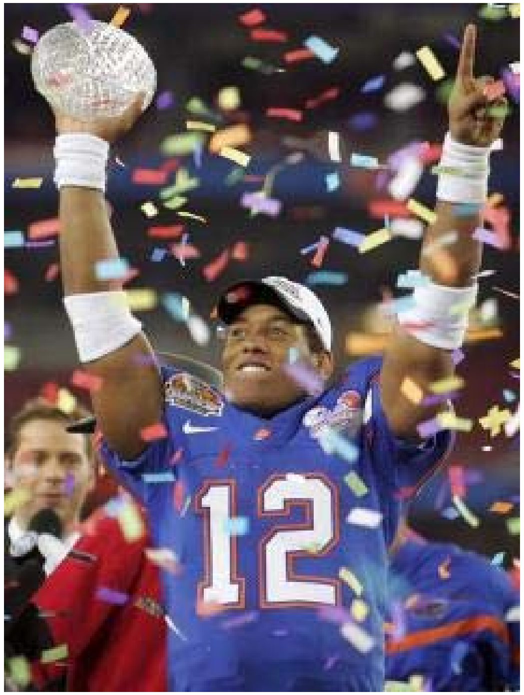
(A pedagogical overview of)

New Physics Signatures and Precision Measurements at the LHC

Konstantin Matchev



UF UNIVERSITY of FLORIDA
The Foundation for The Gator Nation

This talk will not contain

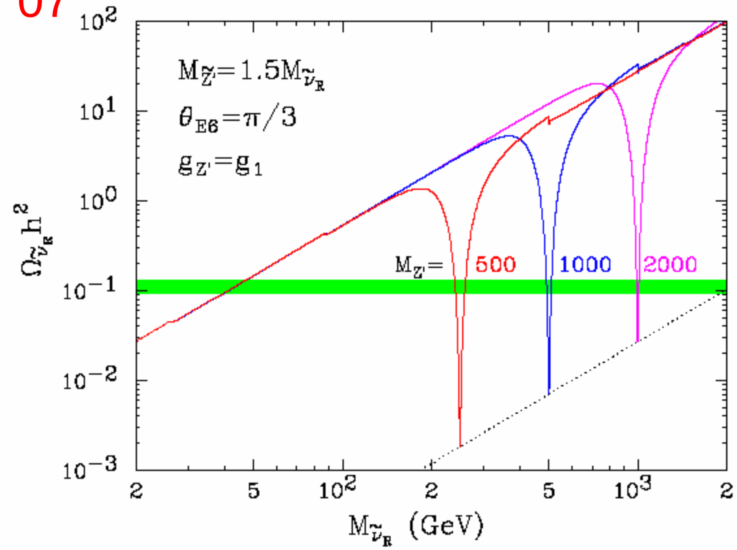
- Predictions of what the LHC will (not) discover
- The model I have recently been working on
  - But in case you are interested: UMSSM = NMSSM + U(1) + N + exotica

Lee,KM,Wang 2007
Luhn,Lee,KM 2007

- New features
  - Scalar WIMP: thermal RH sneutrino DM, unlike
    - Nonthermal Asaka,Ishiwata,Moroi 05
    - Mixed Thomas,Tucker-Smith,Weiner 07
  - TeV scale colored exotics

    Kang,Langacker,Nelson 07
  - Z_3 discrete symmetries
    - B_3 (leptophobic Z')
    - L_3
    - M_3
  - Stable proton

Lee,KM,Nasri 2007

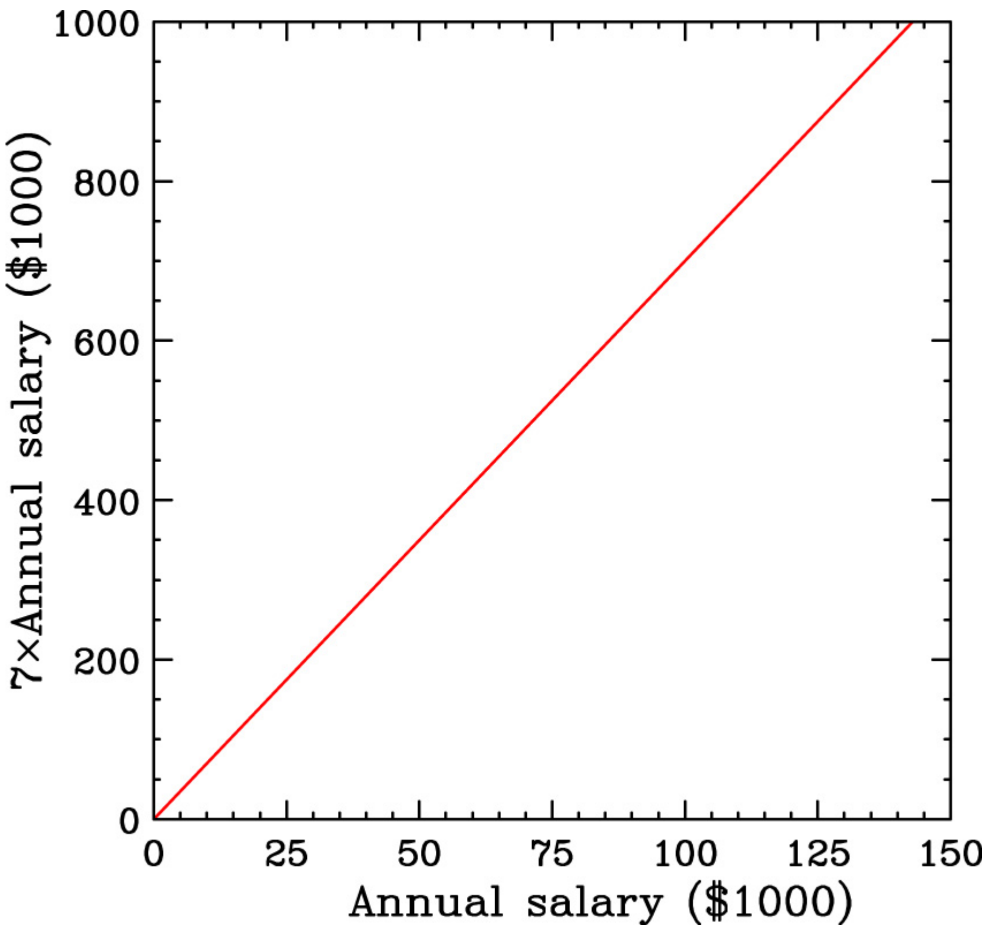


This talk will contain

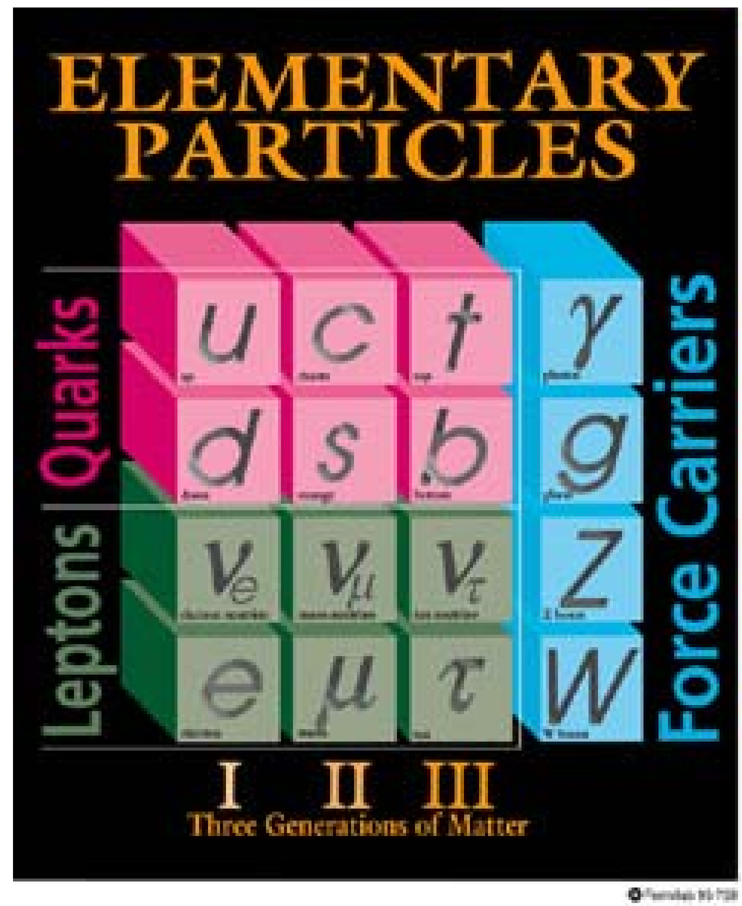
- Jokes
- Homework assignments
- General classification of new physics signatures
  - Bump hunting
  - Bean counting
- Critical and pedagogical review of (some) existing techniques for precision measurements
  - Mass measurements
  - Spin measurements
- The discussion will be largely model-independent
- Useful “take-home lessons”

How do we know LHC will find anything new or interesting?

- The x7 argument

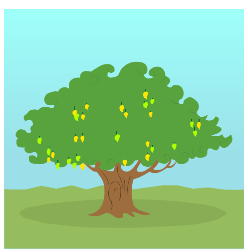


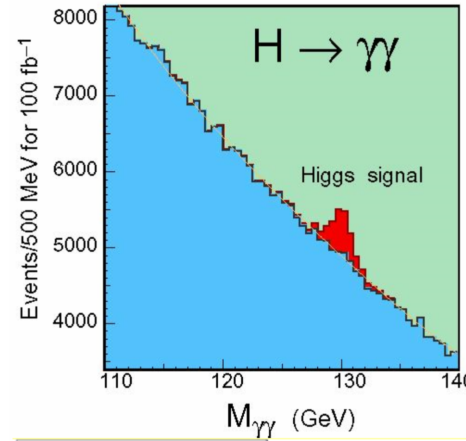
- Where is the Higgs?

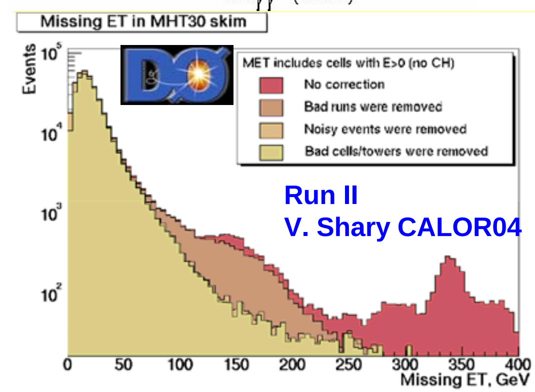


What do we do for a living?

- Look for new particles. How?
  - Full reconstruction (bump hunting)
    - Backgrounds can be measured from data
    - Easy to do mass, width measurements
    - More likely to be done with early LHC data
  - Excess of events (bean counting)
    - Prone to systematic errors
    - Difficult to measure particle properties
    - Less likely to be done with early LHC data



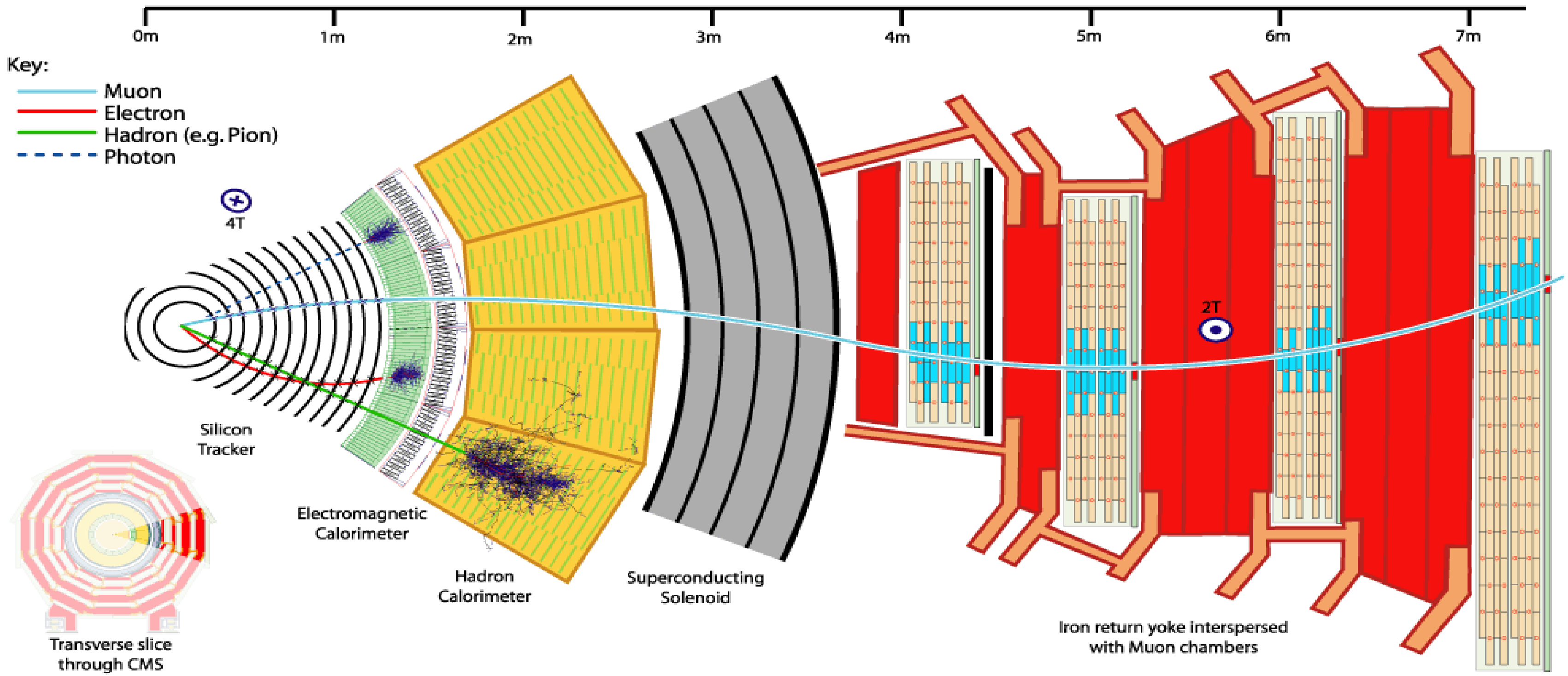




- It is worth thinking about bump hunts <u>now</u>!
- It is possible to give an exhaustive and systematic classification of all resonance searches

Classification of resonance searches

- How many resonances per event? (1 or 2)
- How many objects does the resonance decay to? (2,3,4,…)
- What are those objects?



Note the absence of a “Missing energy calorimeter”

List of all di-object resonances

	μ	e	γ	jet	b	τ	ν
μ	Z’			LQ	LQ		W’
e		Z’		LQ	LQ		W’
γ			h				
jet				Z’		LQ	
b					h	LQ	
τ						h	W’
ν							-

‘Z’, ‘t’, ‘W’…

- The scheme can be generalized to
  - three body decays etc.
  - pair-production etc.

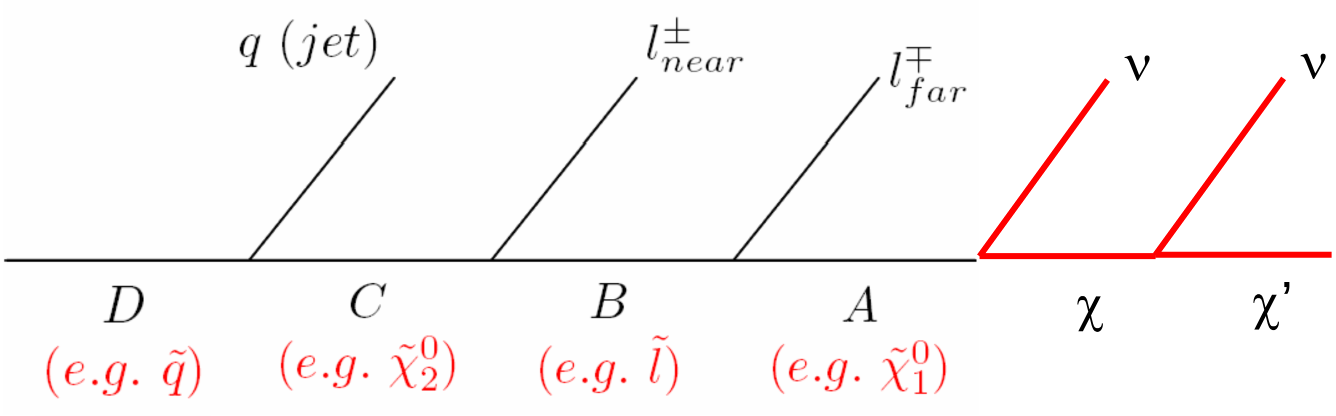
Homework

- (Warm-up exercise) Classify the particles from the models you have worked on in the past.
- Notice if there are any remaining empty slots. Can you think of any reason why such a resonance should not exist?
  - If “yes”, report to me and to the experimentalists
  - If “no”, then think of a model where such a resonance will exist and may give an observable signature in the early LHC data
- Find out which experimental collaboration your institution belongs to. Then find the list of “exotic” resonance searches which are being planned for.
- Are there any omissions? What would be the appropriate theory models? Advertise those theory models to the collaboration.

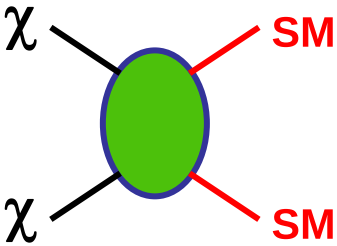
Why you should do the homework

- You may learn something you didn't know
- You may be able to teach the experimentalists something they didn't know
- Bumps are easier and therefore more likely to be the first new physics discoveries in the early LHC (late Tevatron) data
- To summarize: inclusive bump hunting only needs you to specify:
  - How many new resonances are present in each event?
  - How many and which SM particles does the new resonance decay to? (What is the signature?)

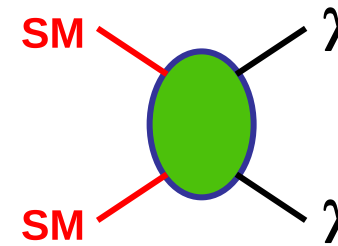
Missing energy signatures



- Motivated by the dark matter argument
- Inevitable model dependence
- What happens to the last guy?
- Why not look for the true dark matter particle χ directly?



Dark Matter at colliders: model-independent approach



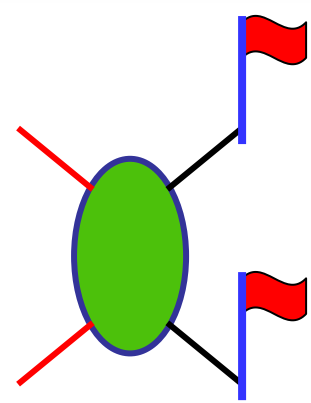
- Relate the WIMP annihilation rate in the early Universe to the WIMP production rate at colliders. Detailed balancing:

$$\frac{\sigma(\chi+\chi\to X_i+\bar{X}_i)}{\sigma(X_i+\bar{X}_i\to\chi+\chi)} = 2\,\frac{v_X^2(2S_X+1)^2}{v_\chi^2(2S_\chi+1)^2}$$

- Predict the WIMP pair production rate **Birkedal,KM,Perelstein 2004**

$$\sigma(X_i\bar{X}_i\to 2\chi) = 2^{2(J_0-1)}\,\kappa_i\sigma_{\rm tot}\,\frac{(2S_\chi+1)^2}{(2S_X+1)^2}\left(1-\frac{4M_\chi^2}{s}\right)^{1/2+J_0}$$

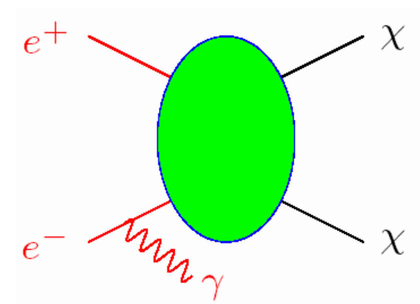
- Known parameters $\{\sigma_{tot}, S_X, s\}$
- Unknown parameters $\{\kappa_i, M_\chi, S_\chi, J_0\}$
- Not an observable signature! What if



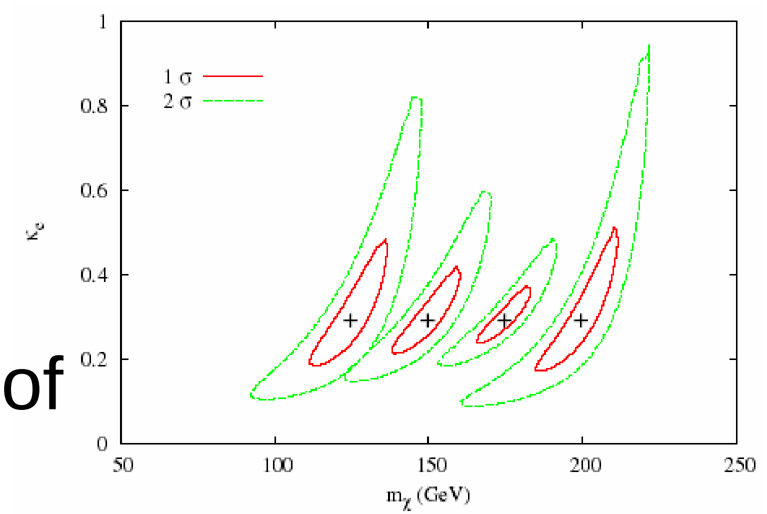
?

DM production at colliders

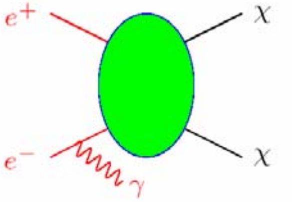
- In order to observe the missing energy, the DM particles must recoil against something visible
- If some sort of ISR (initial state radiation), model-independent prediction still possible, using soft/collinear factorization
  - Very challenging experimental signature
  - Does not seem to work at LHC
  - Might work at the ILC
- May provide a measurement of the mass of χ



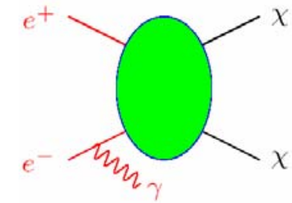
Birkedal,KM,Perelstein 2004



Bernal,Goudelis,Mambrini,Munoz 2008

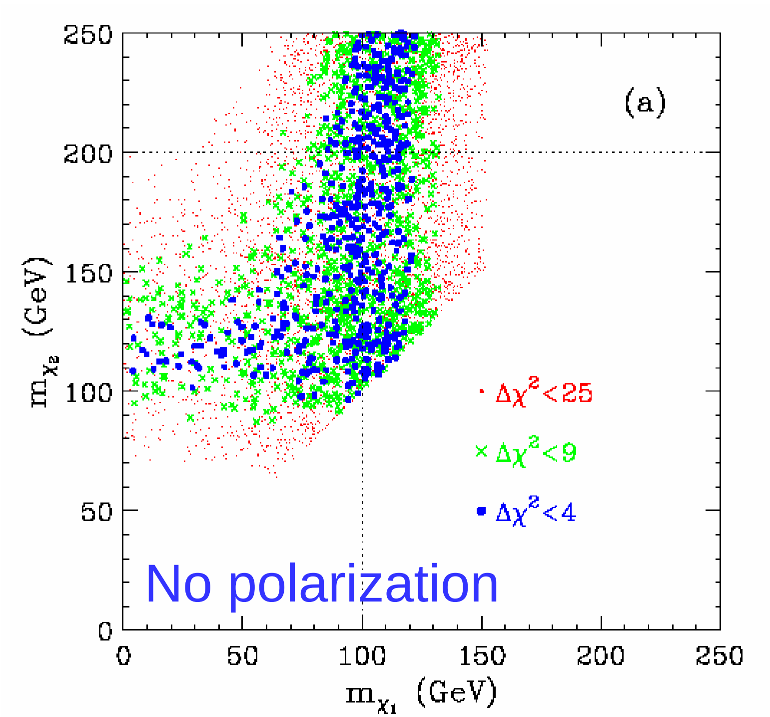


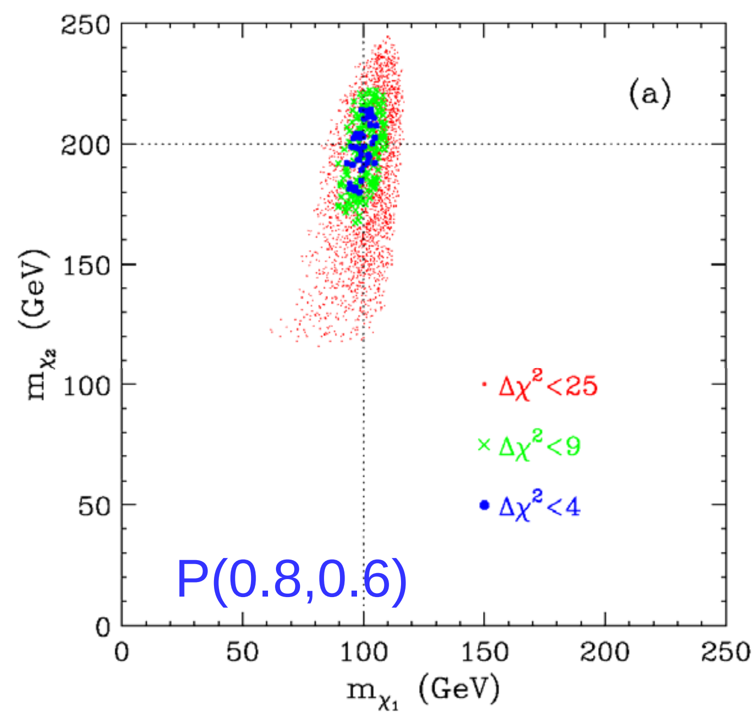
Missing energy at ILC

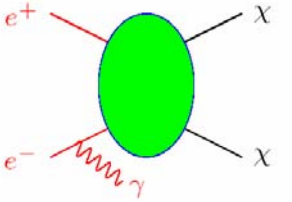


- Can we measure the mass of two invisible particles?
  - m_1=100 GeV m_2=200 GeV
- First example: each contributes equally to the relic density
  - $\kappa_{e1}=\kappa_{e2}$

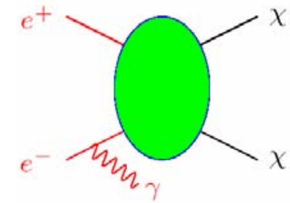
Konar,Kong,Lee,KM,Perelstein (Preliminary)





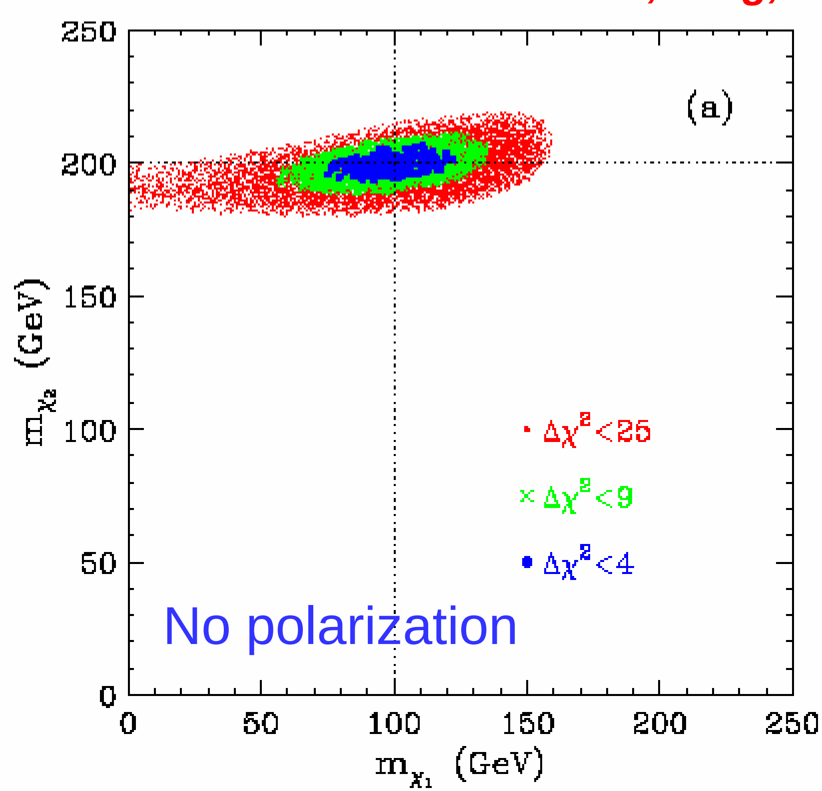


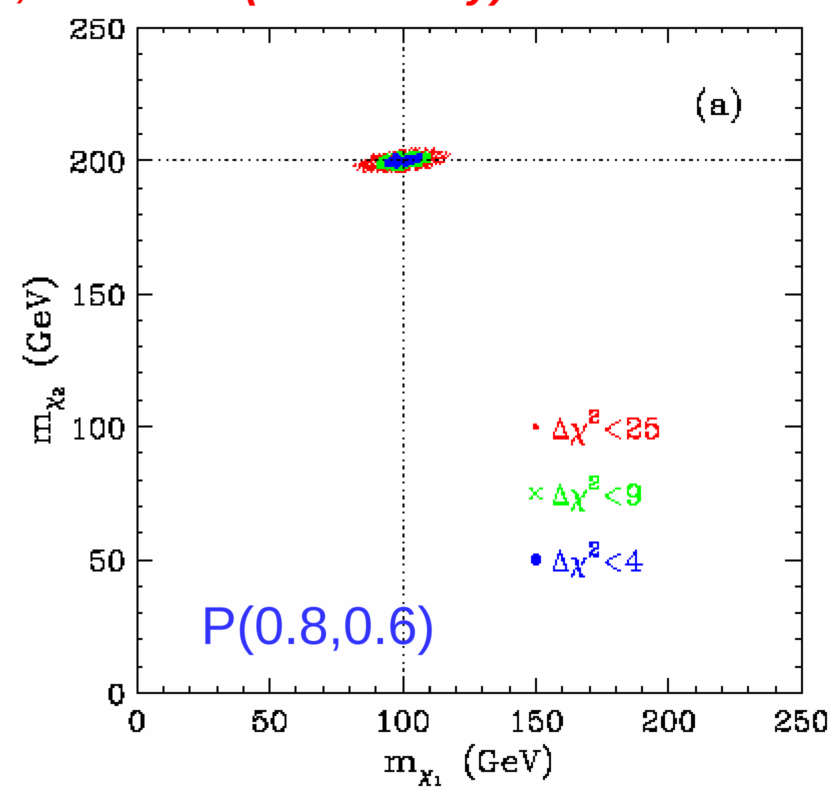
Missing energy at ILC



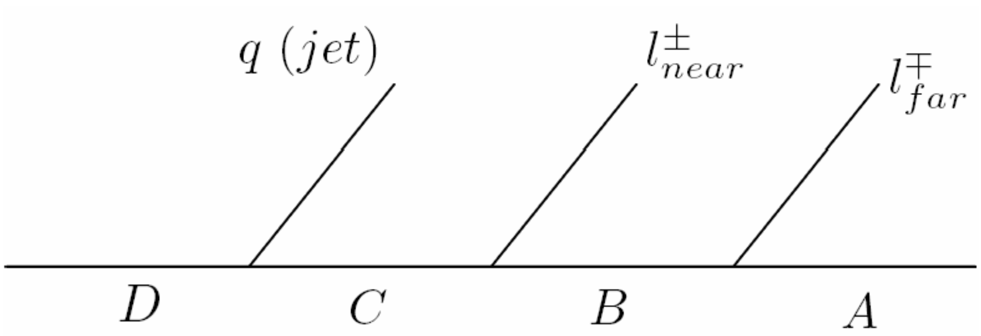
- Another example: one of the particles does not make up a significant fraction of the DM
- Good news: it gives a large signal.

Konar,Kong,Lee,KM,Perelstein (Preliminary)

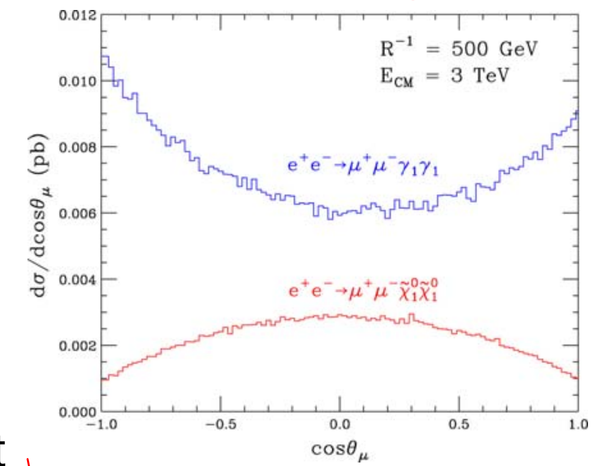




Model discrimination/Spin determination



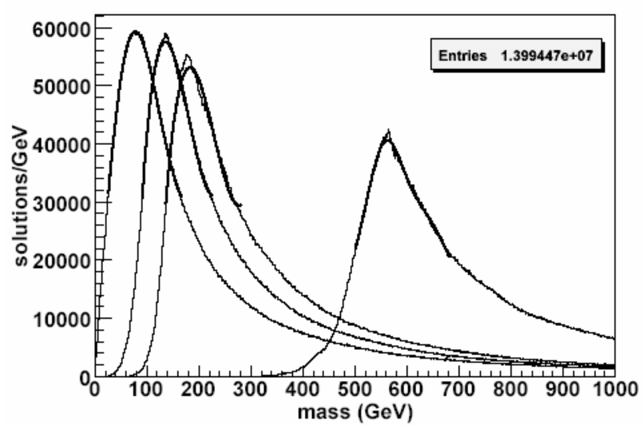
Battaglia,Datta, DeRoeck,Kong,KM 05



- What is the nature of A,B,C,D?
  - Find \$N,000,000,000 and build an ILC
  - Find the momentum of A, fully reconstruct the event
  - Study m² distributions of visible particles

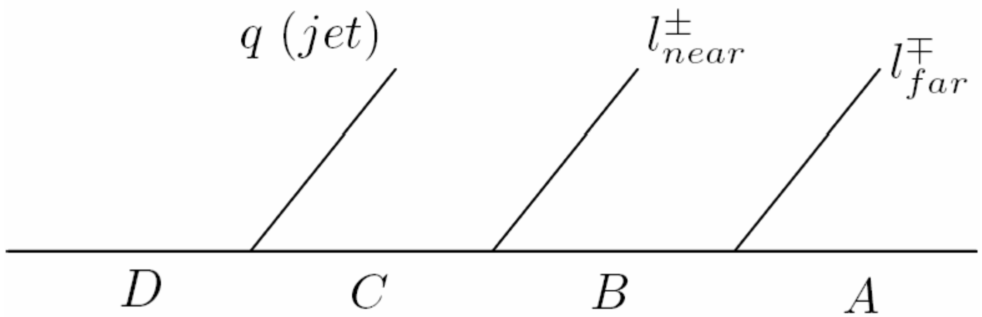
  Athanasiou et al 06, Kilic,Wang,Yavin 07, Csaki,Heinonen,Perelstein 07, S. Thomas (KITP)

Cheng,Engelhardt, Gunion,Han,McElrath 08



- The distributions depend on
  - Spins of A,B,C,D
  - Masses of A,B,C,D
  - Chirality of couplings
  - Initial state (particles vs antiparticles)
- Most spin studies compare two sets of spin assignments, but fix everything else
- That is not a true measurement of the spin

Necessary step: mass measurements

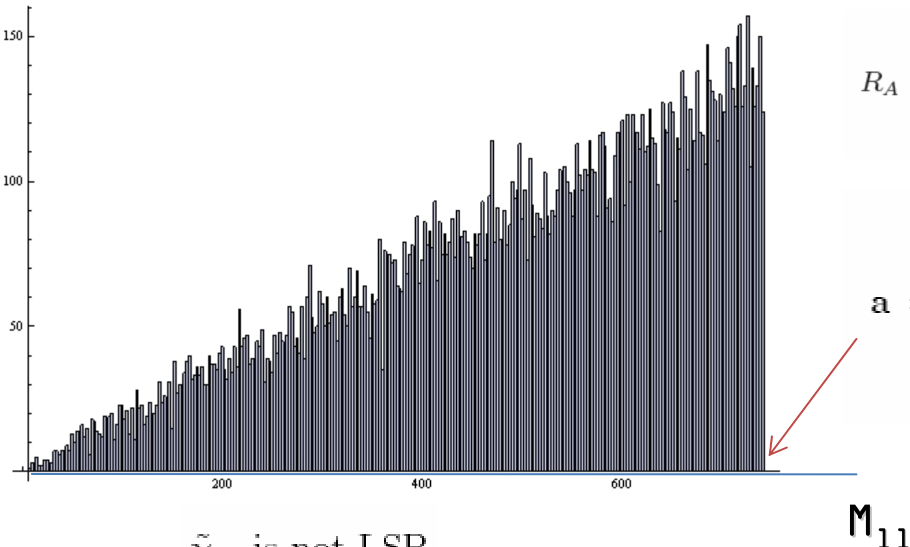


$$\underbrace{(m_D)^2}_{\text{overall scale}} \qquad R_C \equiv \left(\frac{m_C}{m_D}\right)^2 \quad R_B \equiv \left(\frac{m_B}{m_C}\right)^2 \quad R_A \equiv \left(\frac{m_A}{m_B}\right)^2$$

- Form all possible invariant mass distributions
  - M_{ll}, M_{qll}, M_{qln}, M_{qlf}
- Measure the endpoints and solve for the masses of A,B,C,D
- 4 measurements, 4 unknowns. Should be sufficient.
- Not so fast!
  - Ambiguity in the interpretation of the measured endpoints
  - Ambiguity in “near” and “far” lepton
  - The measurements may not be independent
  - Nonlinear equations -> multiple solutions?

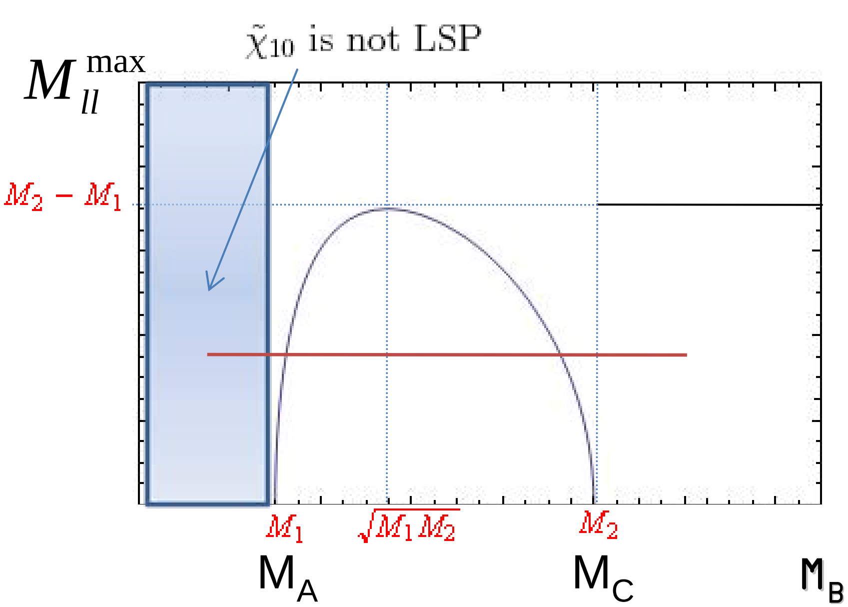
Burns,KM,Park 08

Di-lepton invariant Mass



$$R_A \equiv \left(\frac{m_A}{m_B}\right)^2 \qquad R_B \equiv \left(\frac{m_B}{m_C}\right)^2 \qquad R_C \equiv \left(\frac{m_C}{m_D}\right)^2 \qquad D \equiv (m_D)^2$$

$$a = M_{ll}^{Max} = \begin{cases} M_D\sqrt{R_C(1-R_B)(1-R_A)} & OnShell \\ M_C - M_A & OffShell \end{cases}$$



1. No need to distinguish near
2. But which formula applies?

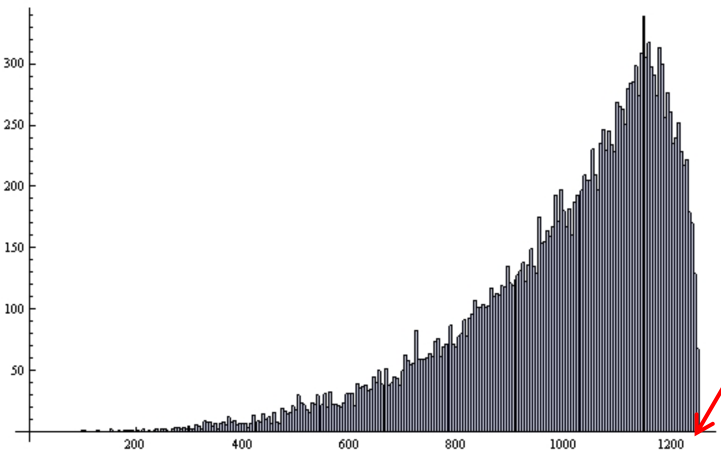
X. Tata, slide 12

3. Can there be multiple soluti

$$M_{\tilde{N}} = \begin{pmatrix} M_1 & 0 & -c_\beta\, s_W\, m_Z & s_\beta\, s_W\, m_Z \\ 0 & M_2 & c_\beta\, c_W\, m_Z & -s_\beta\, c_W\, m_Z \\ -c_\beta\, s_W\, m_Z & c_\beta\, c_W\, m_Z & 0 & -\mu \\ s_\beta\, s_W\, m_Z & -s_\beta\, c_W\, m_Z & -\mu & 0 \end{pmatrix}$$

-PHENO'08 Myeonghun Park

Quark-lepton-lepton invariant Mass



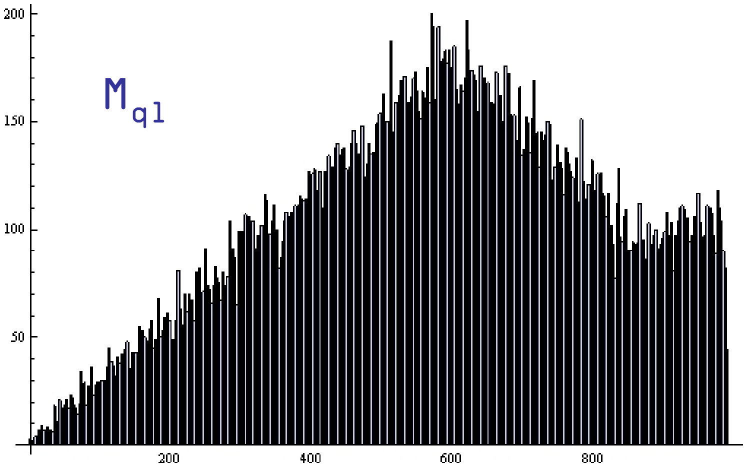
$$
\mathbf{b} = M_{qll}^{Max} = \begin{cases}
M_D\sqrt{(1-R_C)(1-R_A R_B)} & (R_C < R_A R_B) \\
M_D\sqrt{(1-R_B)(1-R_C R_A)} & (R_B < R_C R_A) \\
M_D\sqrt{(1-R_C R_B)(1-R_A)} & (R_A < R_B R_C) \\
M_D\sqrt{(1-\sqrt{R_C R_A R_B})^2} & (others) \\
\hline
M_D(1-\sqrt{R_A R_B R_C}) & (R_C > R_A R_B) \\
M_{ql(high)}^{Max} & (\text{others})
\end{cases}
$$

OnShell (first four cases); *OffShell* (last two cases)

1. No need to distinguish "near" and "far" lepton
2. But which formula should we use?

Answer: Use all possible combinations! Solve for each and at the end check for consistency.

Quark-lepton invariant mass

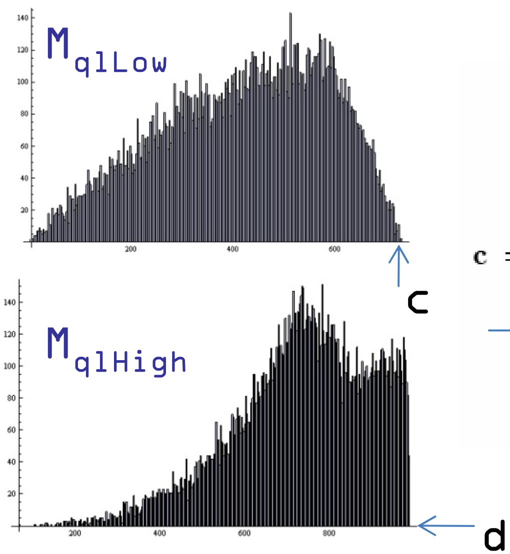


1. But which lepton is "near" and which one is "far"?
2. If we simply add them together, there is only a single endpoint.

Let's order them in inv mass, name

$$m_{ql(low)} \equiv \min[m_{ql_n}, m_{ql_f}]$$

$$m_{ql(high)} \equiv \max[m_{ql_n}, m_{ql_f}]$$



$$\mathbf{c} = M^{Max}_{ql(low)} = \begin{cases} M_D\sqrt{(1-R_C)(1-R_B)} \\ M_D\sqrt{\frac{(1-R_C)(1-R_A)}{2-R_A}} \\ M_D\sqrt{\frac{(1-R_C)(1-R_A)}{2-R_A}} \\ \hline M_D\sqrt{(1-R_C)(1-R_A R_B)} \end{cases}$$

$$\mathbf{d} = M^{Max}_{ql(high)} = \begin{cases} M_D\sqrt{(1-R_C)(1-R_A)} & R_A < 2-\frac{1}{R_B} \\ M_D\sqrt{(1-R_C)(1-R_A)} & R_A < R_B \\ M_D\sqrt{(1-R_C)(1-R_B)} & R_A > R_B \\ \hline \frac{1}{\sqrt{2}}M^{Max}_{ql(high)} \end{cases}$$

Recap: on-shell cases alone

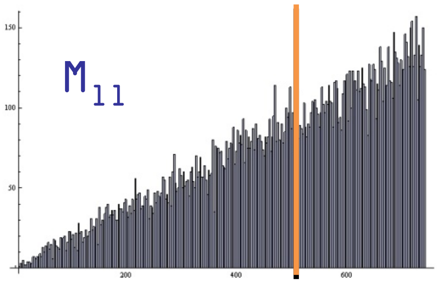
	M_{ql}		
M_{qll}	1	2	3
1	(1,1)	(1,2)	(1,3)
2			(2,3)
3	(3,1)	(3,2)	
4	(4,1)	(4,2)	(4,3)

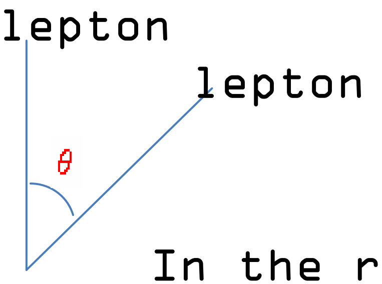
- Good news: 3 of the 12 cases are impossible
- Bad news: for regions (3,1), (3,2) and (2,3) the measured endpoints are not independent:

$$(m_{qll}^{\max})^2 = (m_{ll}^{\max})^2 + (m_{ql(high)}^{\max})^2$$

- Need an additional measurement

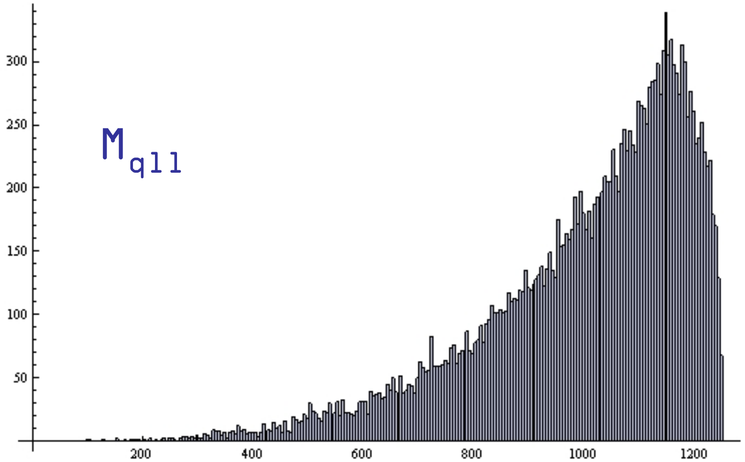
Modified M_{qll}

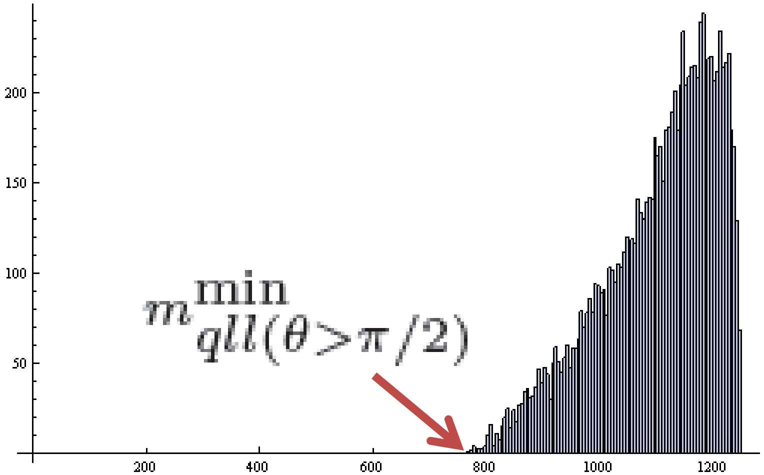




In the rest frame of C

Select lepton pairs which satisfy $M_{ll} > \frac{M_{ll}^{Max}}{\sqrt{2}}$





$$\mathbf{f} = M^{Min}_{qll(\theta)} = \frac{M_D}{2}\sqrt{\left(2(1-R_A R_B)(1-R_C) - \sqrt{(R_B+1)^2(R_A+1)^2 - 16R_A R_B}(1-R_C) + (R_C+1)(1-R_B)(1-R_A)\right)}$$

Notice that it is an unique formula – an advantage over M_{qll}

	M_{qI}		
M_{qII}	1	2	3
1	(1,1)	(1,2)	(1,3)
2			(2,3)
3	(3,1)	(3,2)	
4	(4,1)	(4,2)	(4,3)

	M_{qI}		
$M_{qII(\theta)}$	1	2	3
1	(1,1)	(1,2)	(1,3)

Burns,KM,Park 08

- Good news: we are down only to three cases.

Inversion formulae for the masses

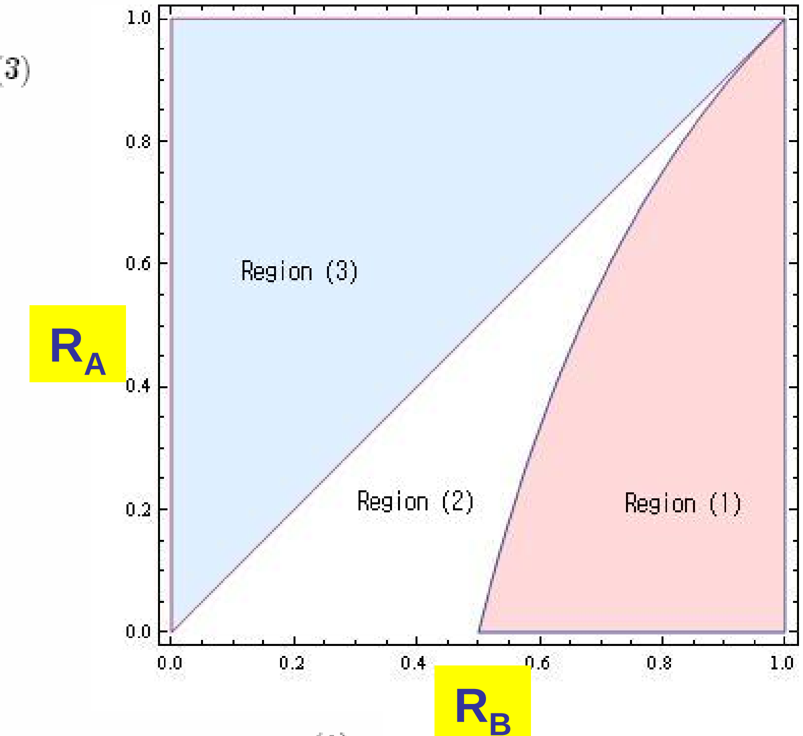
$$R_C(a,b,c,d,f) = \begin{cases} \dfrac{a^4-2a^2f^2}{2(a^4+(c^2+d^2-3f^2)a^2+2f^4-2d^2f^2+c^2(d^2-2f^2))} & (1) \\ \dfrac{a^2\left(\left(3c^2-d^2\right)a^2+2\left(\left(d^2-3f^2\right)c^2+d^2f^2\right)\right)}{(4c^2-2d^2)a^4-2(d^4-3f^2d^2+c^2(5f^2-2d^2))a^2-4(c^2-d^2)f^2(d^2-f^2)} & (2) \\ \dfrac{a^2\left(\left(2c^2-d^2\right)a^2+2\left(\left(d^2-2f^2\right)c^2+d^2f^2\right)\right)}{2(c^2-d^2)a^4-2(d^4-3f^2d^2+2c^2f^2)a^2-2d^2(2f^4-2d^2f^2+c^2(d^2-2f^2))} & (3) \end{cases}$$

$$R_B(a,b,c,d,f) = \begin{cases} -\dfrac{\left(a^2+2c^2-2f^2\right)\left(a^2+d^2-2f^2\right)}{d^2(a^2-2f^2)} & (1) \\ \dfrac{\left(a^2+d^2-2f^2\right)\left(\left(d^2-c^2\right)a^2+2\left(c^2\left(d^2+f^2\right)-d^2f^2\right)\right)}{d^2((3c^2-d^2)a^2+2((d^2-3f^2)c^2+d^2f^2))} & (2) \\ -\dfrac{\left(a^2+2d^2-2f^2\right)\left(\left(d^2-c^2\right)a^2-2d^2f^2+c^2\left(d^2+2f^2\right)\right)}{c^2(a^2-2f^2)(a^2+3d^2-2f^2)} & (3) \end{cases}$$

$$R_A(a,b,c,d,f) = \begin{cases} -\dfrac{\left(a^2+c^2-2f^2\right)\left(a^2+2d^2-2f^2\right)}{c^2(a^2-2f^2)} & (1) \\ 2-\dfrac{d^2}{c^2} & (2) \\ \dfrac{\left(a^2+4c^2-2f^2\right)\left(a^2+d^2-2f^2\right)}{(2c^2-d^2)a^2+2((d^2-2f^2)c^2+d^2f^2)} & (3) \end{cases}$$

$$M_D^2(a,b,c,d,f) = \begin{cases} \dfrac{2c^2d^2\left(a^2-2f^2\right)\left(a^4+\left(c^2+d^2-3f^2\right)a^2+2f^4-2d^2f^2+c^2\left(d^2-2f^2\right)\right)}{(a^4+2(c^2+d^2-2f^2)a^2+4f^4-4d^2f^2+2c^2(d^2-2f^2))^2} & (1) \\ -\dfrac{2c^2d^2\left(\left(2c^2-d^2\right)a^4+\left(-d^4+3f^2d^2+c^2\left(2d^2-5f^2\right)\right)a^2-2\left(c^2-d^2\right)f^2\left(d^2-f^2\right)\right)}{\left(c^2-d^2\right)^2(a^2-2f^2)(a^2+2d^2-2f^2)} & (2) \\ \dfrac{2c^2\left(a^2-2f^2\right)\left(a^2+3d^2-2f^2\right)\left(\left(d^2-c^2\right)a^4+\left(d^4-3f^2d^2+2c^2f^2\right)a^2+d^2\left(2f^4-2d^2f^2+c^2\left(d^2-2f^2\right)\right)\right)}{d^2(a^4+2(c^2+d^2-2f^2)a^2+4f^4-4d^2f^2+2c^2(d^2-2f^2))^2} & (3) \end{cases}$$

$$R_A \equiv \left(\frac{m_A}{m_B}\right)^2 \qquad R_B \equiv \left(\frac{m_B}{m_C}\right)^2$$

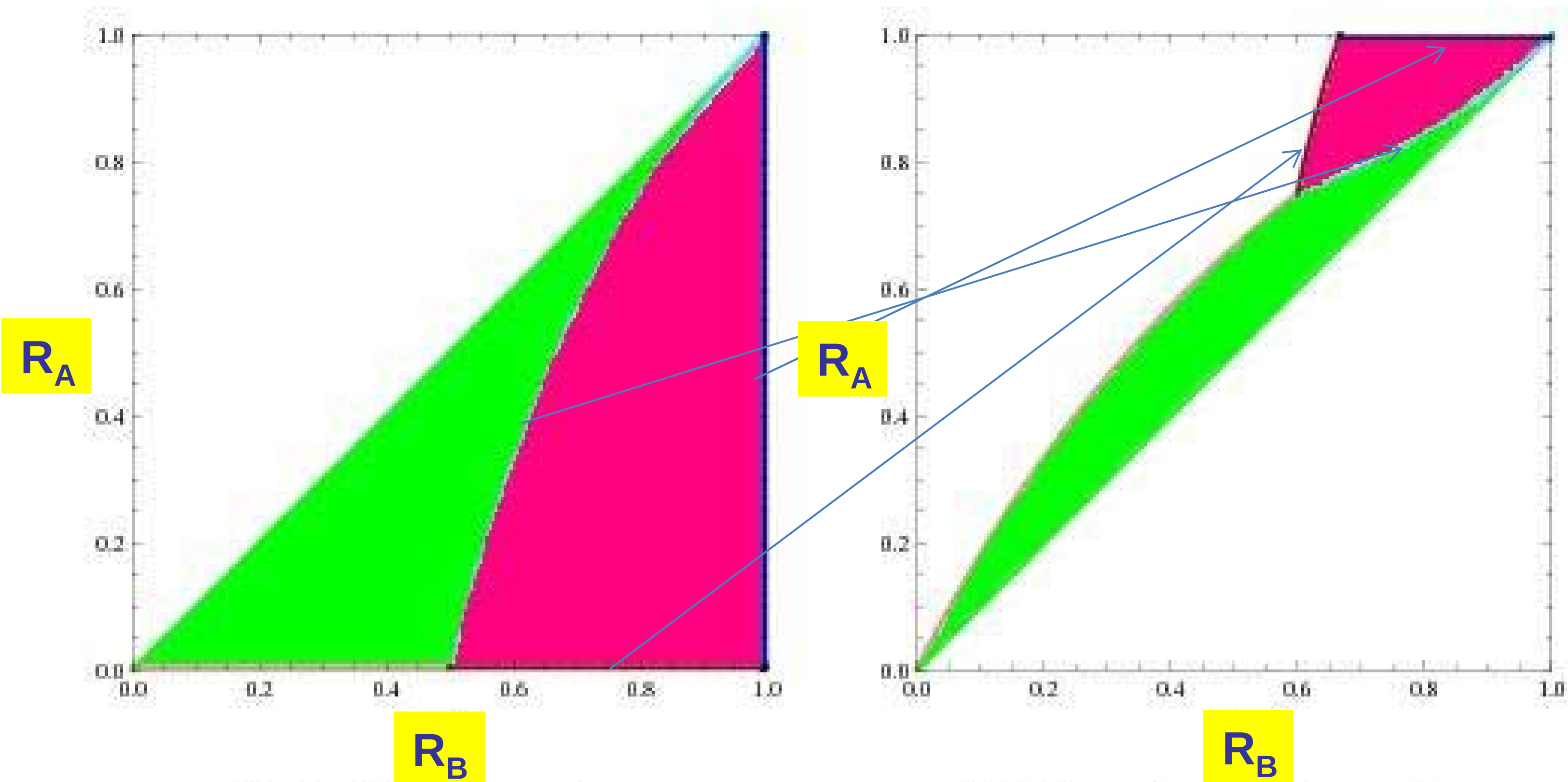


Burns,KM,Park 08

Duplication map

End Points

(R_A , R_B) → (R_A , R_B)

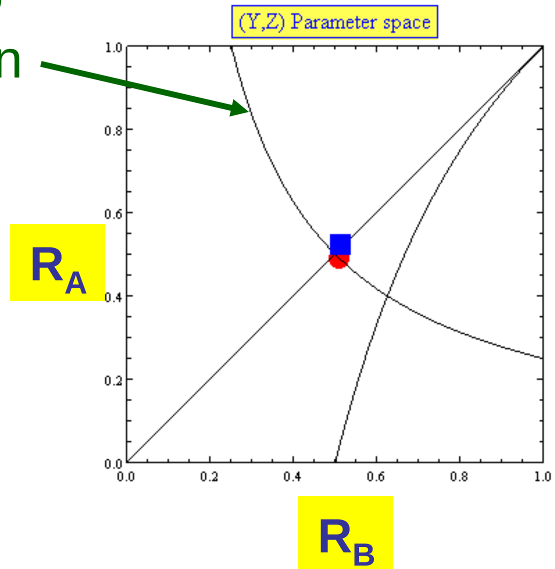


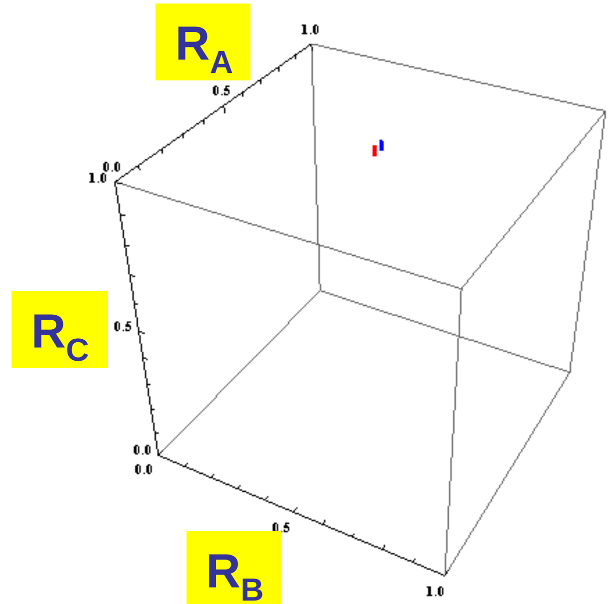
(a) Original boundary

(b) Transformed boundary

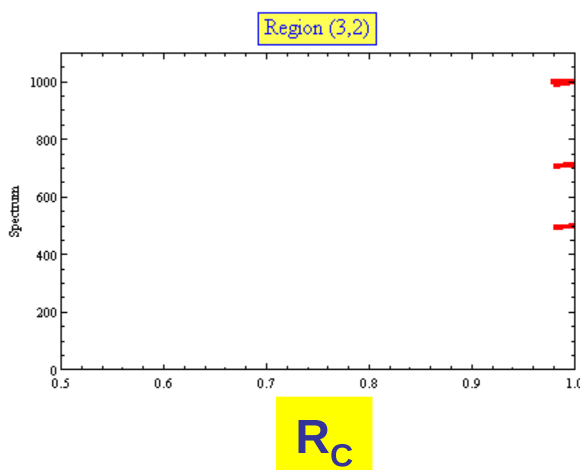
Duplication between regions 2 and 3

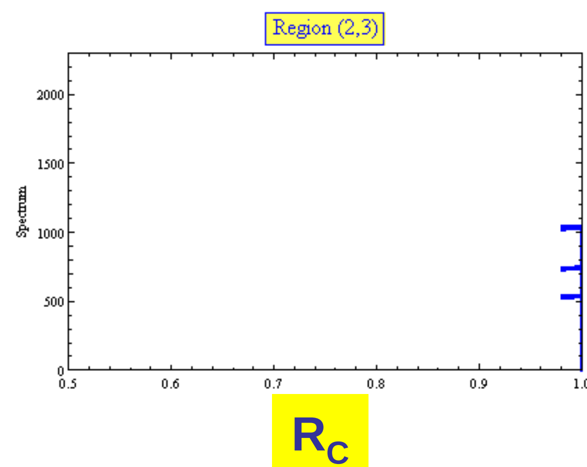
Gaugino unification relation



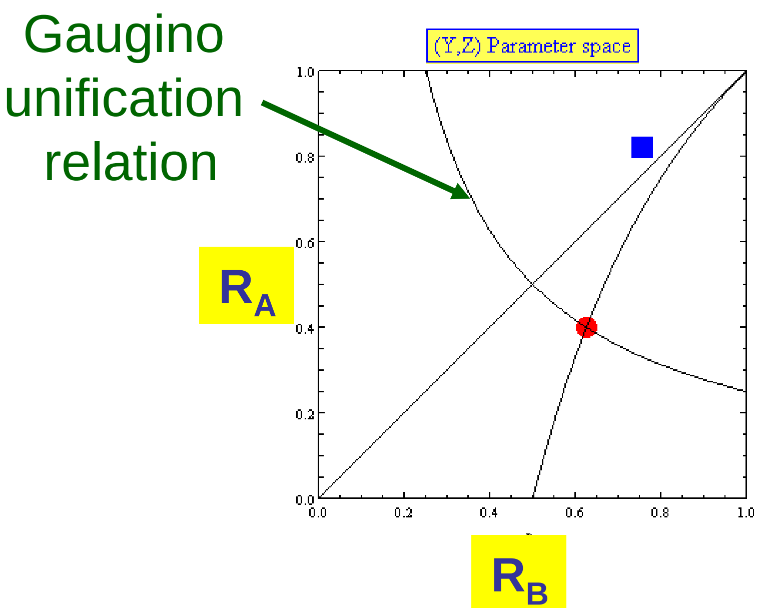


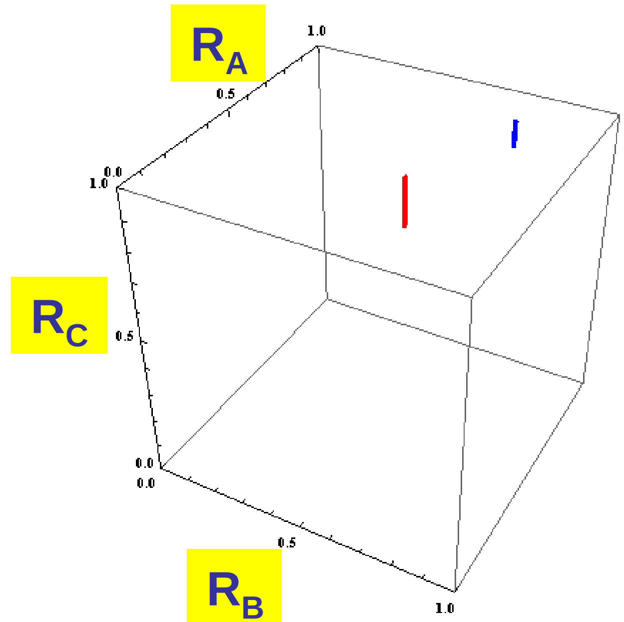
M_D =1 TeV



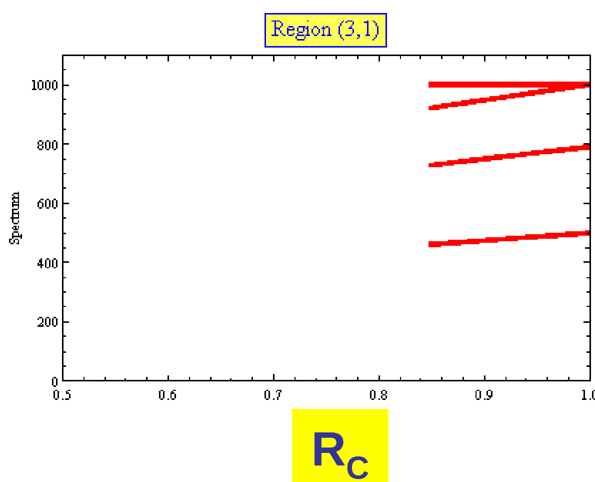


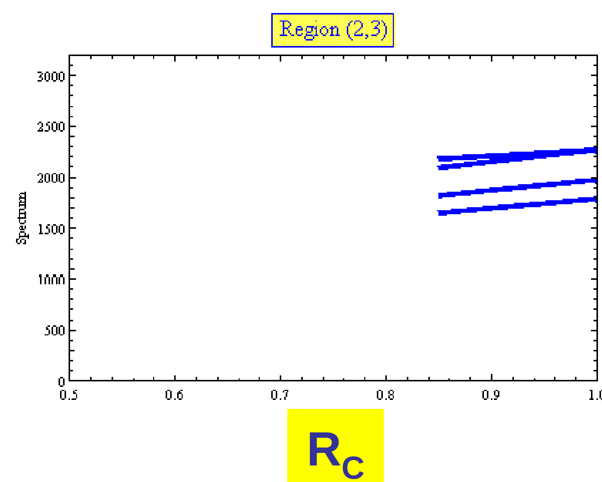
Duplication between regions 1 and 3



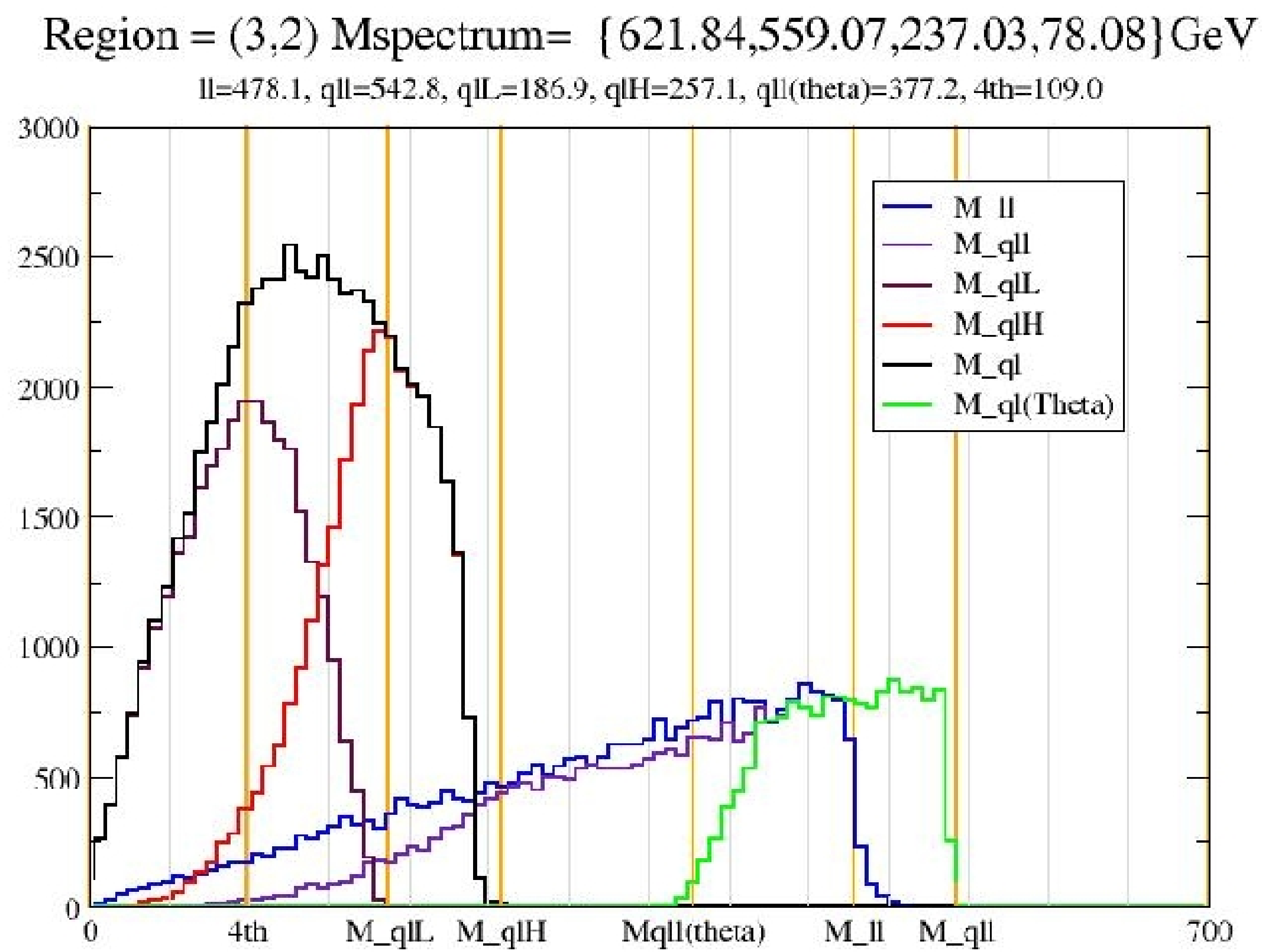


M_D =1 TeV





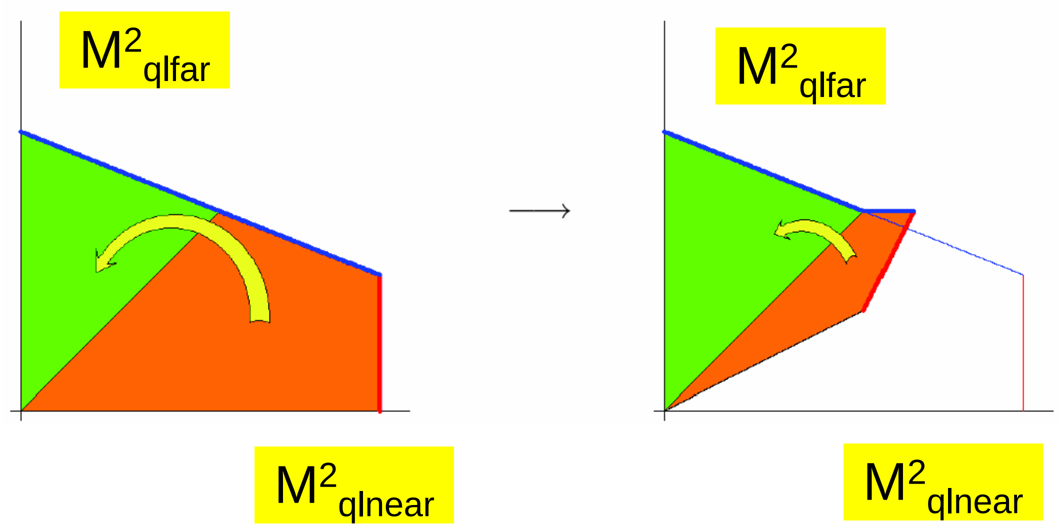
Duplication example

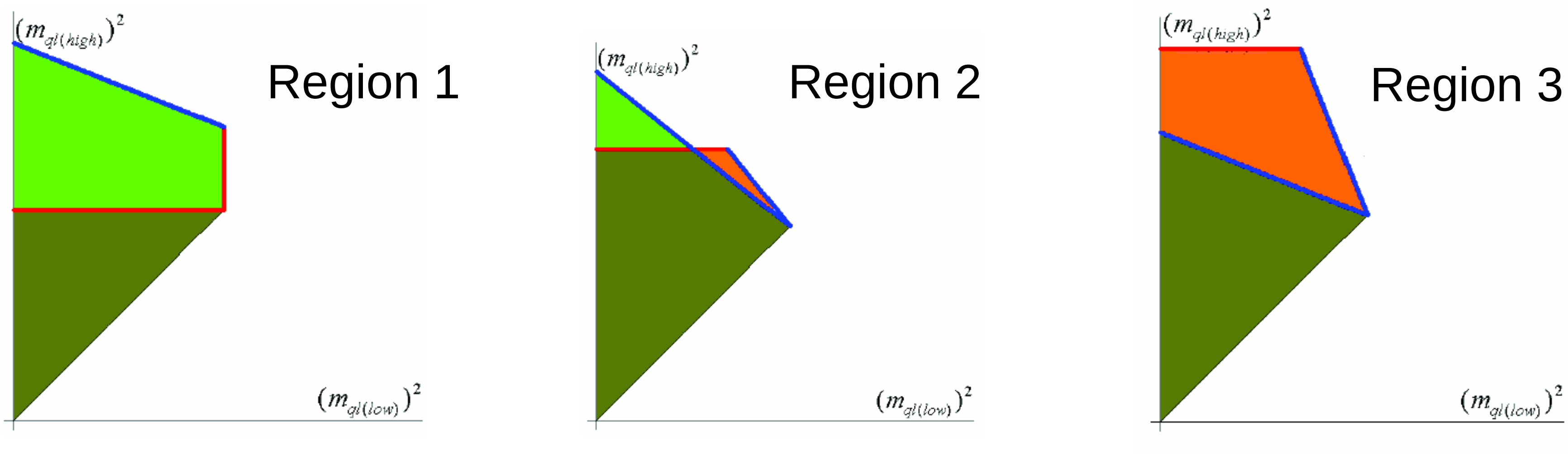


Resoving the ambiguity?

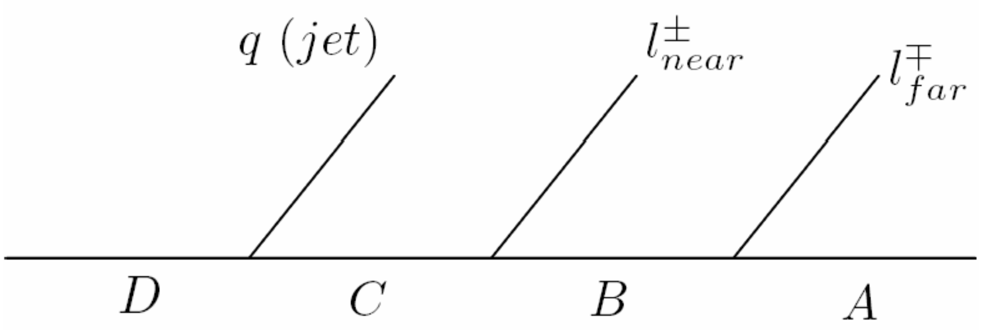
- The M_{qlLow}, M_{qlHigh} ordering is equivalent to the folding along the line $M_{qlnear}=M_{qlfar}$
- Three shapes of the scatter plots
- The shapes are very simple in terms of M^2

Burns,KM,Park 08

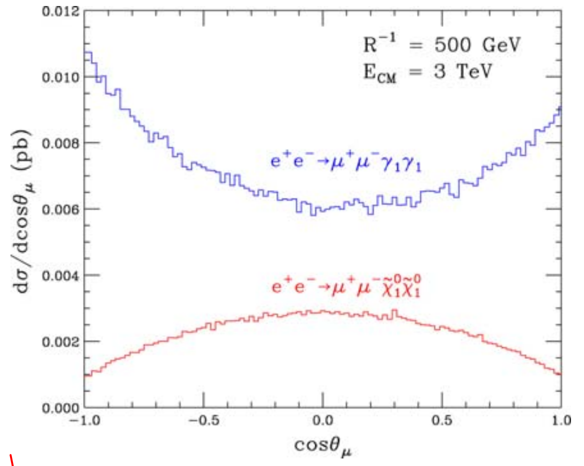




Model discrimination/Spin determination

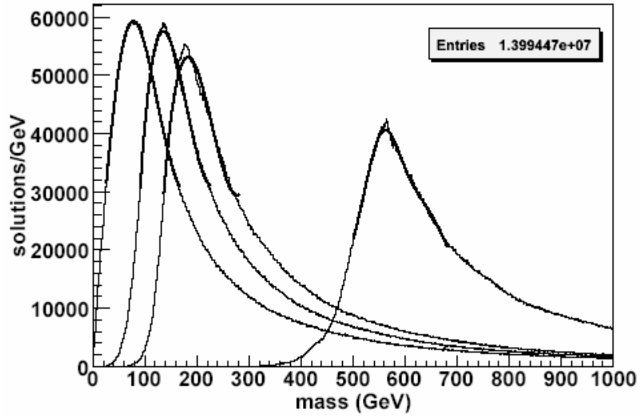


Battaglia,Datta, DeRoeck,Kong,KM 05



- What is the nature of A,B,C,D?
  - Find \$N,000,000,000 and build an ILC
  - Find the momentum of A, fully reconstruct the event
  - Study m² distributions of visible particles
    Athanasiou et al 06, Kilic,Wang,Yavin 07, Csaki,Heinonen,Perelstein 07, S. Thomas (KITP)

Cheng,Engelhardt, Gunion,Han,McElrath 08



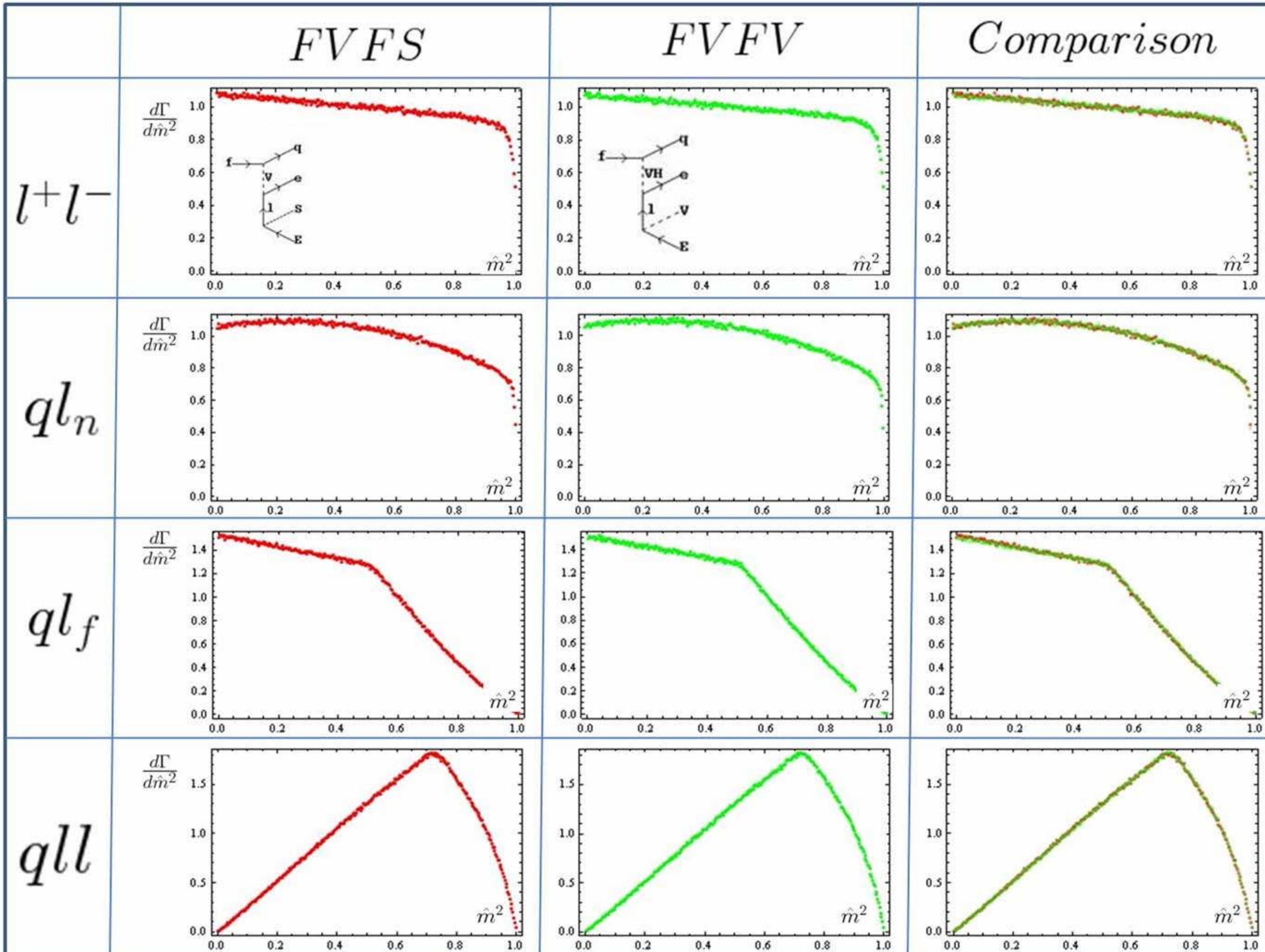
- The distributions depend on
  - Spins of A,B,C,D
  - ~~Masses of A,B,C,D~~
  - Chirality of couplings
  - Initial state (particles vs antiparticles)
- Most spin studies compare two sets of spin assignments, but fix everything else
- That is not a true measurement of the spin

Burns,Kong,KM,Park 08

Distinguishing spins

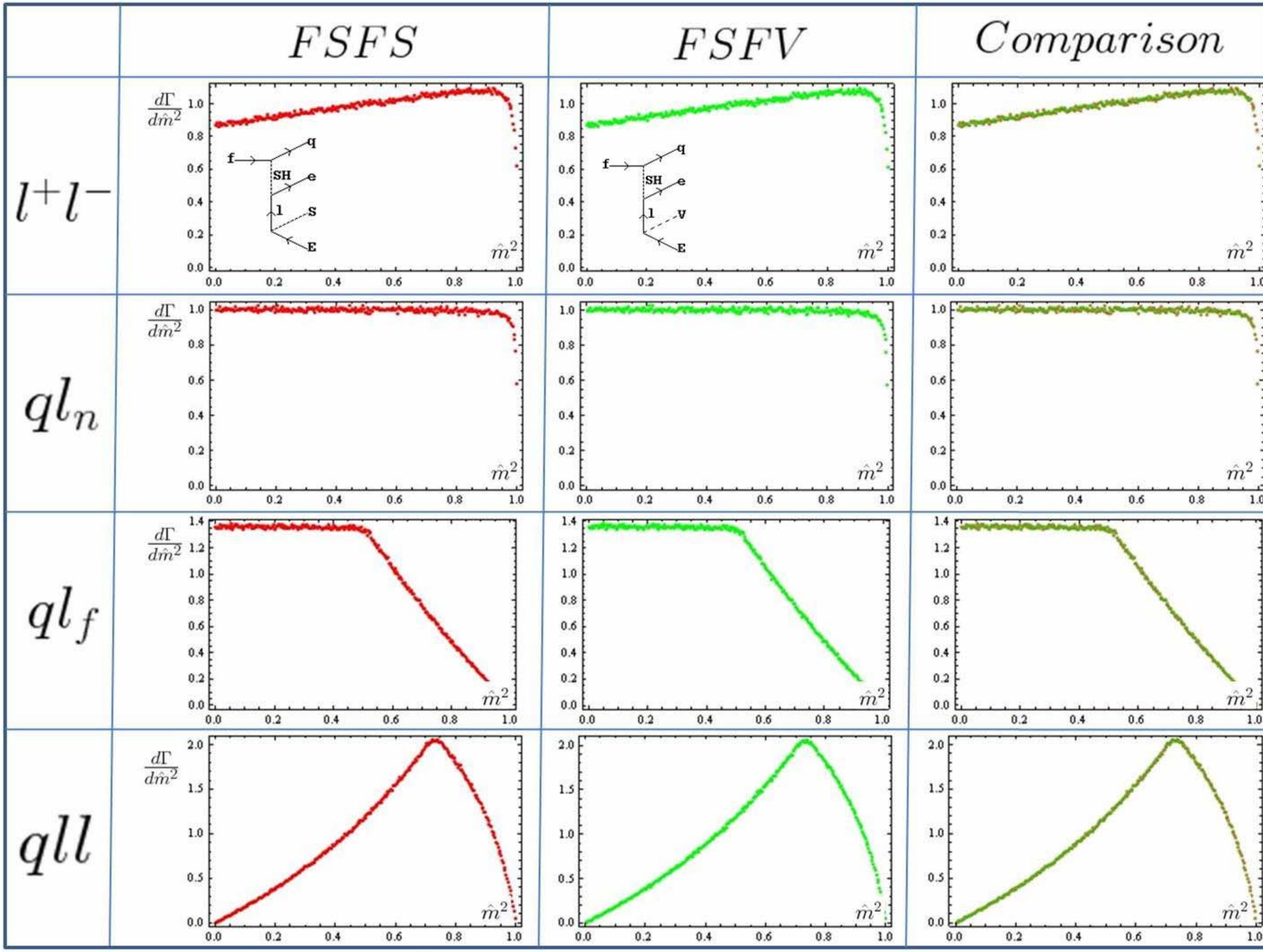
Starting with	Can we fit to					
	SFSF	FSFS	FSFV	SFVF	FVFS	FVFV
SFSF		no	no	no	yes	yes
FSFS	no		yes	no	yes	yes
FSFV	no	yes		no	yes	yes
SFVF	no	no	no		no	no
FVFS	no	no	no	no		yes
FVFV	no	no	no	no	yes	

Burns,Kong,KM,Park 08



$\Gamma = 7.11 \times 10^1 GeV$ $\Gamma = 4.73 \times 10^2 GeV$

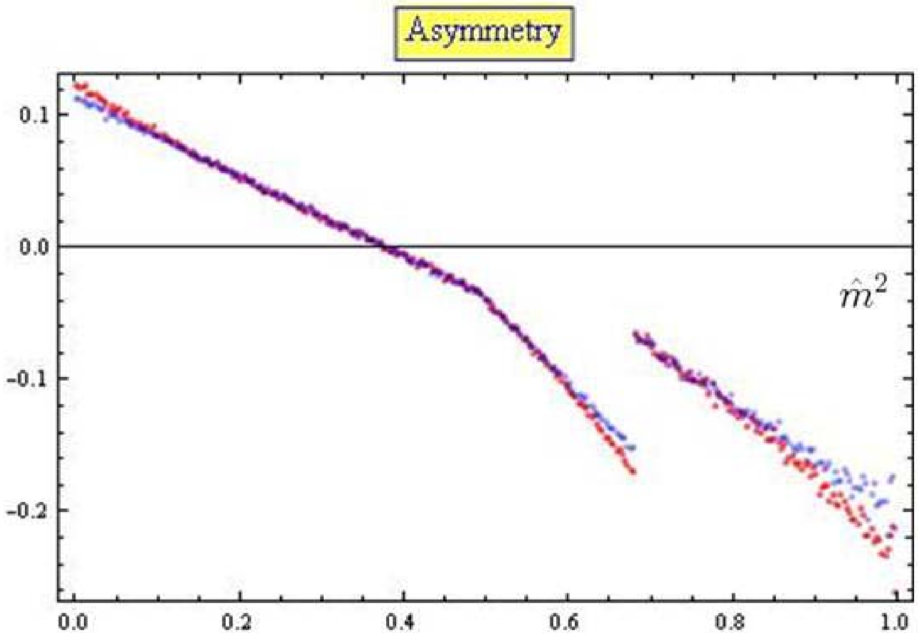
Burns,Kong,KM,Park 08

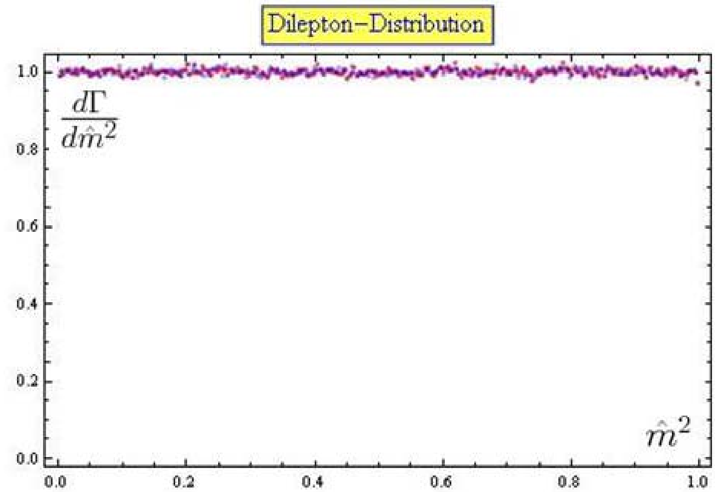


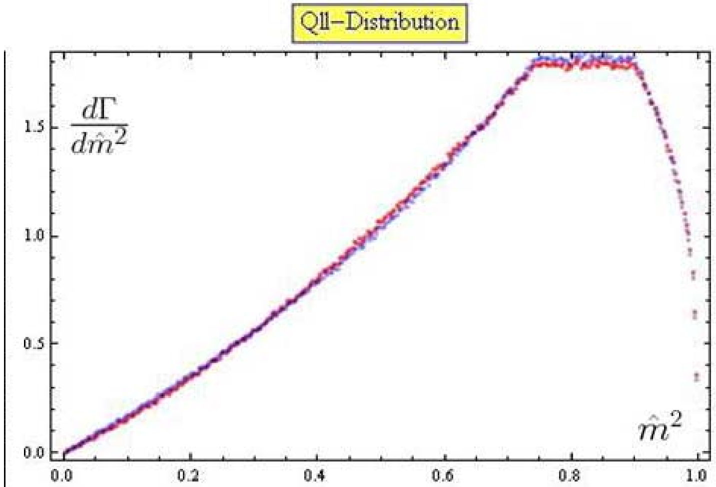
$\Gamma = 2.1047 \times 10^1 \; GeV$ $\Gamma = 1.398 \times 10^2 \; GeV$

“SUSY” vs “UED”

- Mass spectrum {A,B,C,D}={1000,600,420,210} GeV







Burns,Kong,KM,Park 08

Summary and conclusions

- “The University of Florida is in Gainesville, the Gator Nation is everywhere”
- Think about inclusive resonance searches with early LHC data and advertise your favorite exotic resonance to the experimentalists
- The standard endpoint measurements may yield duplicate solutions for the new physics mass spectrum
- The degeneracies might be lifted by looking at the shapes (2-dim plots contain more info than 1-dim plots)
- Measuring the spins in a model-independent (unbiased) way is (still) very difficult