Many Leptons at the LHC from the NMSSM

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The μ problem

- The MSSM superpotential is given by

$$W_{\rm MSSM} = \mu \hat{H}_u \hat{H}_d + \hat{u} y_u \hat{Q} \hat{H}_u - \hat{d} y_d \hat{Q} \hat{H}_d - \hat{e} y_e \hat{L} \hat{H}_d ,$$

- This provides part of the MSSM Higgs potential

$$V = V_F + V_D + V_{\rm soft}$$

where

$$\begin{aligned} V_F &= |\mu|^2 \left(|H_d|^2 + |H_u|^2 \right) \\ V_D &= \frac{g_1^2 + g_2^2}{8} \left(|H_d|^2 - |H_u|^2 \right)^2 + \frac{g_2^2}{2} \left(|H_d|^2 |H_u|^2 - |H_u \cdot H_d|^2 \right) \\ V_{\rm soft} &= m_d^2 |H_d|^2 + m_u^2 |H_u|^2 + \left(B H_u \cdot H_d + {\rm h.c.} \right) \end{aligned}$$

- Minimizing this potential gives the two Higgs VEVs

$$\langle \hat{H}_u^0 \rangle = \frac{v_u}{\sqrt{2}}$$
$$\langle \hat{H}_d^0 \rangle = \frac{v_d}{\sqrt{2}}$$

where

$$v_{\rm SM} = \sqrt{v_u^2 + v_d^2} \approx 246 \text{ GeV}$$

- Note that

$$\mu \rightarrow \text{supersymmetry conserving}$$
$$m_u^2,\, m_d^2,\, B \rightarrow \text{supersymmetry breaking } (\mathcal{O}(\text{TeV}))$$

- Naturalness problem: μ must be $\mathcal{O}$(TeV) to avoid fine-tuning.
- This is the μ problem.

NMSSM

- One possible solution is to generate the μ term dynamically.
- Relate μ to the VEV of a new field:

$$\lambda \hat{S} \hat{H}_u \cdot \hat{H}_d \to \lambda \langle S \rangle \hat{H}_u \cdot \hat{H}_d = \mu_{\text{eff}} \hat{H}_u \cdot \hat{H}_d$$

- Here $\hat{S}$ is a gauge-singlet, chiral superfield and λ is a dimensionless $\mathcal{O}(1)$ parameter.
- *Next-to-Minimal* Supersymmetric Standard Model (NMSSM) is characterized by the superpotential

$$W_{\text{NMSSM}} = W_{\text{MSSM}}|_{\mu \to 0} + \lambda \hat{S} \hat{H}_u \cdot \hat{H}_d + \frac{1}{3} \kappa \hat{S}^3$$

- κ is a dimensionless $\mathcal{O}(1)$ parameter
- The κ term forbids a global $U(1)_{\text{PQ}}$ symmetry (but leaves a discrete Z_3)

- The chiral superfield $\hat{S}$ contains both a complex scalar boson state and a fermion state.
- These mix with the other neutral states, providing two new Higgs bosons and one additional neutralino

	MSSM	NMSSM
CP-Even Higgs H_i	H_1	H_1
	H_2	H_2
		H_3
CP-Odd Higgs A_i	A_1	A_1
		A_2
Neutralinos χ_i^0	χ_1^0-χ_4^0	χ_1^0-χ_4^0
		χ_5^0

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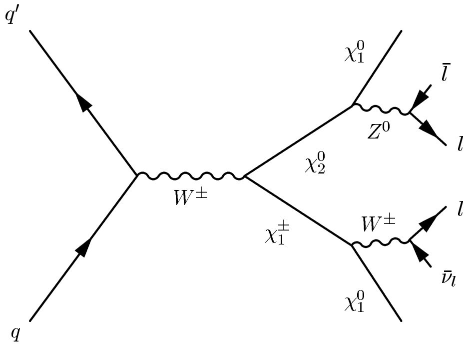
How do these new states affect the collider phenomenology?

- In the MSSM, one possible source of a multi-lepton signal is



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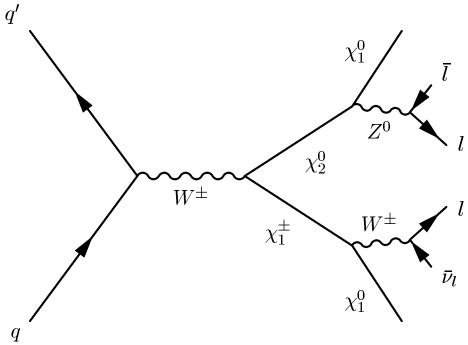

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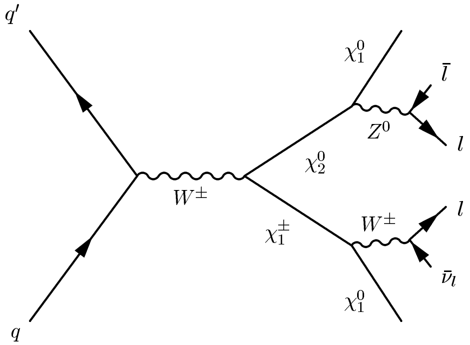
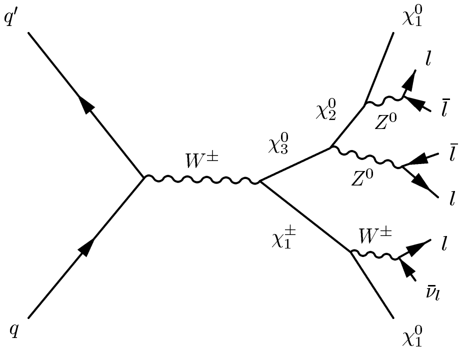
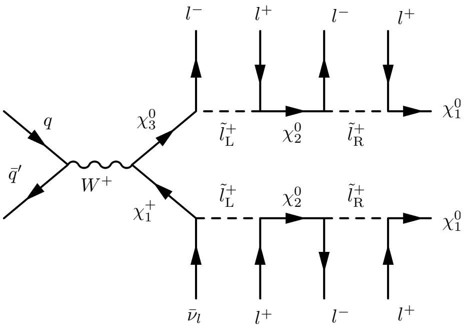


- Important if squarks and gluinos are heavy
- *How does this change for the NMSSM?*
- What if mixing is small and $\chi_1^0 \sim \tilde{S}$ is light?

- For example, an extended decay in the NMSSM could be



- We will actually be looking at the following decay



- This would give a signal with *7 leptons and 0 jets!*
- What would make this have a large cross section?
  - * Large $W^\pm \chi^\mp \chi_3^0$ coupling
  - * Large BR($\chi_i^0 \to \tilde{l}_{L,R}^\pm l^\pm$)
  - * Large BR($\tilde{l}_L^\pm \to l^\pm \chi_2^0$)

- Large $W^{\pm}\chi^{\mp}\chi_3^0$ coupling:
  - * $W^{\pm}$ boson couples to $\tilde{W}^3$ and $\tilde{H}_d$, $\tilde{H}_u$
  - * Therefore, maximize the Wino and Higgsino components of χ_3^0
- Large BR($\chi_i^0 \longrightarrow \tilde{l}_{L,R}^{\pm} l^{\pm}$)
  - * Usually the case when this decay mode is available on-shell
  - * Therefore, require $M_{\chi_3^0}, M_{\chi_1^{\pm}} > M_{\tilde{l}_L^{\pm}} > M_{\chi_2^0} > M_{\tilde{l}_R^{\pm}} > M_{\chi_1^0}$
- Large BR($\tilde{l}_L^{\pm} \longrightarrow l^{\pm}\chi_2^0$)
  - * Under most circumstances the decay to χ_1^0 is larger
  - * BUT, that branching ratio is suppressed if $\chi_1^0 \sim \tilde{S}$
  - Therefore, maximize the Singlino component of χ_1^0

Can we actually do this?

- All the mixing parameters will be determined by the neutralino and chargino mass matrices
- In the basis $(\tilde{B}, \tilde{W}^3, \tilde{H}_d^0, \tilde{H}_u^0, \tilde{S})$

$$\mathbf{M}_{\chi^0} = \begin{pmatrix} M_1 & 0 & -g_1 v_d/2 & g_1 v_u/2 & 0 \\ 0 & M_2 & g_2 v_d/2 & -g_2 v_u/2 & 0 \\ -g_1 v_d/2 & g_2 v_d/2 & 0 & -\mu_{\rm eff} & -\mu_{\rm eff} v_u/s \\ g_1 v_u/2 & -g_2 v_u/2 & -\mu_{\rm eff} & 0 & -\mu_{\rm eff} v_d/s \\ 0 & 0 & -\mu_{\rm eff} v_u/s & -\mu_{\rm eff} v_d/s & \sqrt{2}\kappa s \end{pmatrix}$$

- If
  - $s \gg v_u, v_d$
  - $\sqrt{2}\kappa s < \max[M_1, M_2, \mu_{\rm eff}]$

  then $\chi_1^0 \approx \tilde{S}$

- If the above conditions are met and
  - $M_1 < M_2,\ \mu_{\rm eff}$

  then χ_3^0 may have large $\tilde{W}$ and $\tilde{H}_d^0$, $\tilde{H}_u^0$ components

Parameter Scan

- Now we need to find a benchmark that satisfies:
  - * our requirements for large cross section and
  - * all relevant experimental constraints
- To calculate cross sections we
  - * Implement the NMSSM in MadGraph: Calculate $pp \to W^{*\pm} \to \chi_1^{\pm}\chi_3^0$
  - * Use BRIDGE to calculate all branching fractions
  - * Calculate total branching fractions to multi-lepton final states
- To verify experimental constraints we NMSSMtools:
  - * This program calculates the predicted relic density and compares it to observed value $0.094 < \Omega h^2 < 0.136$ (we only take upper bound).
  - * It also checks collider constraints such as LEP mass limit and limits from $(g-2)_\mu$ and $\mathrm{BR}(b \to s\gamma)$

- The NMSSM-specific parameters are:

$$s,\ \kappa,\ A_\kappa,\ A_s$$

and the parameters shared with the MSSM are

$$\mu_{\rm eff},\ \tan\beta,\ A_t,\ A_b,\ A_\tau,\ M_1,\ M_2,\ M_3,\ M_{Q_i},\ M_{U_i},\ M_{D_i},\ M_{L_i},\ M_{E_i}$$

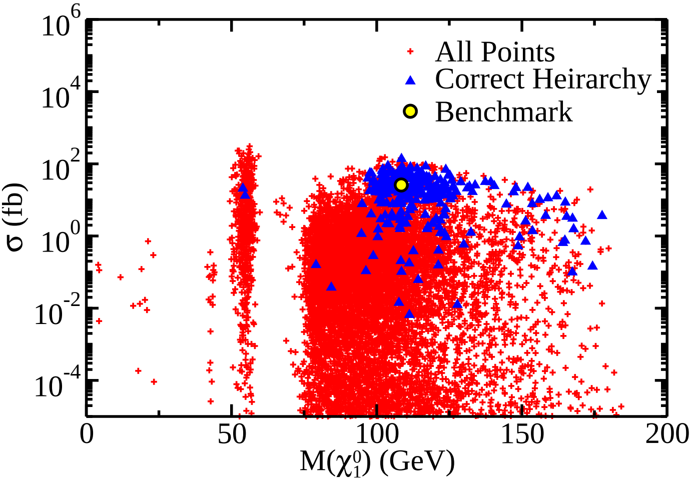
- We can simplify things by making a few assumptions:
  * *Gaugino Mass Unification:*

    $M_1 = \frac{1}{2}M_2 = \frac{1}{6}M_3$
  * *Family-Universal Sfermion Mass Parameters:*

    $M_{L_1} = M_{L_2} = M_{L_3} = M_L$ etc.
  * *Heavy Squarks:*

    $M_Q = M_U = M_D = 2$ TeV
  * *Light sleptons:*

    $M_L, M_E \lesssim 200$ GeV



$$pp \rightarrow W^+ \rightarrow \chi_3^0 \chi_1^+ \rightarrow 5 \text{ leptons} + 0 \text{ jets}$$

Event Generation and Detector Simulation

- To simulate LHC detection we
  - * Generate signal events with MadGraph + BRIDGE (decaying to all final states)
  - * Generate background events with ALPGEN

- These events are then subject to energy smearing as

$$\frac{\Delta E}{E} = \begin{cases} \frac{0.5}{\sqrt{E/\mathrm{GeV}}} \oplus 0.03 \text{ for jets} \\ \frac{0.1}{\sqrt{E/\mathrm{GeV}}} \oplus 0.007 \text{ for leptons} \end{cases}$$

and the following p_T, η, and $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ cuts:

$$p_T > \begin{cases} \text{20 GeV for the hardest two leptons } (e,\mu) \\ \text{7 GeV for all other light leptons} \\ \text{15 GeV for } \tau \text{ leptons} \\ \text{20 GeV for jets} \end{cases}$$

$$|\eta| < \begin{cases} \text{2.4 for electrons} \\ \text{2.1 for muons} \\ \text{2.5 for } \tau\text{-leptons and jets} \end{cases}$$

$$\Delta R > \begin{cases} \text{0.2 for light leptons} \\ \text{0.4 for all others} \end{cases}$$

- We also include
  - basic tagging efficiencies
  - isolated leptons from heavy quark decay ($P \sim 1/200$)
  - a jet veto

Background Cross Sections (fb) *N* leptons												
	WZ	*ZZ*	*WWW*	*WWZ*	*WZZ*	*ZZZ*	*Wtt*	$Zc\bar{c}$	$Zb\bar{b}$	*Ztt*	*tt*	TOTAL
$\sqrt{s} = 7$ TeV												
3*l*	70	7.2	0.22	0.26	0.13	0.012	1.3	5.5	5.3	1.2	7.4	99
... w/ jet veto	70	7.0	0.22	0.07	0.045	0.002	0.007	–	–	0.005	1.8	80
4*l*	–	7.2	–	0.07	0.005	0.020	0.003	–	–	0.12	–	7.4
... w/ jet veto	–	7.2	–	0.06	0.003	0.003	–	–	–	0.002	–	7.3
5*l*	–	–	–	–	–	–	–	–	–	0.002	–	0.002
... w/ jet veto	–	–	–	–	–	–	–	–	–	–	–	–
$\sqrt{s} = 14$ TeV												
3*l*	140	18	0.54	1.5	0.33	0.04	3.6	19	7.5	7.7	36	240
... w/ jet veto	140	17	0.54	0.12	0.087	0.01	0.04	1.5	–	0.02	3.9	170
4*l*	–	19	–	0.12	0.027	0.01	0.01	–	–	0.84	–	20
... w/ jet veto	–	19	–	0.12	0.027	0.01	–	–	–	0.013	–	19
5*l*	–	–	–	–	0.003	–	–	–	–	0.005	–	0.008
... w/ jet veto	–	–	–	–	0.003	–	–	–	–	0.003	–	0.006

Signal Cross Sections (fb) *N* leptons + 0 jets					
$\sqrt{s}$	3*l*	4*l*	5*l*	6*l*	7*l*
7 TeV	25.6	4.91	2.31	0.09	0.03
14 TeV	68.7	13.3	6.09	0.29	0.06

NMSSM Signal $\geq N$ leptons + 0 jets				
	$\geq 3\ l$		$\geq 5\ l$	
	Signal	Background	Signal	Background
$\sqrt{s} = 7$ TeV				
Cross section (fb)	33	87	2.4	~ 0.0
Luminosity for 3σ (fb^{-1})	1.0		3.7	
Luminosity for 5σ (fb^{-1})	2.8		10	
$\sqrt{s} = 14$ TeV				
Cross section (fb)	88.4	187	6.44	0.006
N_{events} (600 fb^{-1})	5.3×10^4	1.1×10^5	3.9×10^3	4
Luminosity for 3σ (fb^{-1})	0.32		1.4	
Luminosity for 5σ (fb^{-1})	0.88		3.9	

- This signal could be discovered with
  - ~ 3 fb^{-1} of data at $\sqrt{s} = 7$ TeV
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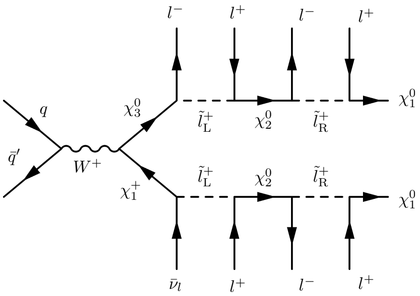
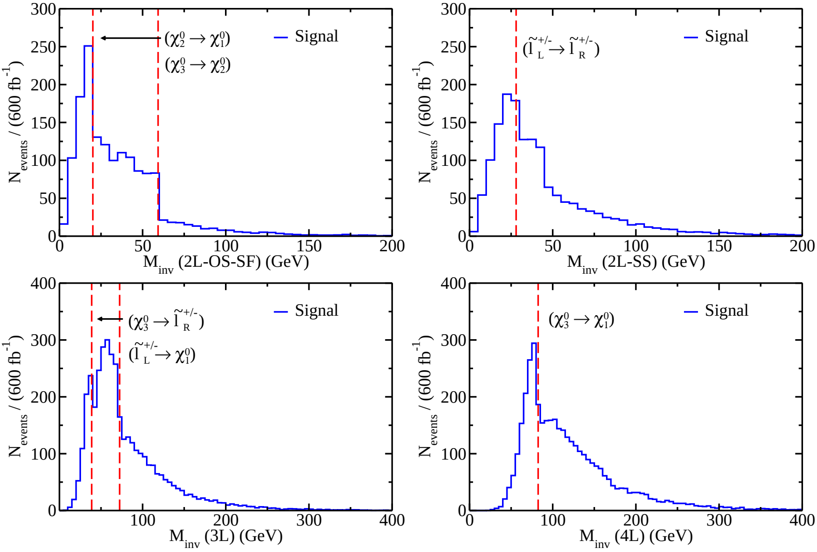
- Can also use kinematic edges to estimate mass differences

Process	Δm (GeV)	M_{max} (GeV)	Distribution
$\chi_3^0 \to \chi_2^0$	62.4	59.3	2L-OS-SF
$\chi_3^0 \to \chi_1^0$	82.5	82.5	4L
$\chi_3^0 \to \tilde{l}_R^\pm$	72.6	72.4	3L
$\tilde{l}_L^\pm \to \tilde{l}_R^\pm$	28.9	28.0	2L
$\tilde{l}_L^\pm \to \chi_1^0$	38.8	38.8	3L
$\chi_2^0 \to \chi_1^0$	20.1	20.1	2L-OS-SF





$\geq$5 leptons + 0 jets, 600 fb^{-1}

Conclusions

- The NMSSM can have large cross sections for signals with $\geq$ 3 leptons + 0 jets and $\geq$ 5 leptons + 0 jets.
- Our benchmark point could be detected at the LHC with
  - $\sim$ 3 fb^{-1} of data at $\sqrt{s} = 7$ TeV
  - $<$ 1 fb^{-1} of data at $\sqrt{s} = 14$ TeV
- With large amounts of accumulated data, kinematic mass edges are clearly visible and can be used to determine a variety of mass differences.

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THANK YOU!

EXTRA SLIDES

- Our benchmark point is defined by the following parameters:

NMSSM Benchmark Model Parameters								
$\tan\beta$	h_s	A_s	μ	κ	A_κ	A_t	A_b	A_τ
7.55	0.056	488	199	0.015	-39.6	-1170	1886	-143
M_1	M_2	M_3	M_Q	M_U	M_D	M_L	M_E	
149	297	891	2000	2000	2000	140	110	

Sparticle Mass Spectrum (GeV)			
χ_1^0 :	109	$\tilde{l}_L^{\pm}$:	147
χ_2^0 :	129	$\tilde{l}_R^{\pm}$:	118
χ_3^0 :	191	$\tilde{\tau}_1^{\pm}$:	114
χ_4^0 :	206	$\tilde{\tau}_2^{\pm}$:	150
χ_5^0 :	333	$\tilde{\nu}_l$:	125
$\chi_1^{\pm}$:	173	$\tilde{\nu}_\tau$:	125
$\chi_2^{\pm}$:	333		

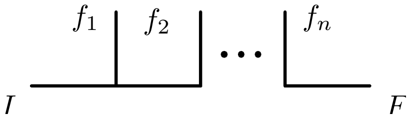
Neutralino Composition

	$\tilde{B}$	$\tilde{W}$	$\tilde{H}_u$	$\tilde{H}_d$	$\tilde{S}$
χ_1^0 :	0.02	< 0.01	0.01	0.01	0.95
χ_2^0 :	0.64	0.03	0.20	0.09	0.04
χ_3^0 :	0.33	0.17	0.26	0.24	< 0.01
χ_4^0 :	0.01	0.01	0.47	0.51	< 0.01
χ_5^0 :	0.01	0.79	0.06	0.14	< 0.01

Dominant Leptonic Branching Fractions		
$\chi_3^0 \rightarrow$	$l^{\pm}\tilde{l}_{\mathrm{R}}^{\mp}$	0.40
	$l^{\pm}\tilde{l}_{\mathrm{L}}^{\mp}$	0.12
	$\nu_l\tilde{\nu}_l$	0.01
$\chi_1^{\pm} \rightarrow$	$l^{\pm}\tilde{\nu}_l$	0.53
	$\nu_l\tilde{l}_{\mathrm{L}}^{\pm}$	0.08
$\tilde{l}_L^{\pm} \rightarrow$	$l^{\pm}\chi_2^0$	0.97
	$l^{\pm}\chi_1^0$	0.03
$\chi_2^0 \rightarrow$	$l^{\pm}\tilde{l}_R^{\mp}$	0.48
	$\nu_l\tilde{\nu}_l$	0.04
$\tilde{\nu}_l \rightarrow$	$\nu_l\chi_1^0$	1.00
$\tilde{l}_R^{\pm} \rightarrow$	$l^{\pm}\chi_1^0$	1.00

Kinematic Edges

- Consider the decay $I \longrightarrow f_1 f_2 ... f_n F$



where

* I, F are massive particles
* f_i are n massless final-state fermions

- The total mass of the system can be related to invariant mass of the n fermions

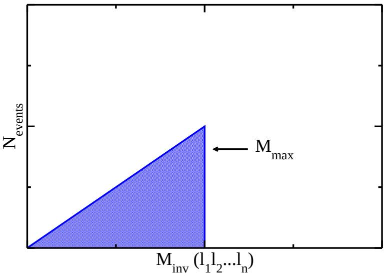
$$
\begin{aligned}
m_I^2 &= (p_1 + p_2 + ... + p_n + p_F)^2 \\
m_I^2 &= m^2(f_1 ... f_n) + 2p_I \cdot p_F - m_F^2
\end{aligned}
$$

- In the rest-frame of I this gives

$$m^2(f_1...f_n) = m_I^2 + m_F^2 - 2m_I E_F$$
$$m^2(f_1...f_n) \leq (m_I - m_F)^2$$

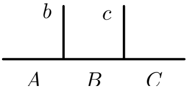
with the maximum reached when F is at rest in the rest-frame of I.

- This shows up as an edge in an invariant mass plot
- However, it is not always possible to reach this kinematic limit.



2 fermions

- For the process $A \longrightarrow bB \longrightarrow bcC$



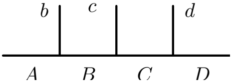
the kinematic upper limit will be given by

$$M^2_{max}(bc) = \frac{(m_A^2 - m_B^2)(m_B^2 - m_C^2)}{m_B^2}$$

(*This will occur when particles b and c are emitted back-to-back*)

3 fermions

- For the process $A \longrightarrow bB \longrightarrow bcC \longrightarrow bcdD$

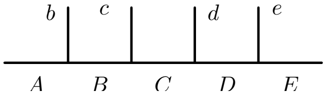


the kinematic upper limit will be given by

$$M^2_{\max}(bcd) = \begin{cases} \frac{(m_A^2 - m_B^2)(m_B^2 - m_D^2)}{m_B^2} & \text{iff} \quad \frac{m_A}{m_D} > \frac{m_B^2}{m_D^2} \\ \frac{(m_A^2 m_C^2 - m_B^2 m_D^2)(m_B^2 - m_C^2)}{m_B^2 m_C^2} & \text{iff} \quad \frac{m_A}{m_D} < \frac{m_B^2}{m_C^2} \\ \frac{(m_A^2 - m_C^2)(m_C^2 - m_D^2)}{m_C^2} & \text{iff} \quad \frac{m_A}{m_D} < \frac{m_C^2}{m_D^2} \\ (m_A - m_D)^2 & \text{otherwise} \end{cases}$$

4 fermions

- For the process $A \longrightarrow bB \longrightarrow bcC \longrightarrow bcdD \longrightarrow bcdeE$



the kinematic limit will be given by

$$M^2_{\max}(bcde) = \begin{cases} \frac{(m_A^2 - m_B^2)(m_B^2 - m_E^2)}{m_B^2} & \text{iff} \quad \frac{m_A}{m_E} > \frac{m_B^2}{m_E^2} \\ \frac{(m_A^2 m_C^2 - m_B^2 m_E^2)(m_B^2 - m_C^2)}{m_B^2 m_C^2} & \text{iff} \quad \frac{m_A}{m_E} < \frac{m_B^2}{m_C^2} \\ \frac{(m_A^2 m_D^2 - m_C^2 m_E^2)(m_C^2 - m_D^2)}{m_C^2 m_D^2} & \text{iff} \quad \frac{m_A}{m_E} < \frac{m_C^2}{m_D^2} \\ \frac{(m_A^2 - m_D^2)(m_D^2 - m_E^2)}{m_D^2} & \text{iff} \quad \frac{m_A}{m_E} < \frac{m_D^2}{m_E^2} \\ (m_A - m_E)^2 & \text{otherwise} \end{cases}$$

- It is interesting to note that these may all be written as

$$M^2_{max}(f_1 ... f_n) = (m_I - m_F)^2 - (m_I m_F)\left(x + \frac{1}{x} - 2\right)$$

where $x \geq 1$ and depends on a product of mass ratios.

- If $m_I \approx m_F$ then $x \approx 1$ and

$$M^2_{max}(f_1 ... f_n) \approx (m_I - m_F)^2$$

- Therefore, we can think about these kinematics edges as mass differences if the differences are not too large.