General analysis of decay chains with three-body decays involving missing energy

Chien-Yi Chen
Carnegie Mellon University

In collaboration with Prof. Ayres Freitas,

BNL Forum 2011

Oct. 20, 2011

Purpose

- Properties of new heavy particles beyond the standard model.

  e.g.

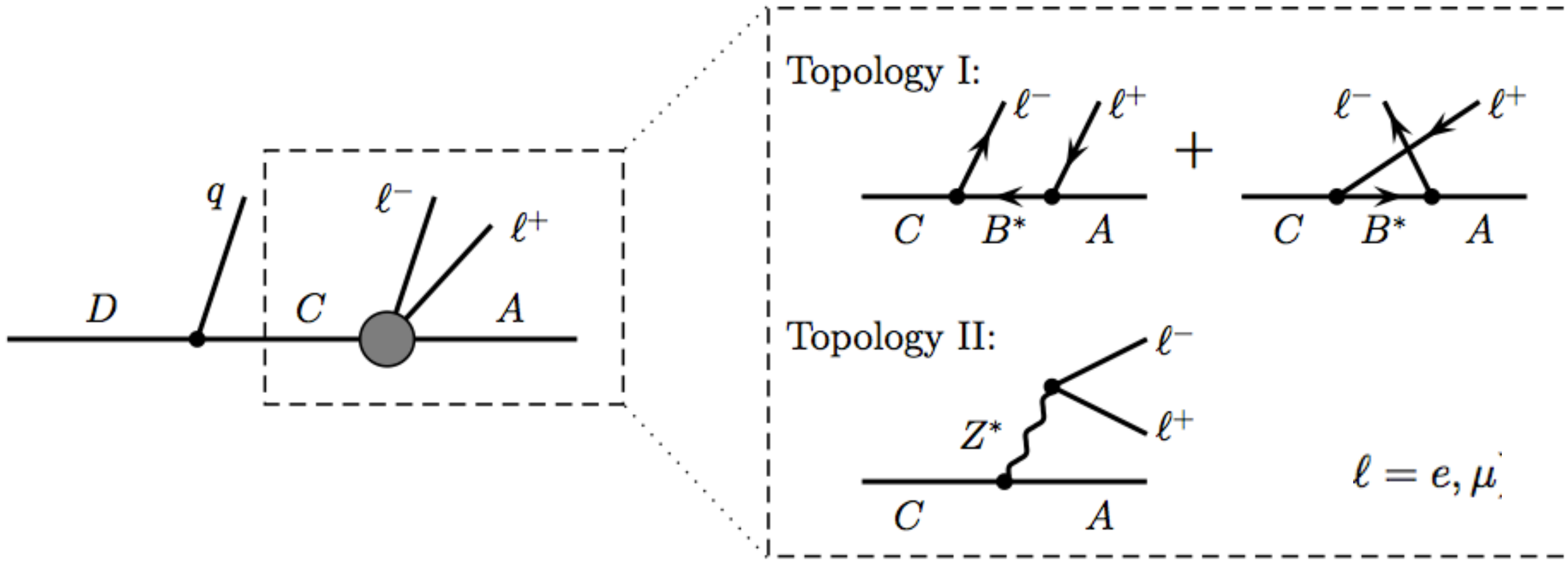
  - Mass
  - Spin
  - Coupling

- Focusing on channels in which the new heavy particles decay into the stable Weakly Interacting Massive Particles (missing energy in the detector or dark matter candidates)

- Model independent approach; making only minimum assumptions

- Consider all possible spin assignments and keep the couplings arbitrary.

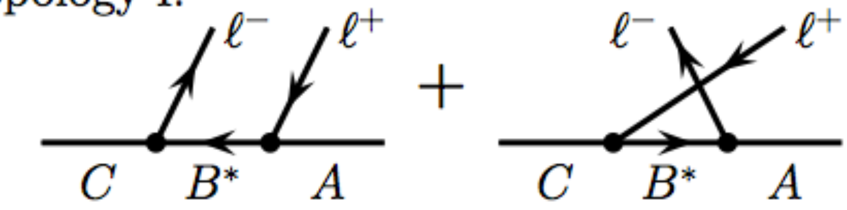
Topology



- D: Color triplet and charged particle
- C: Neutral self-conjugate massive particle
- B: Charged massive particle
- A: Neutral self-conjugate massive particle; Dark matter candidate
- Z: Standard Model Z boson
- Mass hierarchy : MD>MC; MB>MC>MA (for topology I) or MZ>MC-MA (for topology II) so that particle C decay off-shell to particle B. (This can often happen in scenarios with relatively small splitting in the mass spectrum of new physics particles.)
    - For particle C decaying on-shell to particle B [JHEP 0810 ,081 (2008) M. Burns et. al.]
    - MB>>MC [JHEP 1008, 035 (2010) L. Edelhaeuser et. al.]

Spin assignment

Topology I:

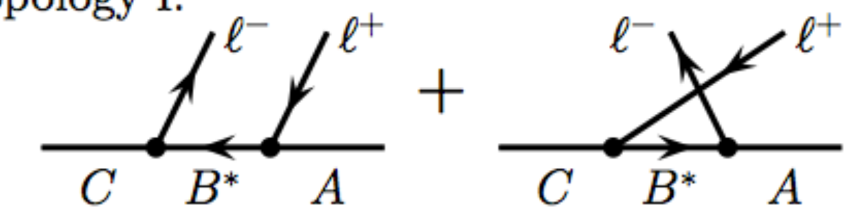


F=Fermion, S=Scalar, V=Vector,

	S	D	C	B	A
Topology I	1	S	F	S	F
	2	F	S	F	S
	3	F	S	F	V
	4	F	V	F	S
	5	F	V	F	V
	6	S	F	V	F

Spin assignment

Topology I:



F=Fermion, S=Scalar, V=Vector,

Topology I

S	D	C	B	A
1	S	F	S	F
2	F	S	F	S
3	F	S	F	V
4	F	V	F	S
5	F	V	F	V
6	S	F	V	F

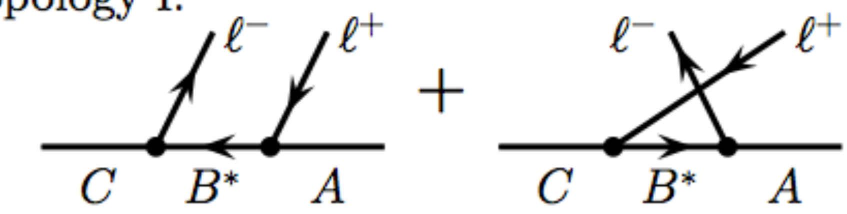
e.g.

$$\tilde{q} \to \tilde{\chi}_2^0 \to \tilde{\ell}^* \to \tilde{\chi}_1^0$$

$\tilde{q}$, $\tilde{\ell}$, and $\tilde{\chi}_i^0$ are squark, slepton and neutralinols in MSSM.

Spin assignment

Topology I:



F=Fermion, S=Scalar, V=Vector,

	S	D	C	B	A
Topology I	1	S	F	S	F
	2	F	S	F	S
	3	F	S	F	V
	4	F	V	F	S
	5	F	V	F	V
	6	S	F	V	F
Topology II	7	F	S		S
	8	F	S		V
	9	F	V		S
	10	F	V		V
	11	S	F		F

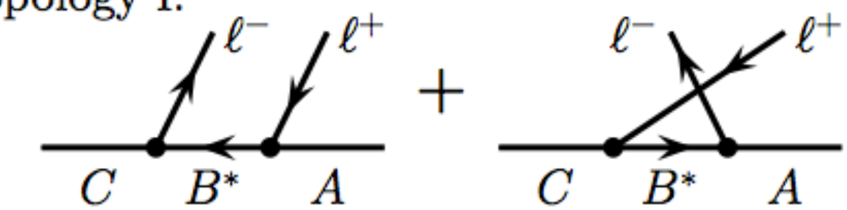
e.g.

$\tilde{q} \to \tilde{\chi}_2^0 \to \tilde{\ell}^* \to \tilde{\chi}_1^0$

$\tilde{q}$, $\tilde{\ell}$, and $\tilde{\chi}_i^0$ are squark, slepton and neutralinols in MSSM.

Spin assignment

Topology I:



F=Fermion, S=Scalar, V=Vector,

	S	D	C	B	A
Topology I	1	S	F	S	F
	2	F	S	F	S
	3	F	S	F	V
	4	F	V	F	S
	5	F	V	F	V
	6	S	F	V	F
Topology II	7	F	S		S
	8	F	S		V
	9	F	V		S
	10	F	V		V
	11	S	F		F

e.g.

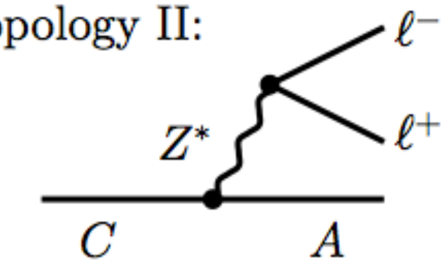
$\tilde{q} \to \tilde{\chi}_2^0 \to \tilde{\ell}^* \to \tilde{\chi}_1^0$

$\tilde{q}$, $\tilde{\ell}$, and $\tilde{\chi}_i^0$ are squark, slepton and neutralinols in MSSM.

e.g.

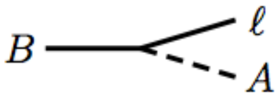
$\tilde{q} \to \tilde{\chi}_2^0 \to \tilde{\chi}_1^0$

Topology II:

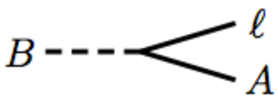


Coupling assignment : Topology I

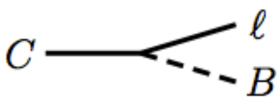
For scalar-fermion-fermion vertices



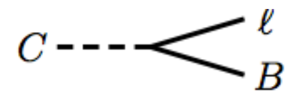
$\overline{\psi}_B\, A\,(a_L\omega_- + a_R\omega_+)\,\psi_\ell + \text{h.c.}$



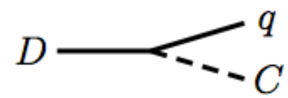
$\overline{\psi}_A\, B\,(a_L\omega_- + a_R\omega_+)\,\psi_\ell + \text{h.c.}$



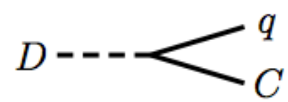
$\overline{\psi}_C\, B\,(b_L\omega_- + b_R\omega_+)\,\psi_\ell + \text{h.c.}$



$\overline{\psi}_B\, C\,(b_L\omega_- + b_R\omega_+)\,\psi_\ell + \text{h.c.}$



$\overline{\psi}_D\, C\,(c_L\omega_- + c_R\omega_+)\,\psi_q + \text{h.c.}$



$\overline{\psi}_C\, D\,(c_L\omega_- + c_R\omega_+)\,\psi_q + \text{h.c.}$

where $\omega_\pm = \frac{1}{2}(1 \pm \gamma_5)$.

For vector-fermion-fermion vertices, replace A by $\not{A}$

- Only relative sign and magnitude of aL and aR is known

$$a_L = \cos\alpha, \qquad b_L = \cos\beta, \qquad c_L = \cos\gamma,$$
$$a_R = \sin\alpha, \qquad b_R = \sin\beta, \qquad c_R = \sin\gamma.$$

$$\alpha \in [-\pi/2, \pi/2],\ \beta, \gamma \in [0, \pi/2]$$

- Impossible to tell whether a quark and an antiquark is initiated by particle D or anti-D
- Assume that f is the fraction of events stemming from D decays and anti-f is the fraction of events stemming from anti-D decays.

$$f + \bar{f} = 1.$$

e.g at the Tevatron $f = \bar{f} = \frac{1}{2}$

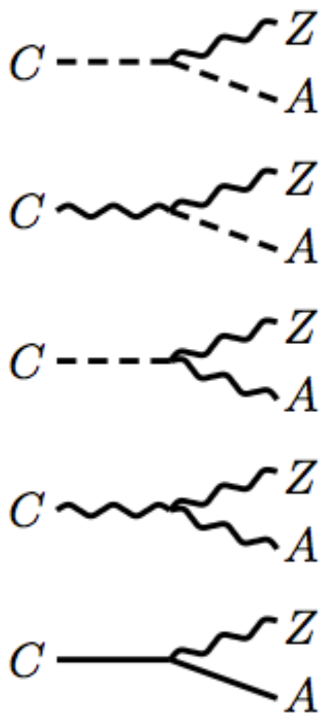
at the LHC $f = 0.7, \quad \bar{f} = 0.3$

- It is convenient to introduce the parameter $\tilde{\gamma}$

$$\cos^2\tilde{\gamma} = f\cos^2\gamma + \bar{f}\sin^2\gamma,$$
$$\sin^2\tilde{\gamma} = f\sin^2\gamma + \bar{f}\cos^2\gamma.$$

$$\tilde{\gamma} \in [0, \pi/2].$$

Coupling assignment : Topology II



$$iC\overleftrightarrow{\partial}_\mu A\, Z^\mu,$$

$$-\,C_\mu\, A\, Z^\mu,$$

$$-\,C\, A_\mu\, Z^\mu,$$

$$(C_\mu A_\nu - A_\mu C_\nu)\partial^\mu Z^\nu + \text{cycl.},$$

$$\overline{\psi}_C \gamma_\mu \gamma_5 \psi_A\, Z^\mu,$$

- Since the Z-boson is CP-odd, while the self-conjugate A and C are C-even

Invariant-mass distribution: S=1-6

- Dilepton:

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\hat{m}_{\ell\ell}} = (\cos^2\alpha\,\sin^2\beta + \sin^2\alpha\,\cos^2\beta)\, f_1^{(\ell\ell)}(\hat{m}_{\ell\ell}^2;\, m_A^2, m_B^2, m_C^2)$$
$$+(\cos^2\alpha\,\cos^2\beta + \sin^2\alpha\,\sin^2\beta)\, f_2^{(\ell\ell)}(\hat{m}_{\ell\ell}^2;\, m_A^2, m_B^2, m_C^2)$$
$$+(\cos\alpha\,\sin\alpha\,\cos\beta\,\sin\beta)\, f_3^{(\ell\ell)}(\hat{m}_{\ell\ell}^2;\, m_A^2, m_B^2, m_C^2),$$

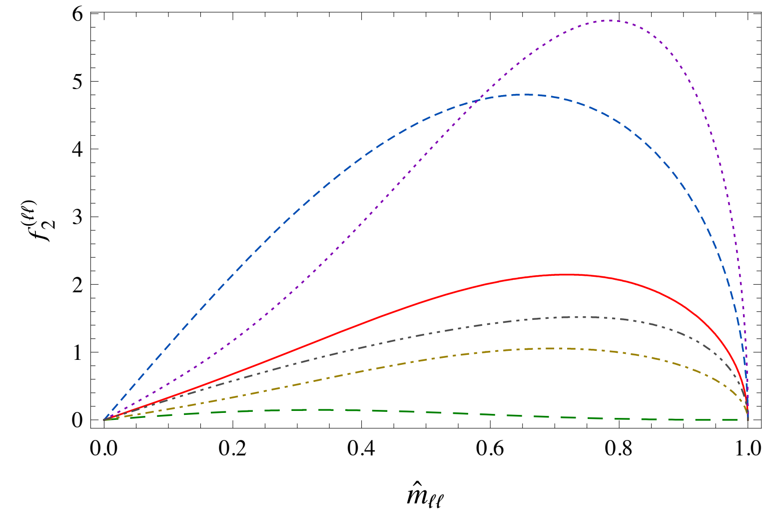
- The last term comes from the interference term and is sensitive to the sign of the couplings.

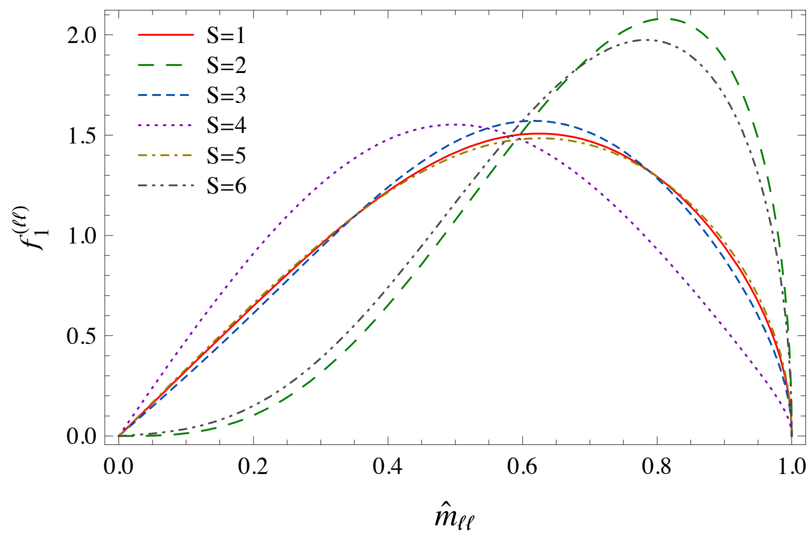
- Two fold ambiguity: $\{\alpha,\,\beta\} \to \{\mathrm{sign}\,\alpha\,(\frac{\pi}{2} - |\alpha|),\, \frac{\pi}{2} - \beta\}$

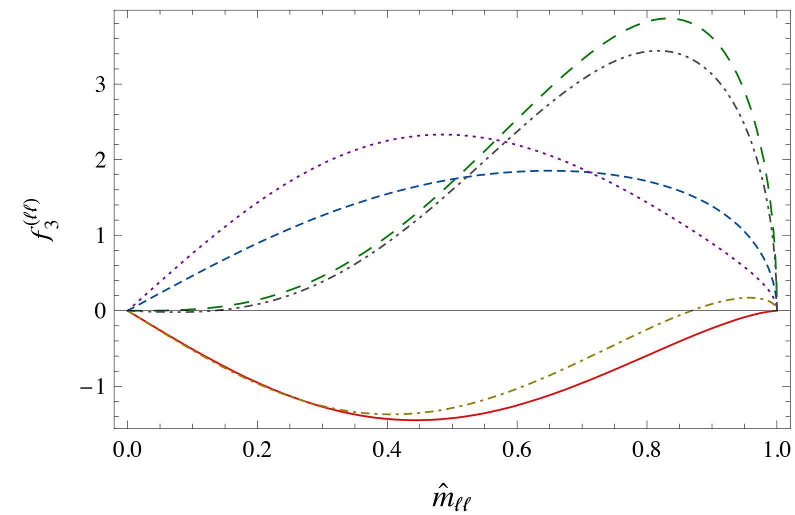
Invariant-mass distribution: S=1-6

- Dilepton:

MC=184
MB=200
MA=98







- The overall normalization constants have been fixed by requiring that $f_1^{(\ell\ell)}$ is unit-normalized.

- $f_1^{(\ell\ell)}$ and $f_2^{(\ell\ell)}$ must be positive because one can choose the couplings such that only one of these terms survives. (since the physical distribution corresponds to a probability distributions)

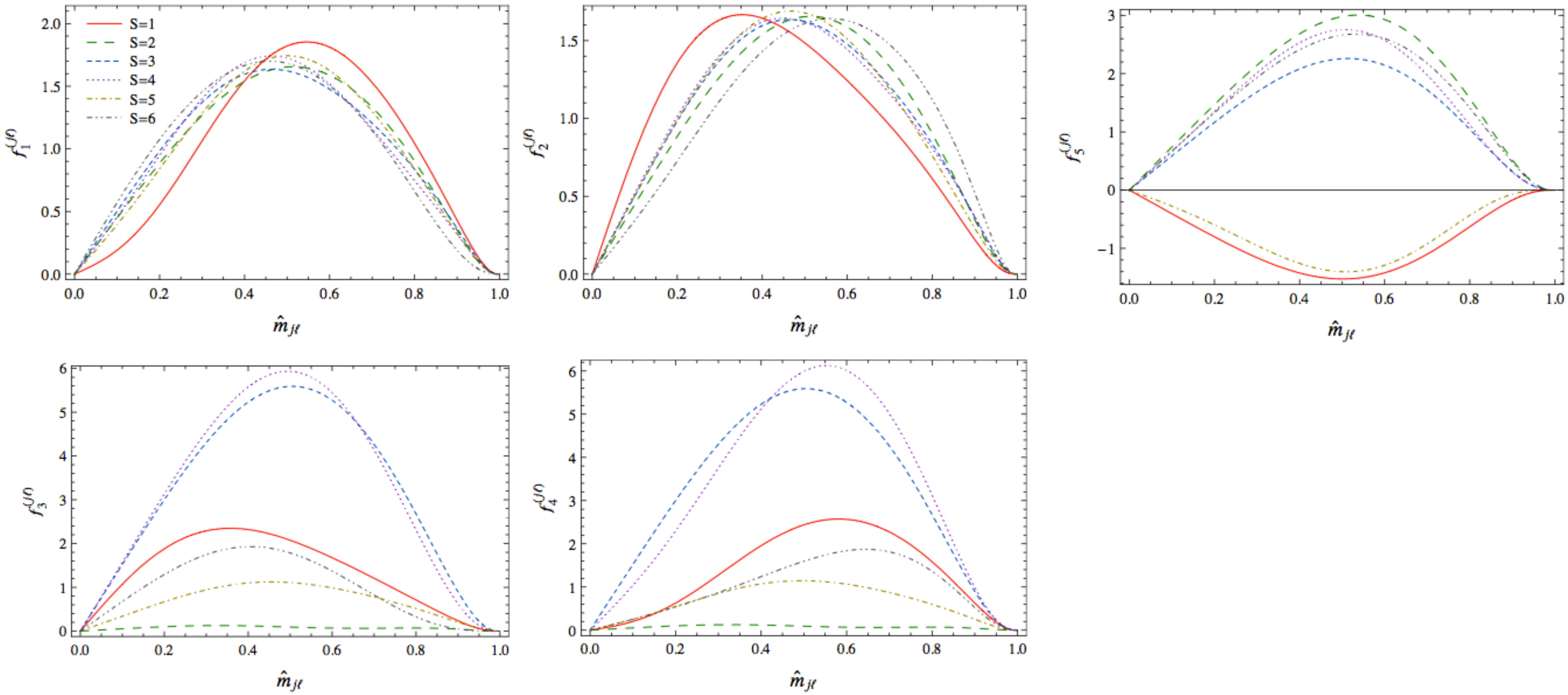
Invariant-mass distribution: S=1-6

- Jet-lepton:

$$
\begin{aligned}
\frac{1}{\Gamma}\frac{d\Gamma}{d\hat{m}_{j\ell}} = & (\cos^2\alpha\,\sin^2\beta\,\cos^2\tilde{\gamma} + \sin^2\alpha\,\cos^2\beta\,\sin^2\tilde{\gamma})\, f_1^{(j\ell)}(\hat{m}_{j\ell}^2;\, m_A^2, m_B^2, m_C^2, m_D^2) \\
& + (\cos^2\alpha\,\sin^2\beta\,\sin^2\tilde{\gamma} + \sin^2\alpha\,\cos^2\beta\,\cos^2\tilde{\gamma})\, f_2^{(j\ell)}(\hat{m}_{j\ell}^2;\, m_A^2, m_B^2, m_C^2, m_D^2) \\
& + (\cos^2\alpha\,\cos^2\beta\,\cos^2\tilde{\gamma} + \sin^2\alpha\,\sin^2\beta\,\sin^2\tilde{\gamma})\, f_3^{(j\ell)}(\hat{m}_{j\ell}^2;\, m_A^2, m_B^2, m_C^2, m_D^2) \\
& + (\cos^2\alpha\,\cos^2\beta\,\sin^2\tilde{\gamma} + \sin^2\alpha\,\sin^2\beta\,\cos^2\tilde{\gamma})\, f_4^{(j\ell)}(\hat{m}_{j\ell}^2;\, m_A^2, m_B^2, m_C^2, m_D^2) \\
& + (\cos\alpha\,\sin\alpha\,\cos\beta\,\sin\beta)\, f_5^{(j\ell)}(\hat{m}_{j\ell}^2;\, m_A^2, m_B^2, m_C^2, m_D^2),
\end{aligned}
$$

  - The last term comes from the interference term.
  - Two fold ambiguity: $\{\alpha,\, \beta,\, \gamma\} \to \{\mathrm{sign}\,\alpha\,(\frac{\pi}{2} - |\alpha|),\, \frac{\pi}{2} - \beta,\, \frac{\pi}{2} - \gamma\}$.

Invariant-mass distribution: S=1-6

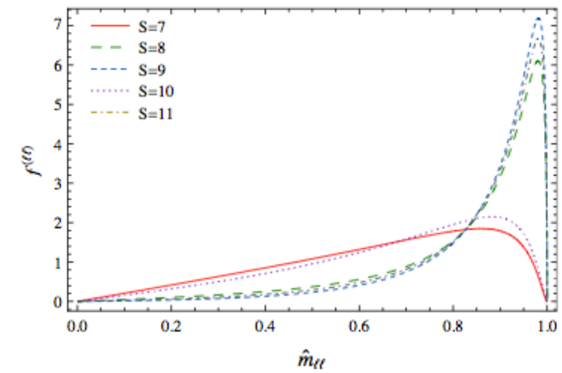


- The overall normalization constants have been fixed by requiring that $f_1^{(j\ell)}$ is unit-normalized.
- f1-f4 must be positive because one can choose the couplings such that only one of these terms survives. (since the physical distribution corresponds to a probability distributions)

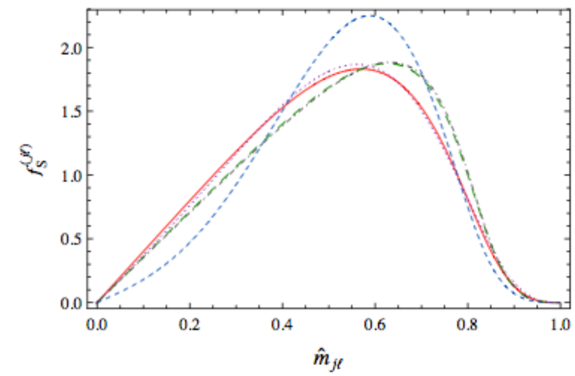
Invariant-mass distribution: S=7-11

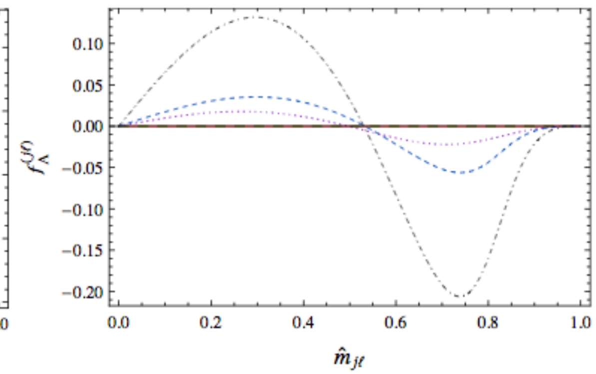
- Dilepton:

MD=565 GeV
MC=184 GeV
MA=98 GeV



- Jet-lepton:





$$\frac{1}{\Gamma}\frac{d\Gamma}{d\hat{m}_{\ell\ell}} = f^{(\ell\ell)}(\hat{m}^2_{\ell\ell};\, m^2_A, m^2_B, m^2_C),$$
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\hat{m}_{j\ell}} = f^{(j\ell)}_{\rm S}(\hat{m}^2_{j\ell};\, m^2_A, m^2_B, m^2_C, m^2_D) + \cos 2\tilde{\gamma}\, f^{(j\ell)}_{\rm A}(\hat{m}^2_{j\ell};\, m^2_A, m^2_B, m^2_C, m^2_D).$$

- The overall normalization constants have been fixed by requiring that $f_{\rm S}^{(j\ell)}$ is unit-normalized.

Fitting Procedure

“Data” : $S=1, \quad \alpha=0,\ \beta=\pi/2,\ \tilde{\gamma}=0, \quad m_B=200$ GeV
(corresponding to the MSSM decay chain $\tilde{q}_L \to \tilde{\chi}_2^0 \to \tilde{l}_L^* \to \tilde{\chi}_1^0$);

- Based on 1000 events and10 bins histograms.
- Perform χ^2 fit of the theoretical distribution functions to these fake “data” histogram for each of the spin configurations S=1-11, searching for the minimum value as a function of the parameters α, β, $\tilde{\gamma}$, and m_B

Results

"Data", using only $\hat{m}_{\ell\ell}$ distribution:

S	$\min \chi^2$	best-fit parameters α	β	m_B [GeV]
1 [SFSF]	0.00	0.00	1.57	200.0
2 [FSFS]	0.00	−1.22	1.05	209
3 [FSFV]	0.00	+1.14	0.43	197.7
4 [FVFS]	0.27	−1.34	0.23	216
5 [FVFV]	0.05	−0.38	0.38	197
6 [SFVF]	0.05	−0.65	0.92	191.3

S	$\min \chi^2$
7 [FSS]	140
8 [FSV]	3100
9 [FVS]	4200
10 [FVV]	290
11 [SFF]	3700

- Difficult to distinguish "data" from S=2-6.
- There are 3 parameters, α, β and m_B, which can be adjusted so as to mimic the data distribution.
- S=7-11 can be distinguished from "data", because there are no free parameters to adjust.
- Also S=7-11 and "data" come from different topology.

Results

"Data", using only $\hat{m}_{\ell\ell}$ distribution:

S	$\min\chi^2$	best-fit parameters α	β	m_B [GeV]
1 [SFSF]	0.00	0.00	1.57	200.0
2 [FSFS]	0.00	−1.22	1.05	209
3 [FSFV]	0.00	+1.14	0.43	197.7
4 [FVFS]	0.27	−1.34	0.23	216
5 [FVFV]	0.05	−0.38	0.38	197
6 [SFVF]	0.05	−0.65	0.92	191.3

S	$\min\chi^2$
7 [FSS]	140
8 [FSV]	3100
9 [FVS]	4200
10 [FVV]	290
11 [SFF]	3700

"Data" A, using both $\hat{m}_{\ell\ell}$ and $\hat{m}_{j\ell}$ distributions:

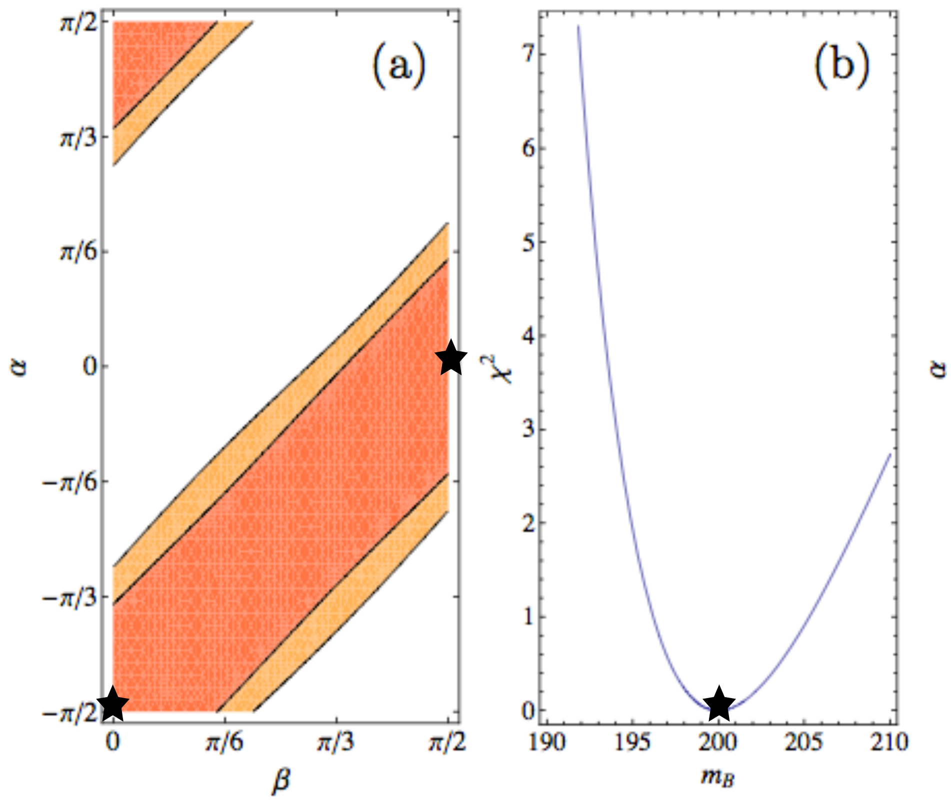
S	$\min\chi^2$	best-fit parameters α	β	$\tilde{\gamma}$	m_B [GeV]
1 [SFSF]	0	0.00	1.57	0.00	200.0
2 [FSFS]	150	−0.08	0.07	1.57	754
3 [FSFV]	87	±1.57	1.57	0.29	210
4 [FVFS]	48	±1.19	0.00	1.57	220
5 [FVFV]	46	−0.93	0.25	1.57	224
6 [SFVF]	37	−0.50	0.53	1.57	197.4

S	$\min\chi^2$	best-fit $\tilde{\gamma}$
7 [FSS]	200	?
8 [FSV]	3100	?
9 [FVS]	4300	0.39
10 [FVV]	330	1.57
11 [SFF]	3700	1.08

? indicates that χ^2 is independent of that parameter

- All possible spin configurations can be discriminated with at least six standard deviations, for a given number of 1000 events.

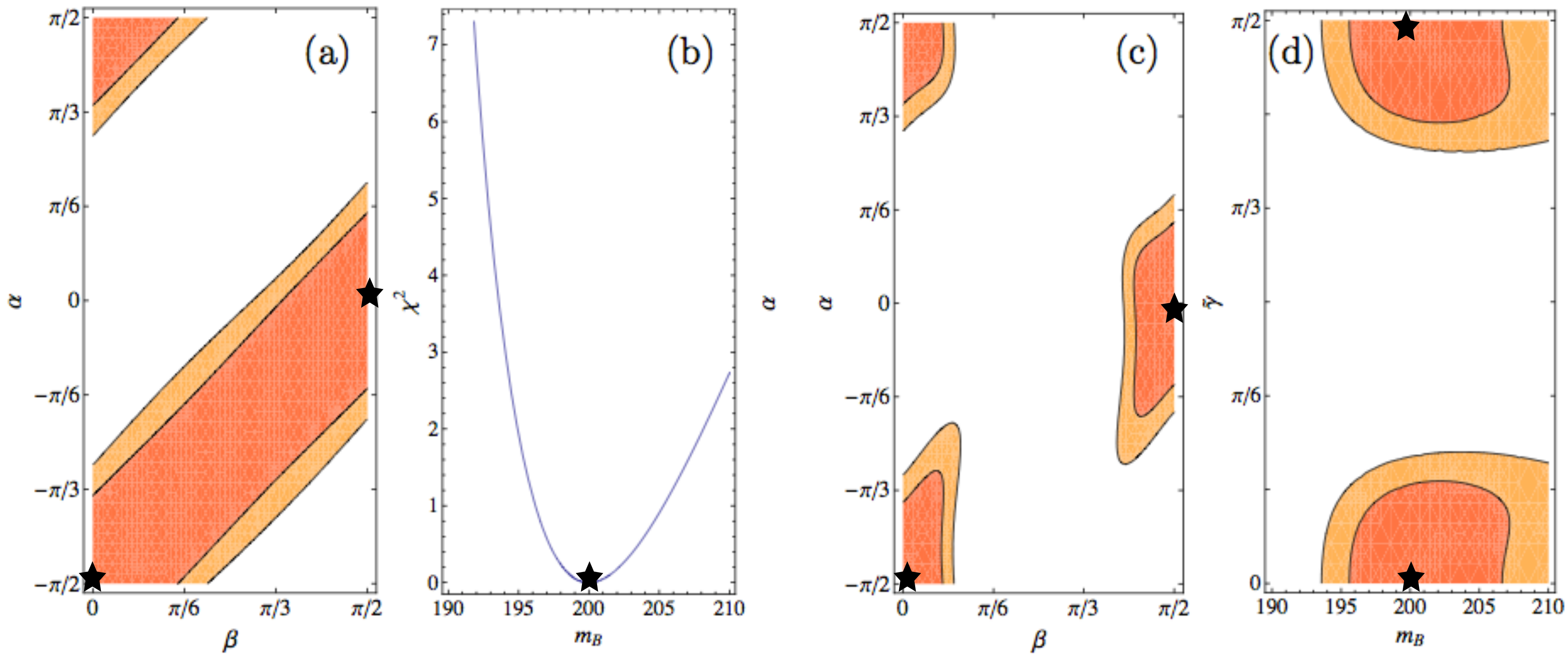
Results



- Depict the constraints on α, β and MB obtained from fitting the mˆ ll distribution alone.

- The dark/light bands corresponds to 68%/95% confidence-level region.

Results



- Depict the constraints on α, β and MB obtained from fitting the mˆ ll distribution alone.
- The inclusion of both m^ll and m^ql, lead to a constraint on $\tilde{\gamma}$
- Bounds on α and β are improved.
- The dark/light bands corresponds to 68%/95% confidence-level region.

Conclusion

- No assumptions about the masses, spins and couplings of new particles have been made.
- Di-lepton invariant-mass distribution is sometimes not sufficient.
- Possible to unambiguously discriminate between all possible spin configuration with high significance.
- The results are based on parton-level analysis. The model discrimination and the precision for the parameter determination may be diluted by jet energy smearing and combinatorics in the realistic experiment but the main conclusions are not affected much.

Thank you