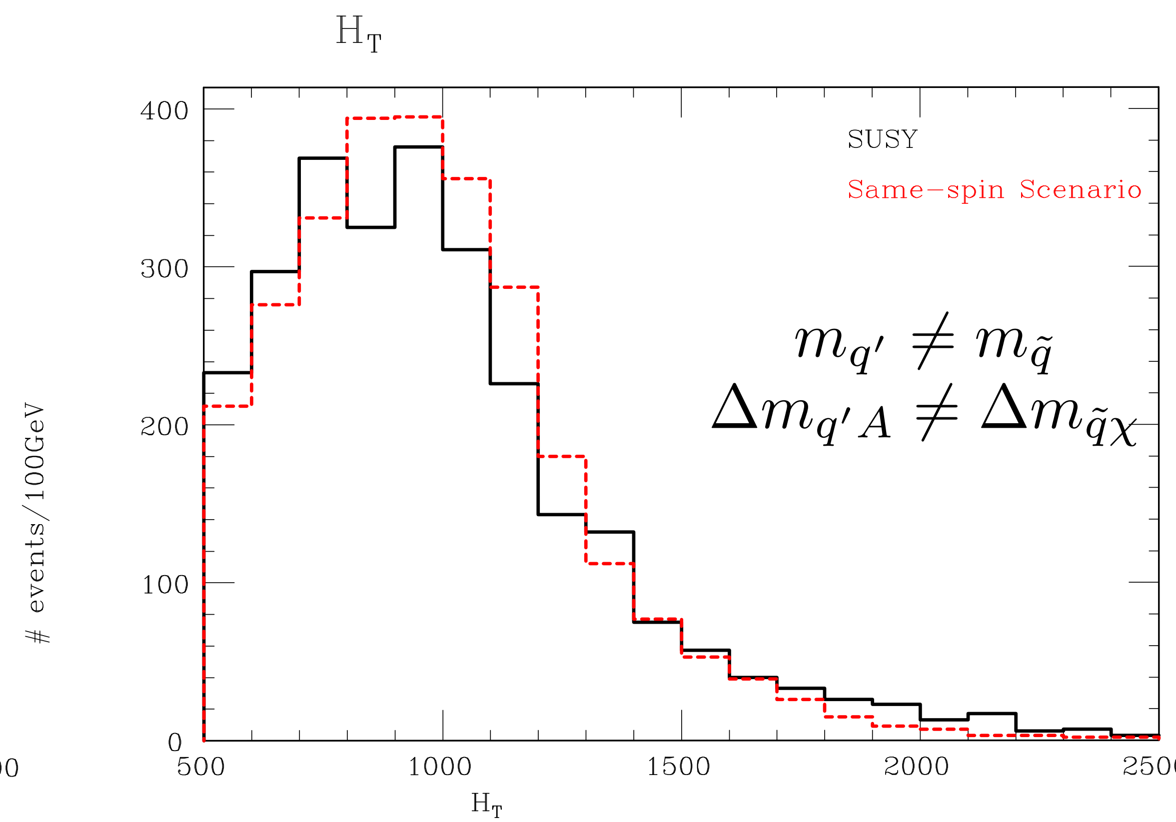
	MSSM	**U-UED**
Production Cross sections	$\sigma_{\tilde{g}\tilde{g}} = 4.51$ pb	$\sigma_{g_1 g_1} = 65.95$ pb
Branching Fractions	$\tilde{g} \to q\bar{q}'\chi_1^{\pm} = 0.45$ $\tilde{g} \to q\bar{q}\chi_2^0 = 0.28$ $\tilde{g} \to q\bar{q}\chi_1^0 = 0.27$	$g_1 \to q\bar{q}'W_1^{\pm} = 0.45$ $g_1 \to q\bar{q}'Z_1 = 0.28$ $g_1 \to q\bar{q}'B_1 = 0.27$
	$\chi_1^{\pm} \to q\bar{q}'\chi_1^0 = 0.67$ $\chi_1^{\pm} \to \ell\nu\chi_1^0 = 0.33$ $\chi_2^0 \to q\bar{q}\chi_1^0 = 0.94$ $\chi_2^0 \to \ell\bar{\ell}\chi_1^0 = 0.04$ $\chi_2^0 \to \nu\bar{\nu}\chi_1^0 = 0.01$	$W_1^{\pm} \to q\bar{q}'B_1 = 0.18$ $W_1^{\pm} \to \ell\nu B_1 = 0.82$ $Z_1^{\pm} \to q\bar{q}B_1 = 0.22$ $Z_1^{\pm} \to \ell\bar{\ell}B_1 = 0.39$ $Z_1^{\pm} \to \nu\bar{\nu}B_1 = 0.39$
Cascade Fractions		
1-lepton	0.248	0.385
OS 2-lepton	0.030	0.183
SS 2-lepton	0.011	0.068
3-lepton	0.003	0.081
Cascade Rates		
1-lepton	1.12 pb	25.39 pb
OS 2-lepton	0.13 pb	12.06 pb
SS 2-lepton	0.05 pb	4.48 pb
3-lepton	0.014 pb	5.34 pb

➡ Higher spins mean higher cross sections (for given masses)

Datta, Kane, Toharia hep-ph/0510204

Cross sections imply spins (2)

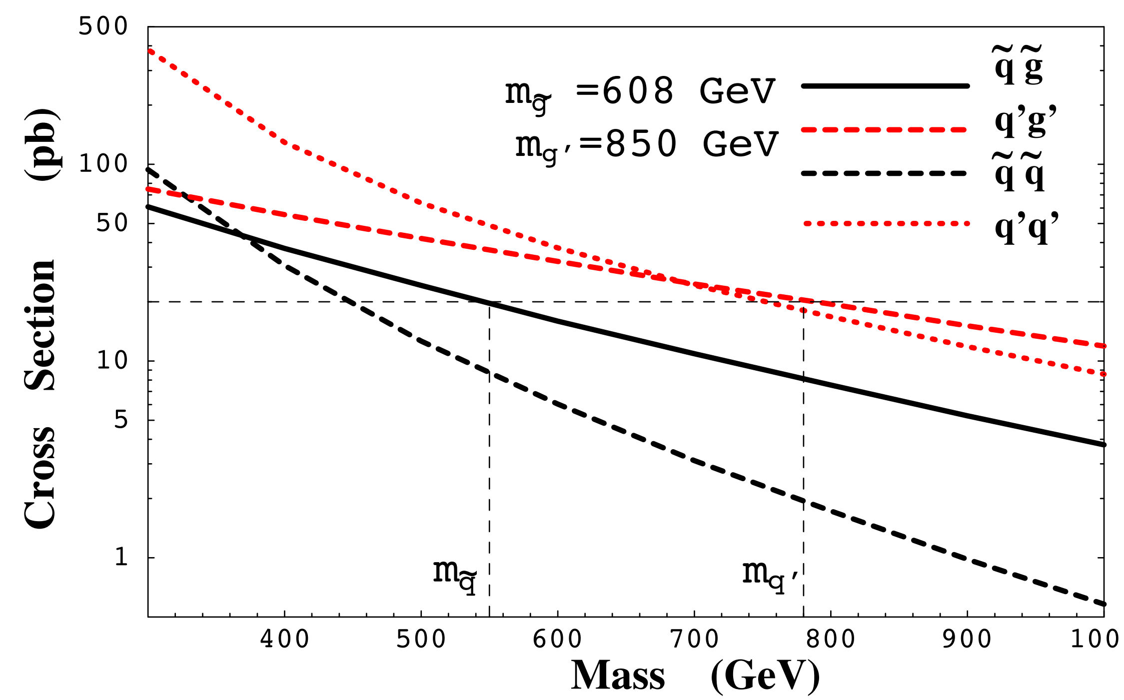




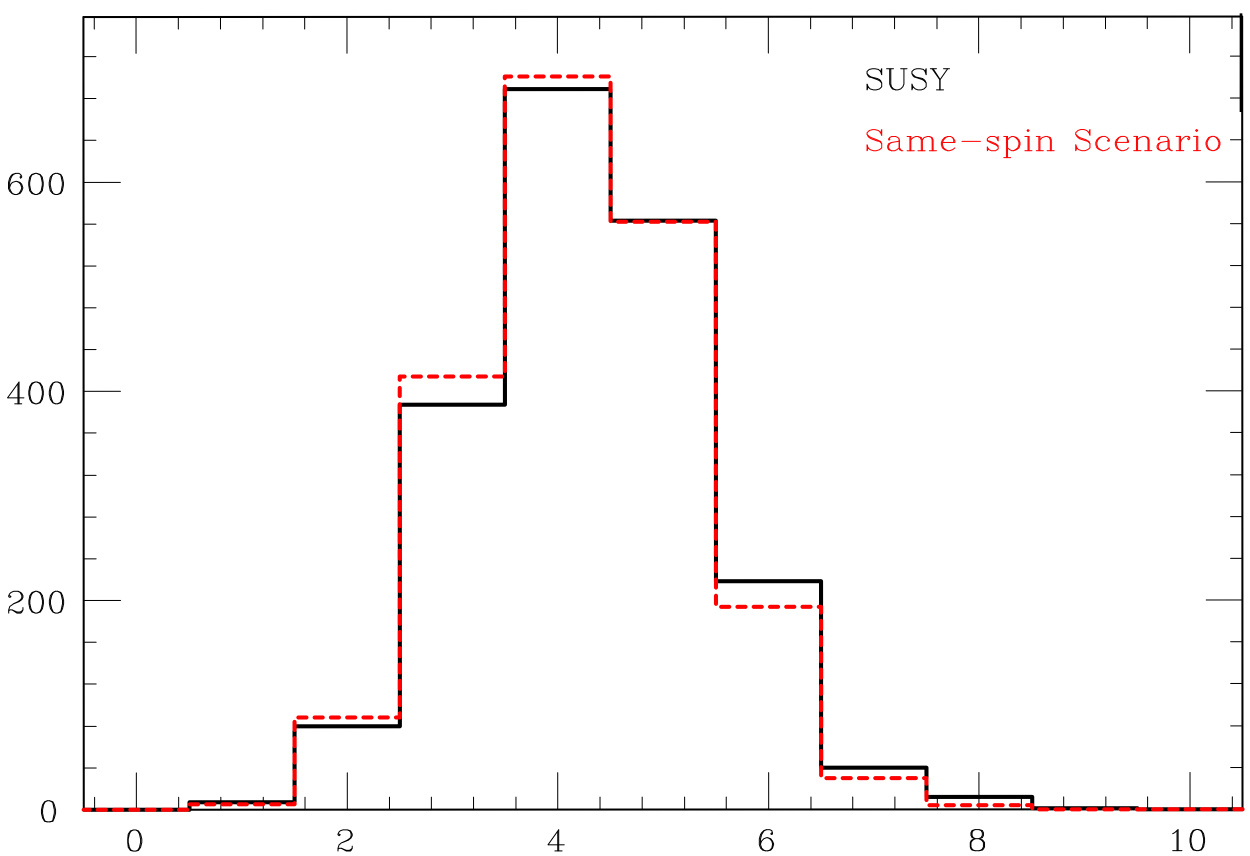
$$H_T = \sum E_T + \not{E}_T$$

- Can match cross section and one distribution by adjusting masses
- Cannot match several cross sections or distributions ...

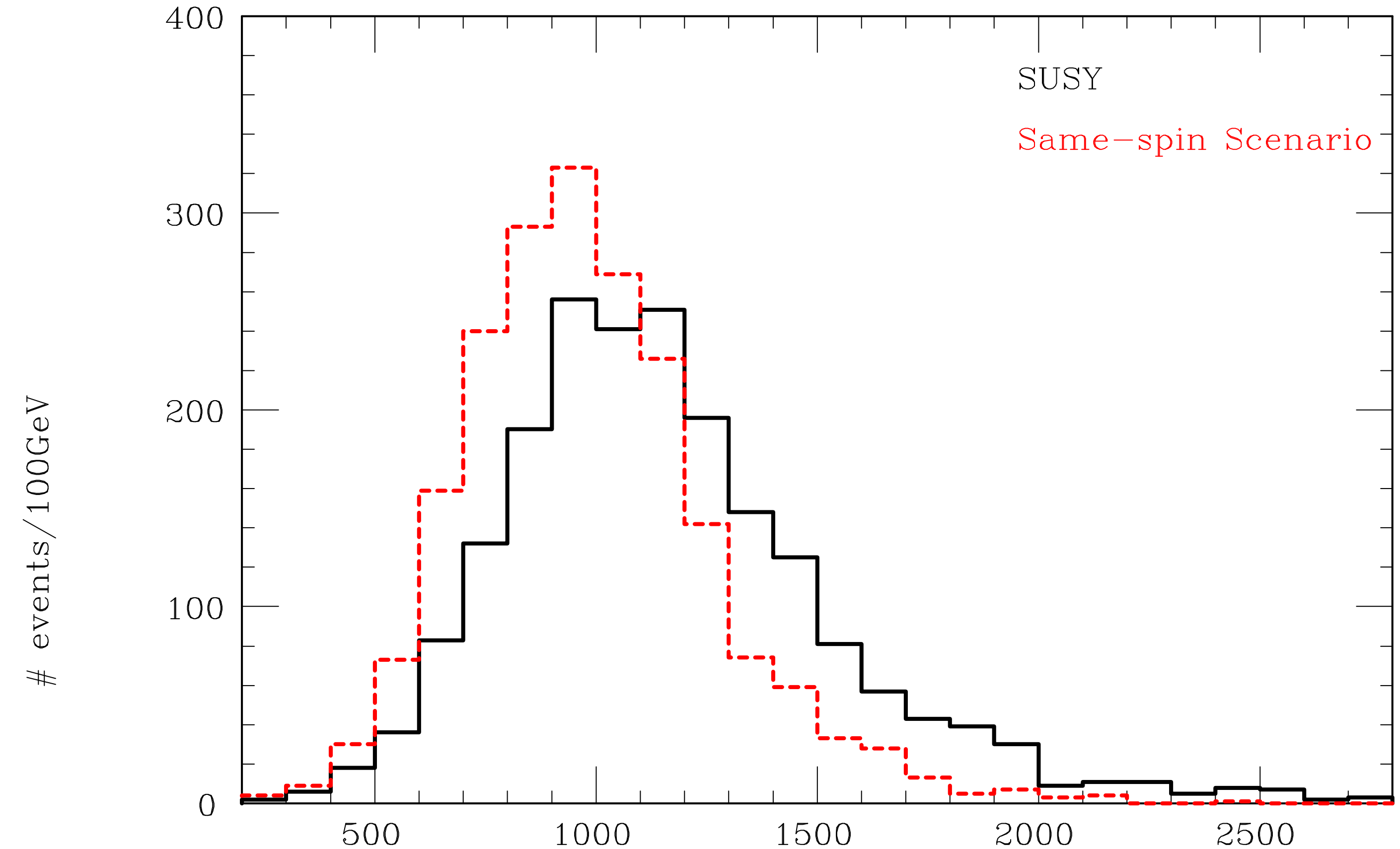
Kane, Petrov, Shao, Wang, J.Phys.G37(2010)045004



Cross sections imply spins (3)



Jet multiplicity



H_T

- Can vary masses to fit cross section and one distribution
- E.g. match jet counts → H_T doesn't match → ambiguity resolved

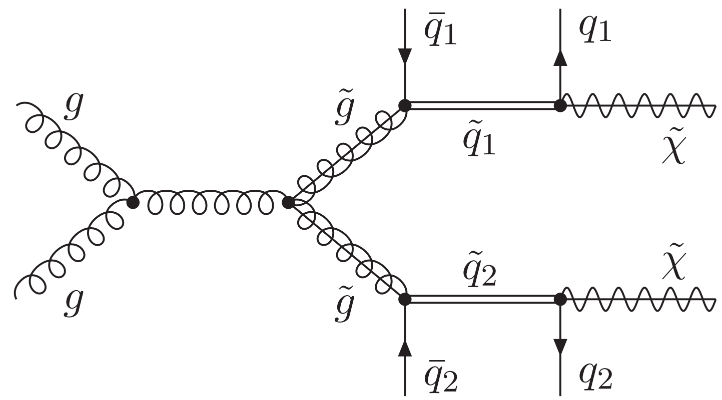
Conclusions on Spins

- Sequential decay chains
  - Possibilities -- but difficult for degenerate masses
- Dileptons
  - SUSY vs UED difficult at LHC -- other cases possible
- Three-body decays
  - M_{T2} assistance looks useful here (and elsewhere?)
- Cross sections
  - Should be included

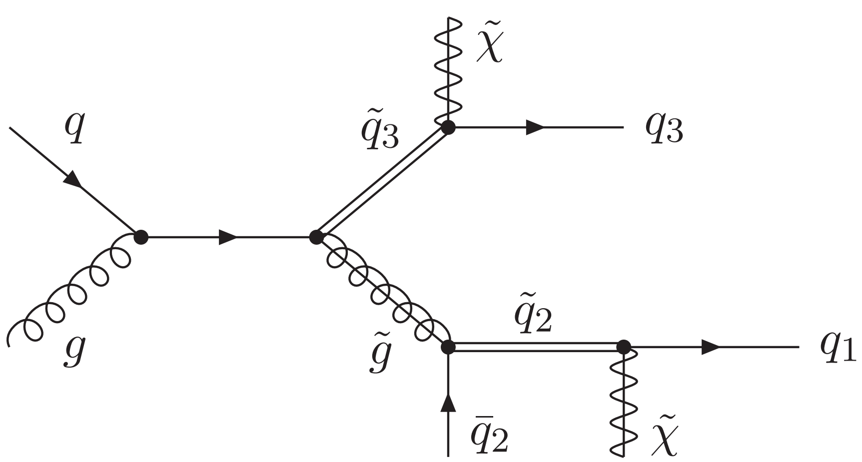
→ Full simulations (and data) needed!

Backup slides

Gluino spin correlations



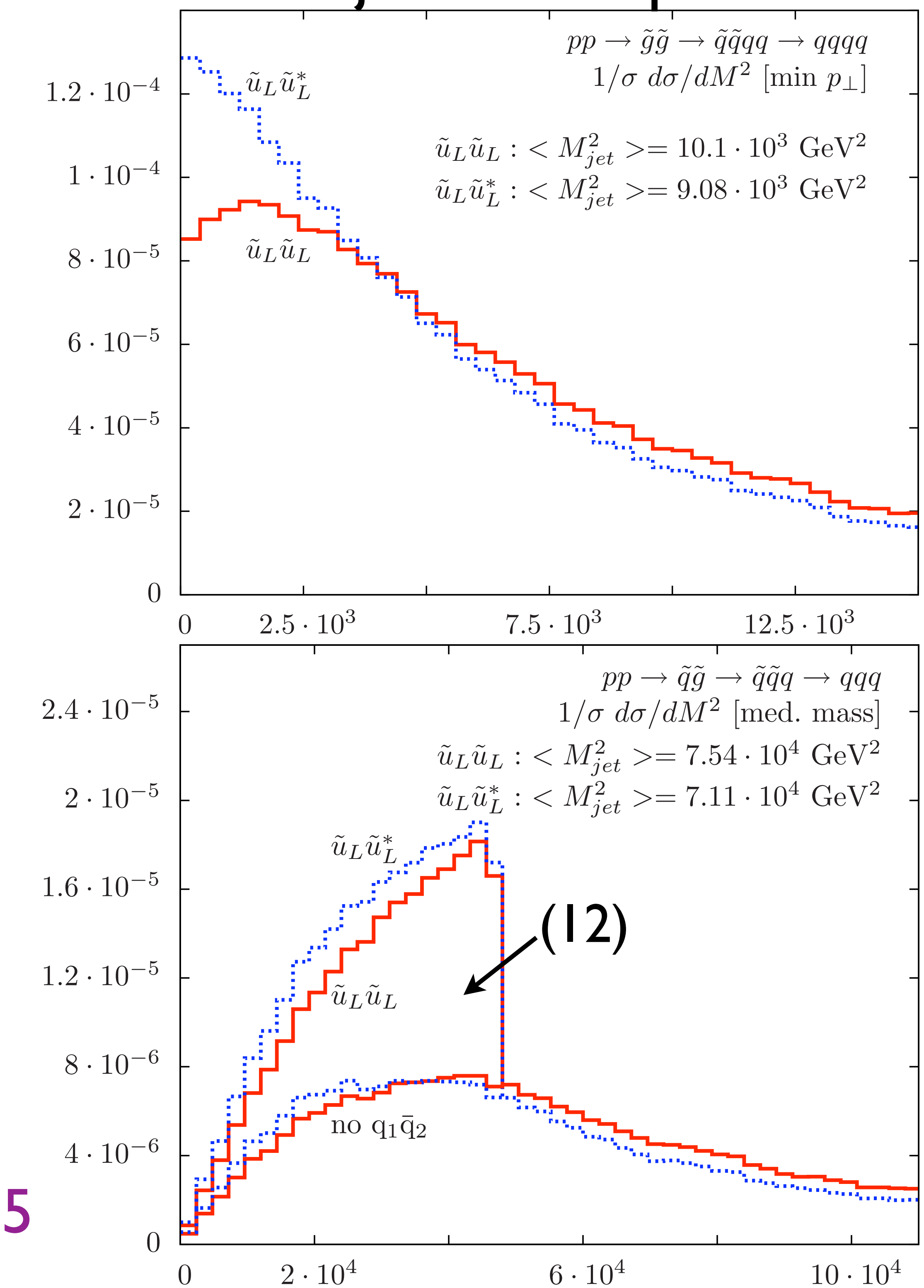
- Lowest p_T jets from gluinos



- Lowest mass dijet ~ (12)
  Medium mass dijet ~ (23)

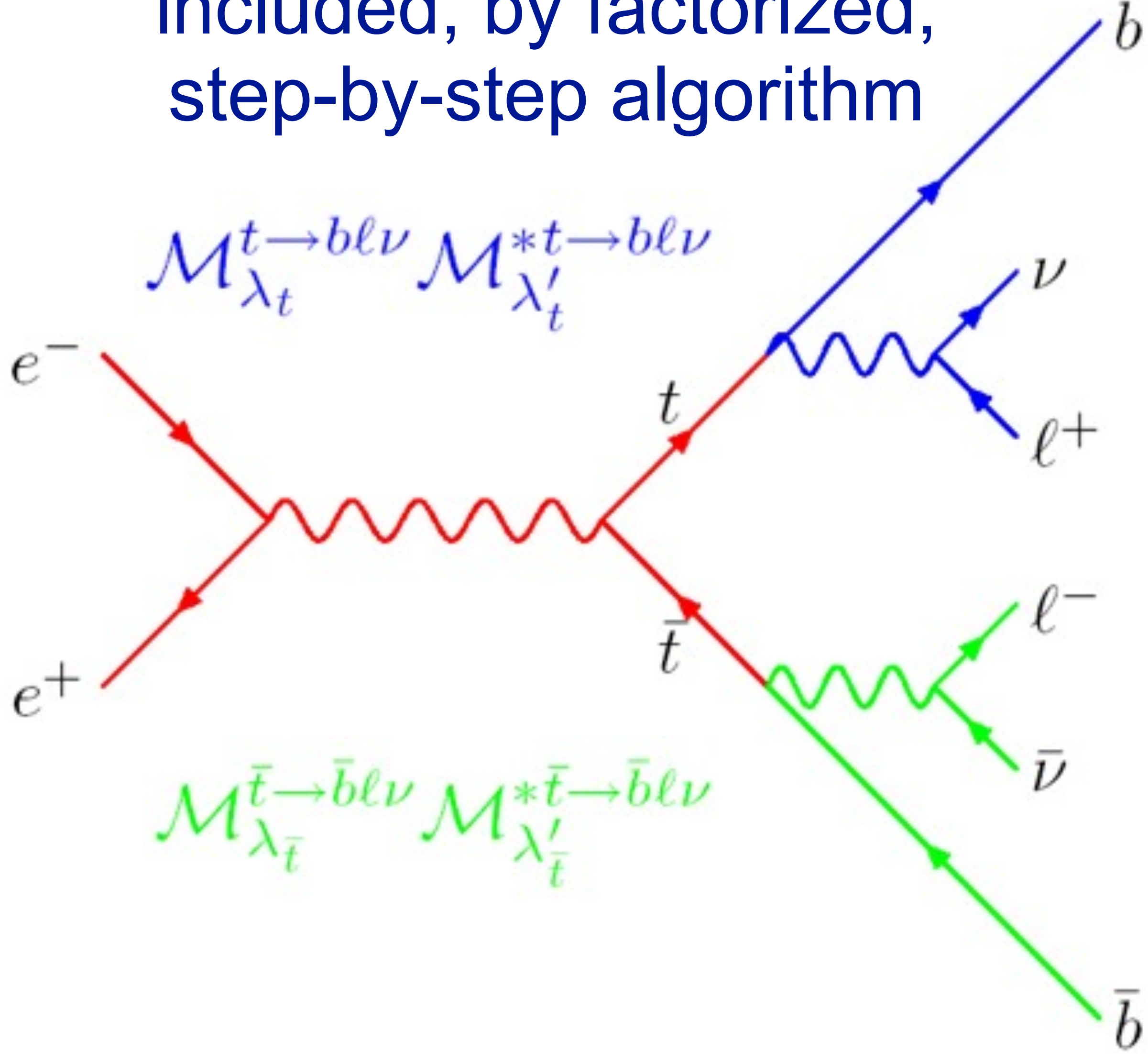
Krämer, Popenda, Spira, Zerwas, 0902.3795

Dijet mass-squared



Production/Decay Spin Correlations in Herwig

Full spin correlations included, by factorized, step-by-step algorithm



$$\rho_{\rm prod}^{\lambda_c\lambda'_c\lambda_d\lambda'_d} = \mathcal{M}^{\lambda_c\lambda_d}_{ab\to cd}\mathcal{M}^{*\lambda'_c\lambda'_d}_{ab\to cd},$$

$$D_c^{\lambda_c\lambda'_c} = \mathcal{M}^{\lambda_c}_{c\ {\rm decay}}\mathcal{M}^{*\lambda'_c}_{c\ {\rm decay}},$$

$$|\mathcal{M}|^2 = \rho_{\rm prod}^{\lambda_c\lambda'_c\lambda_d\lambda'_d} D_c^{\lambda_c\lambda'_c} D_d^{\lambda_d\lambda'_d}$$

$$= \rho_{\rm prod}^{\lambda_c\lambda_c\lambda_d\lambda_d}\left(\frac{\rho_{\rm prod}^{\lambda_c\lambda'_c\lambda_d\lambda_d} D_c^{\lambda_c\lambda'_c}}{\rho_{\rm prod}^{\lambda_c\lambda_c\lambda_d\lambda_d}}\right)$$

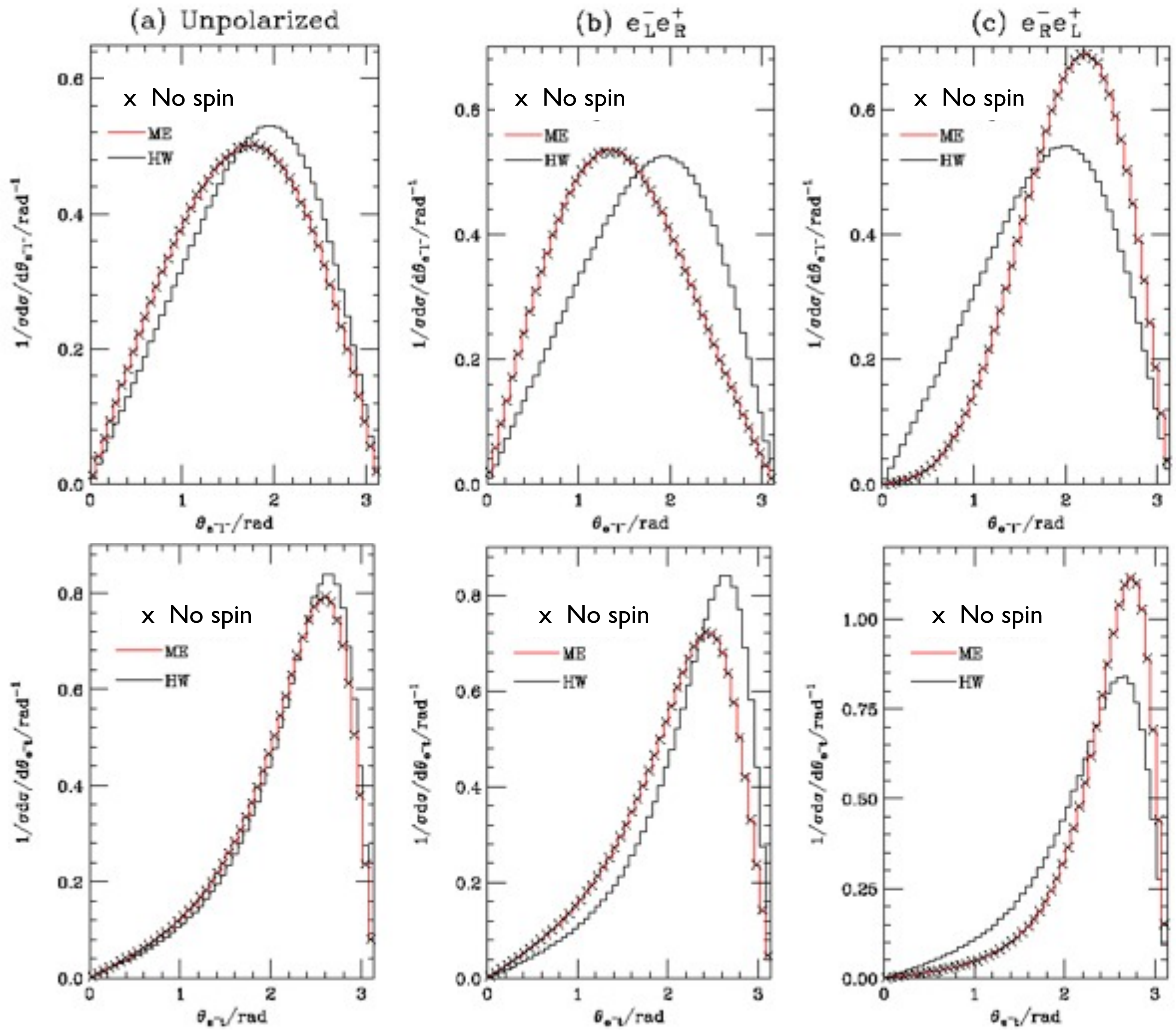
$$\times\left(\frac{\rho_{\rm prod}^{\lambda_c\lambda'_c\lambda_d\lambda'_d} D_c^{\lambda_c\lambda'_c} D_d^{\lambda_d\lambda'_d}}{\rho_{\rm prod}^{\lambda_c\lambda'_c\lambda_d\lambda_d} D_c^{\lambda_c\lambda'_c}}\right)$$

Richardson, hep-ph/0110108

Top spin correlations in Herwig

Lepton-beam correlation →

Top-beam correlation →

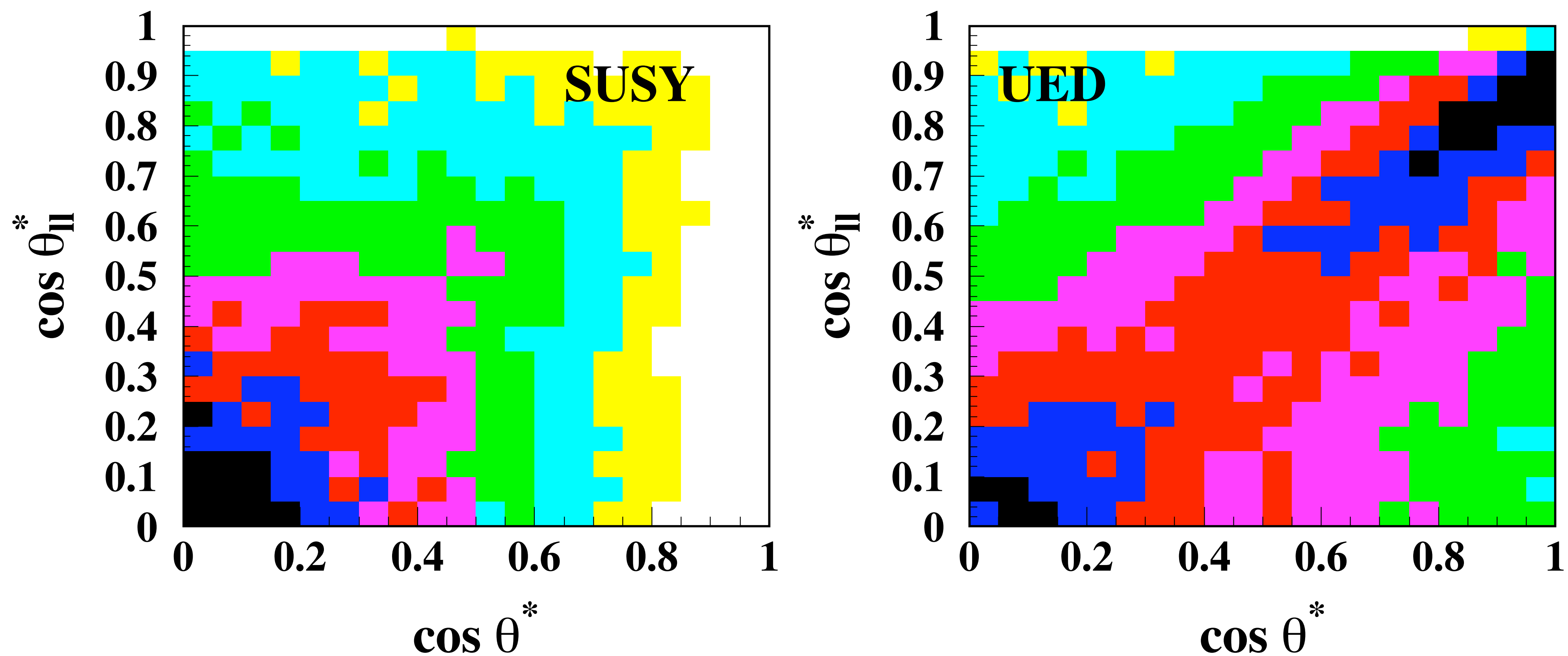


- SM, SUSY & UED in Herwig++

Hw++ manual: Bähr et al., 0803.0883

Dislepton production

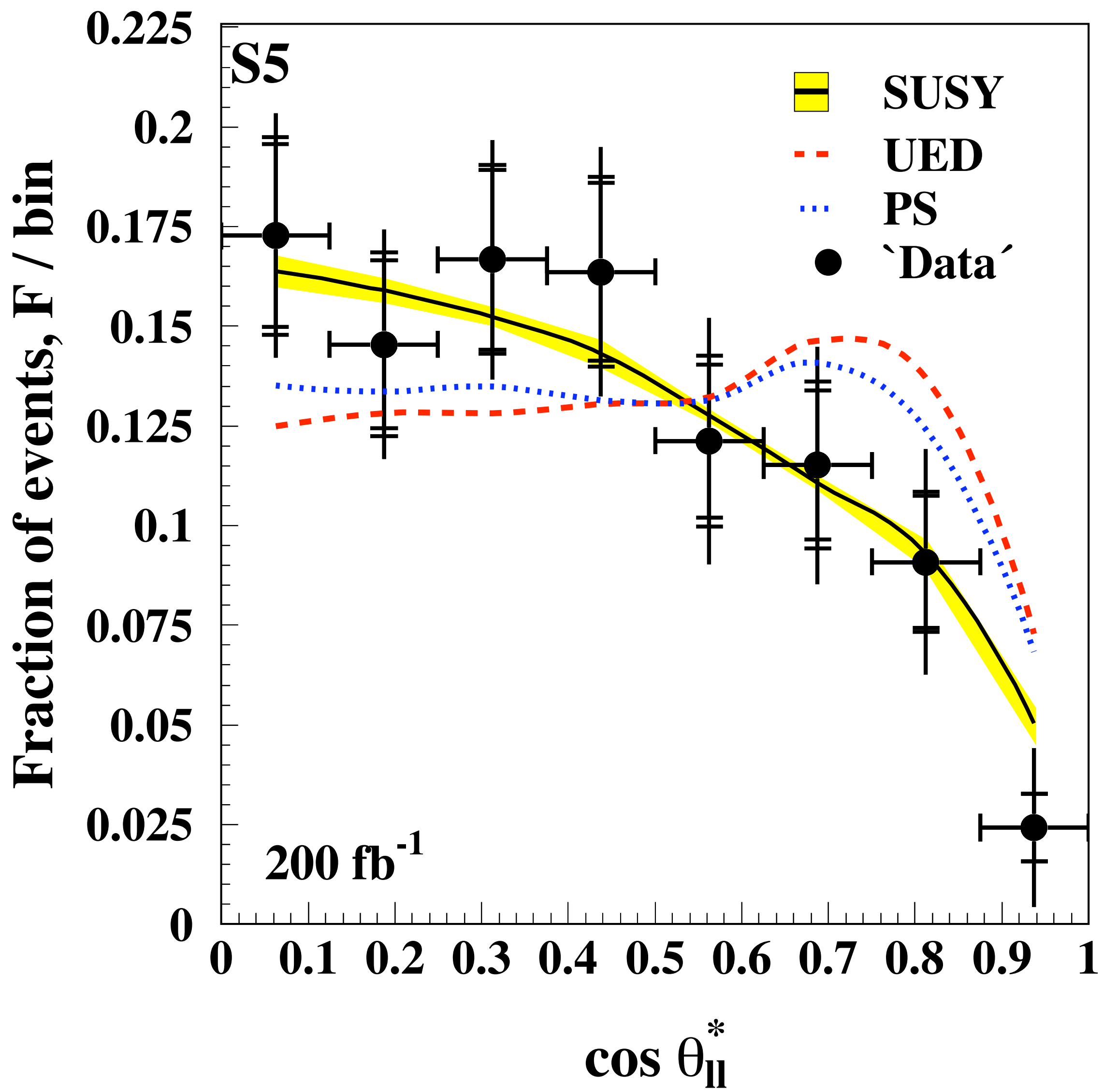
- $q\bar{q} \to Z^0/\gamma \to \tilde{\ell}^+\tilde{\ell}^- \to \tilde{\chi}_1^0\ell^+\ \tilde{\chi}_1^0\ell^-$
- Distribution of $\cos\theta_{ll}^* \equiv \tanh(\Delta\eta_{\ell^+\ell^-}/2)$
  is correlated with Z^0/γ decay angle θ^*

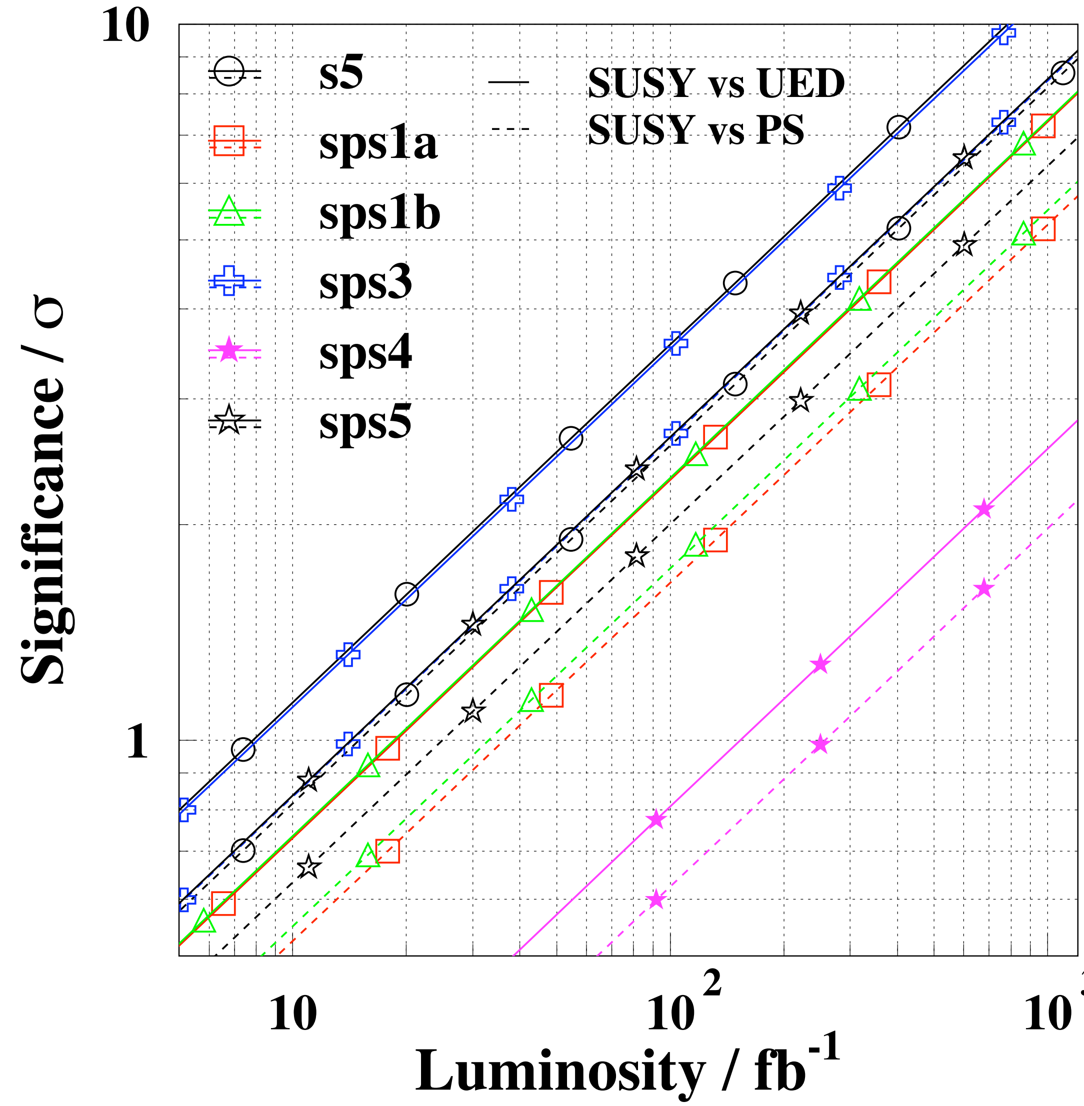


(neglects KKlepton polarisation)

A Barr, hep-ph/0511115

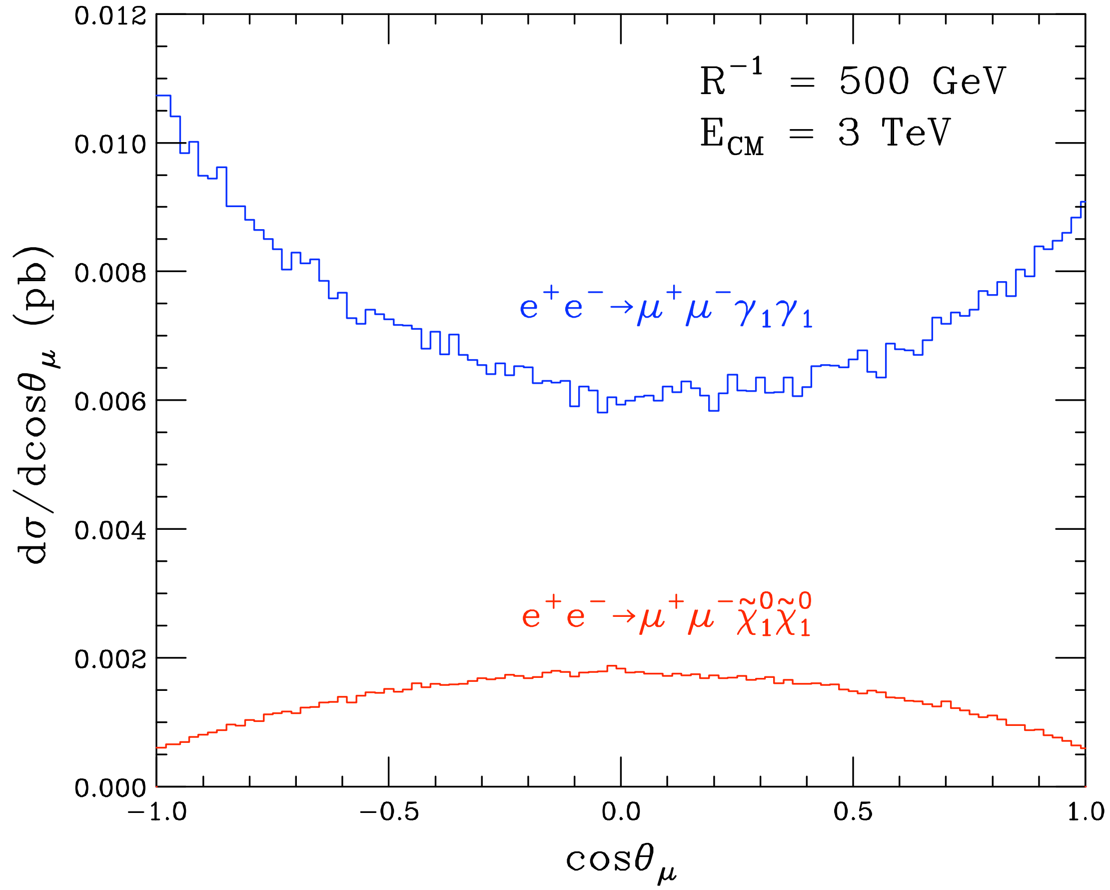
Dislepton production (2)

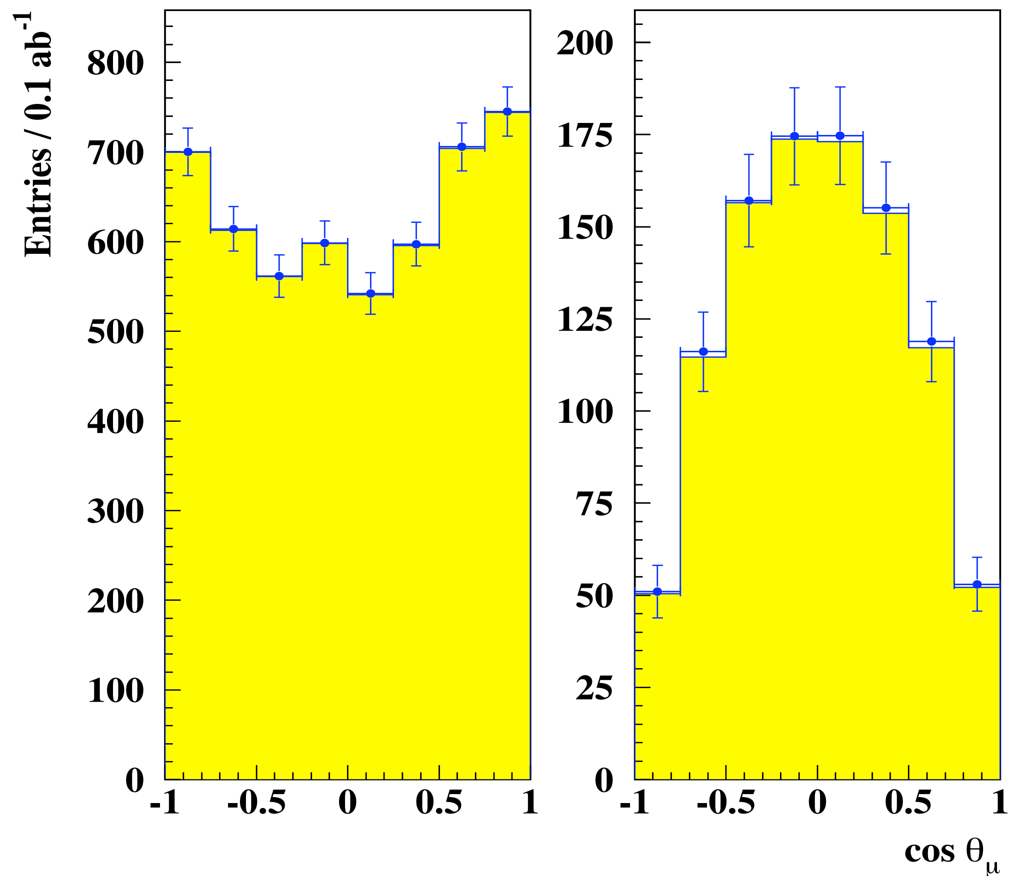




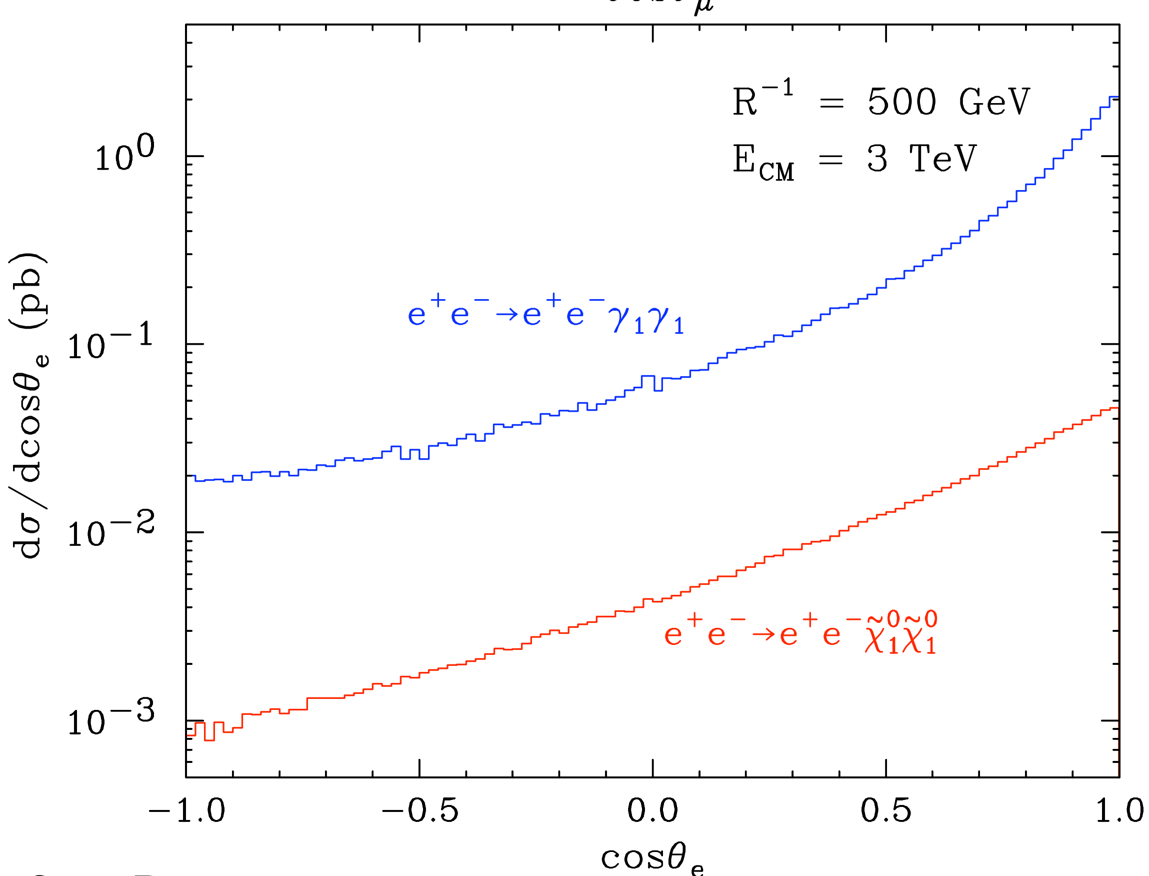
- Outer error bars: after SUSY & SM background subtraction
- Significance strongly dependent on mass spectrum

Disleptons at CLIC





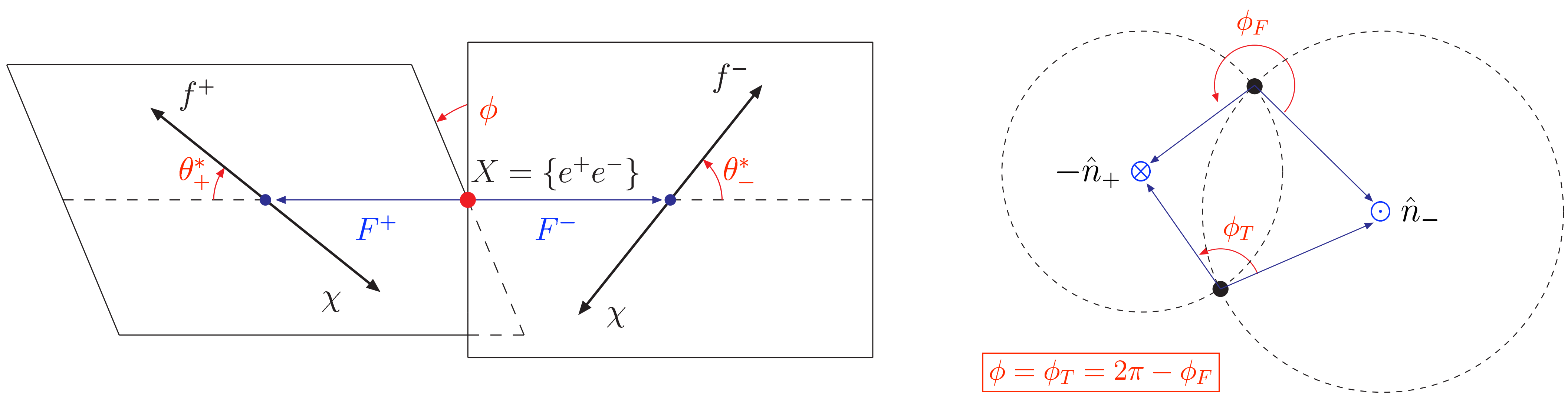
Detector level

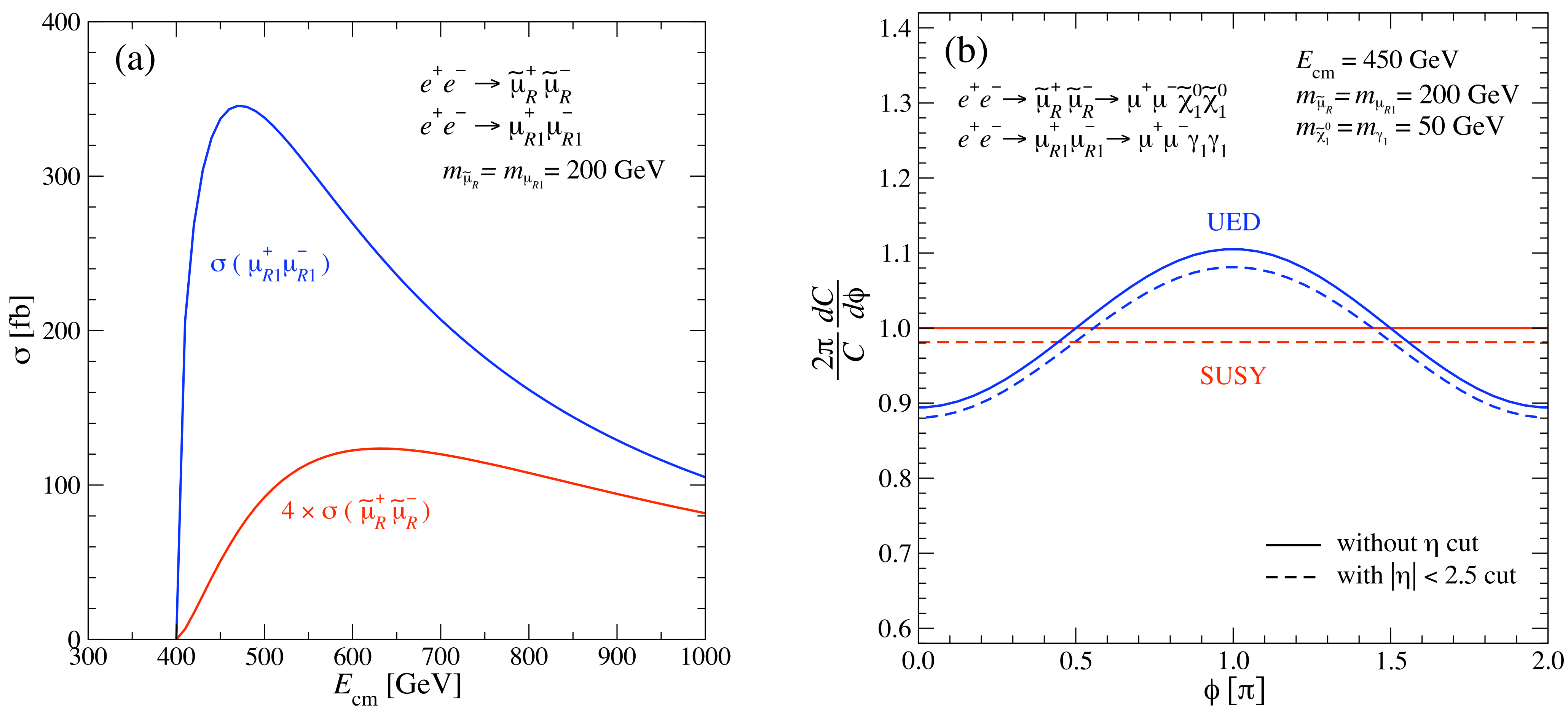


Battaglia, Datta, DeRoeck, Kong, Matchev, hep-ph/0502041, 0507084

UED: Bhattacharya, Dey, Kundu, Raychaudhuri, hep-ph/0502031

Azimuthal correlations in e^+e^-

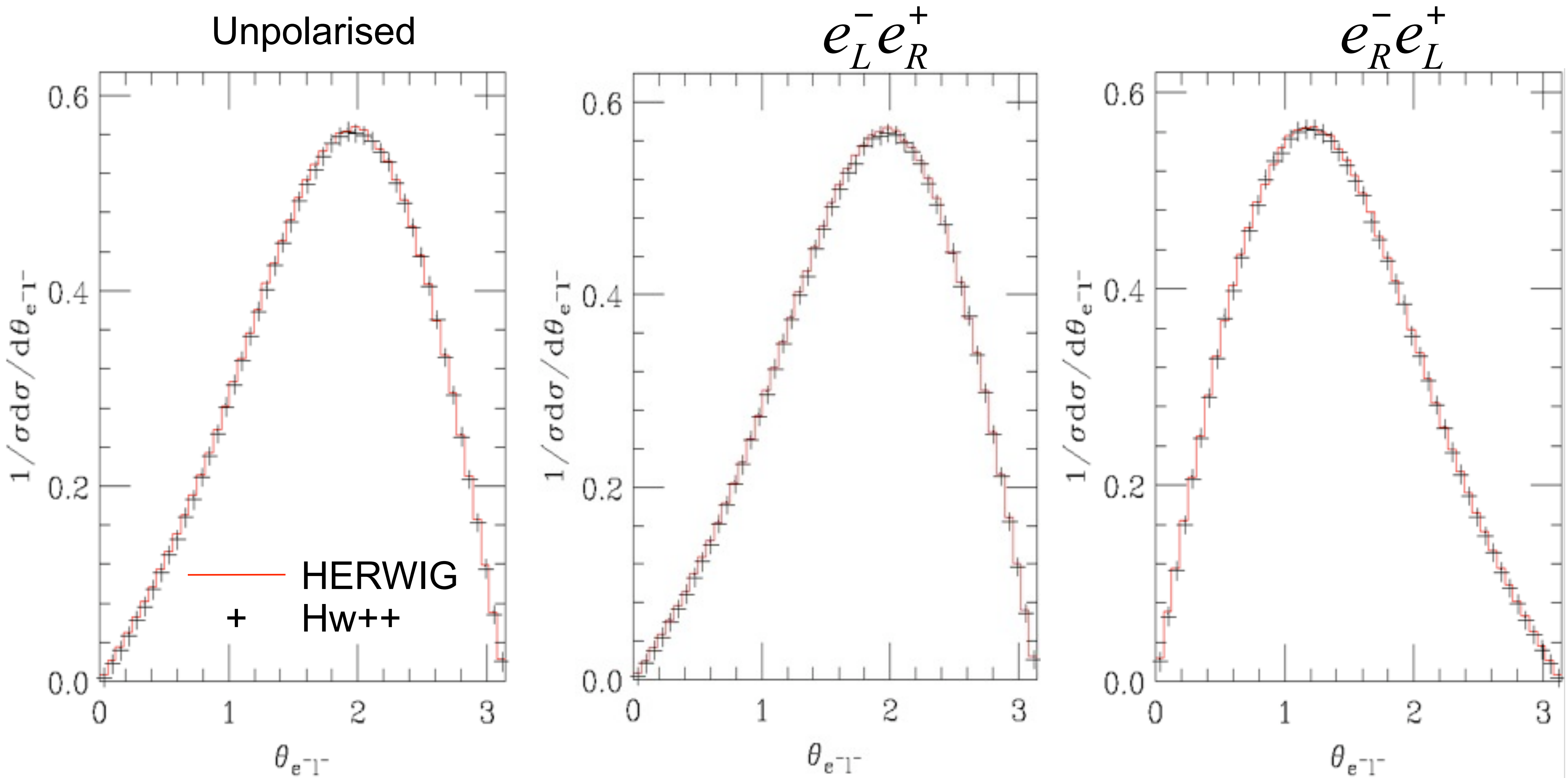




Buckley, Choi, Mawatari, Murayama, 0811.3030

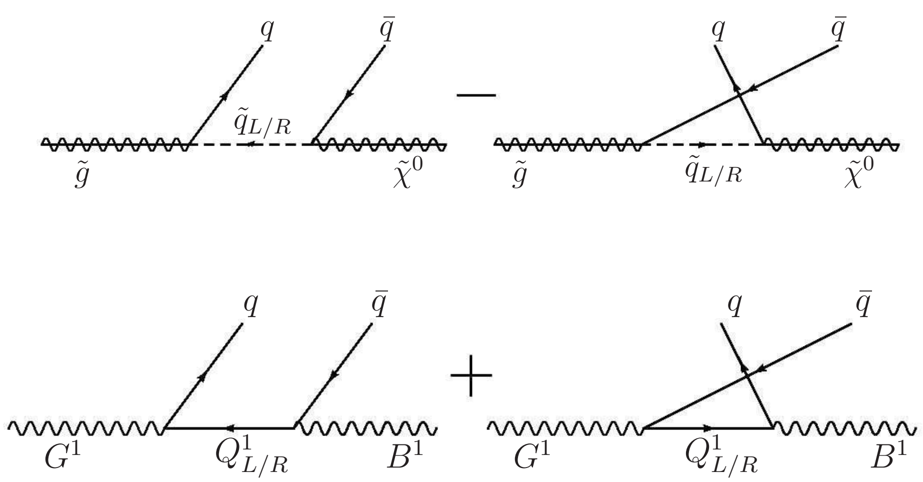
Spin Correlations in HERWIG

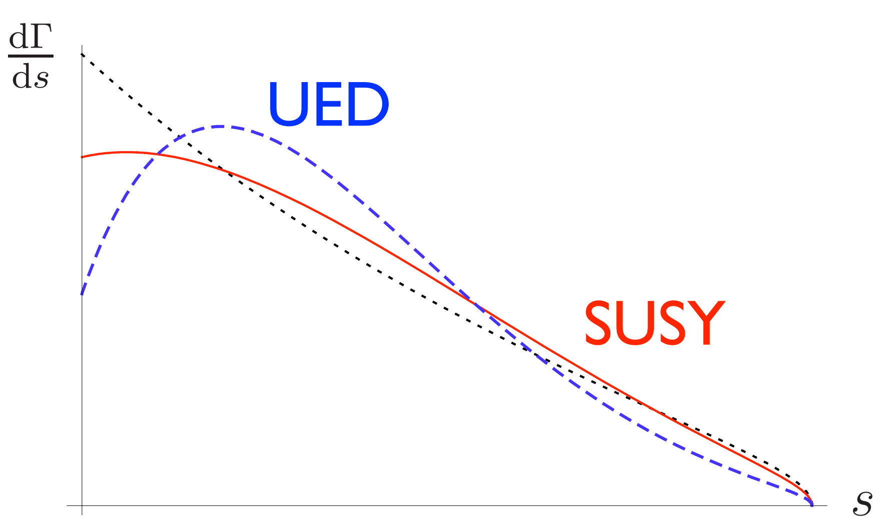
$$e^+e^- \to \tilde{\chi}_2^0\tilde{\chi}_1^0 \to \tilde{l}_R^+ l^- \tilde{\chi}_1^0 \to l^+l^-\tilde{\chi}_1^0\tilde{\chi}_1^0$$



Gigg, Richardson, hep-ph/0703199

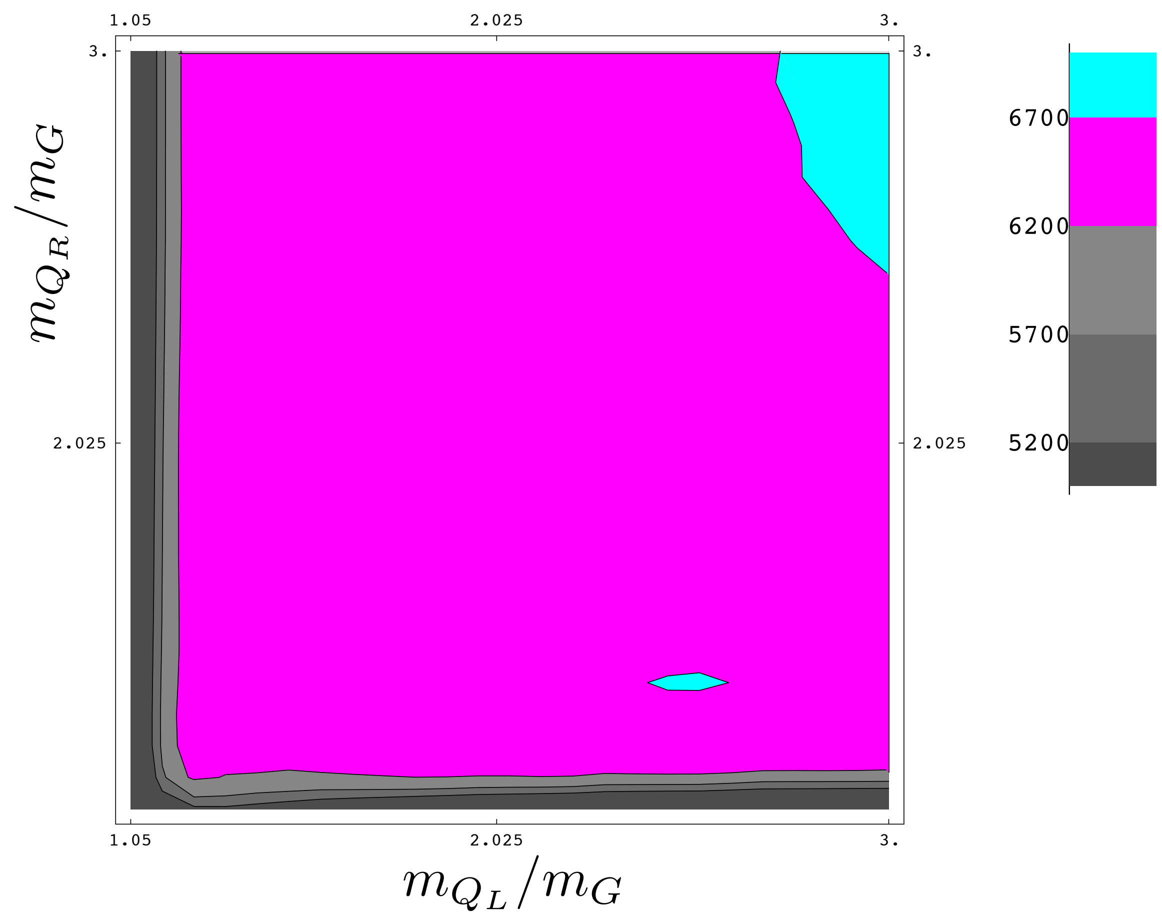
Three-body gluino decays





Dijet inv. mass-squared

Number of events needed to discriminate



Kullback-Leibler measure:

$$N \sim \log R/\mathrm{KL}(T,S)$$

$$\mathrm{KL}(T,S) = \int_m \log\left(\frac{p(m|T)}{p(m|S)}\right) p(m|T)\, dm$$

Csaki, Heinonen, Perelstein, 0707.0014