Violations of the Narrow Width Approximation in SUSY

Daniel Berdine

University of Rochester

With D. Rainwater and N. Kauer

PHENO 06 May 16, 2006

Outline

- Simplest case
- Sanity Checks
- More complicated examples
- Process Observable @ LHC
- Summary

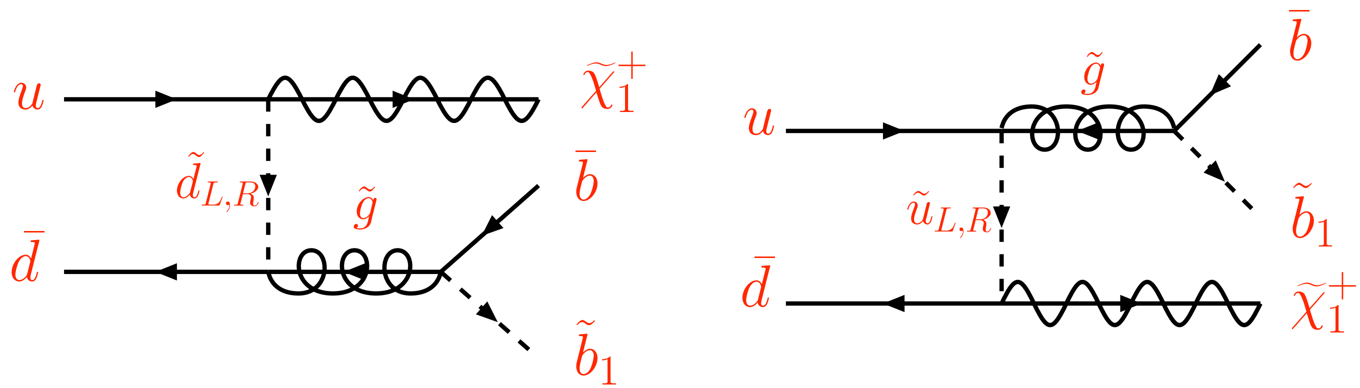
Introduction

We investigate the validity of the Narrow Width Approximation

- Usually treat intermediate states on shell, then decay
- Makes several assumptions about the process
- Violations normally due to non-resonant diagrams
- We show the SUSY mass spectrum $\longrightarrow$ new violations
- Effects are usually jumbled with other complications (PDFs, interference, etc.)
- More diagrams $\longrightarrow$ worse complications

Simplest: One resonance, Fixed Energy Beams

Few diagrams, with charged currents & mixed gauge couplings
$u\bar{d} \to \widetilde{\chi}_1^+ \bar{b}\tilde{b}_1$ is:



- No other resonant or non-resonant diagrams
- See NWA violations even *without* non-resonant diagrams
- χ_1^+ can be long-lived; ignore decay cascade

Examine validity of NWA without complications

The Narrow Width Approximation

n-body phase space factorizes:

$$d\Phi^n = (2\pi)^4 \delta^4\Big(k_1 + k_2 - \sum_i p_i\Big) \prod_{i=1}^{n} \frac{d^3 p_i}{(2\pi)^3 2E_i}$$

$$= (2\pi)^4 \delta^4\Big(k_1 + k_2 - q - \sum_i p_i\Big) \prod_{i=3}^{n} \frac{d^3 p_i}{(2\pi)^3 2E_i} \times \frac{d^3 q}{(2\pi)^3 2E_q^0} \times \frac{dq^2}{2\pi} \times d\Phi^2(q; p_1, p_2)$$

Ideal for resonances, via $\int dq^2$ and a 2-body decay.
Assume the Breit-Wigner propagator is separable, then:

$$\int_{q^2_{\min}}^{q^2_{\max}} \frac{dq^2}{2\pi} \left(\frac{1}{q^2 - m^2 + im\Gamma} \right)^2 = \int_{q^2_{\min}}^{q^2_{\max}} \frac{dq^2}{2\pi} \frac{1}{(q^2 - m^2)^2 + (m\Gamma)^2}$$

$$= \int_{q^2_{\min} - m^2}^{q^2_{\max} - m^2} dx \frac{1}{x^2 + (m\Gamma)^2} = \int_{-m^2}^{s - m^2} dx \frac{1}{x^2 + (m\Gamma)^2}$$

$$\approx \int_{0}^{\infty} dx \frac{1}{x^2 + (m\Gamma)^2} = 2 \int_{-\infty}^{\infty} dx \frac{1}{x^2 + (m\Gamma)^2} = \frac{\pi}{m\Gamma} .$$

Assumes massless final states!

Comparisons

We look at $u\bar{d} \longrightarrow \widetilde{\chi}_1^+ \bar{b}\tilde{b}_1$ over a variety of $\sqrt{s}$ Compare:

- σ_{tot} = cross section w/o decays $[fb]$
- σ_{ONS} = cross section w/ decays calculated on-shell
- σ_{OFS} = cross section w/ decays calculated off-shell
- $\sigma_{ONS}/\sigma_{ONS}$

$\longrightarrow$ If NWA is valid, $\sigma_{ONS}/\sigma_{ONS} = 1$ for all $\sqrt{s}$

Simplest case with fixed beams

$\sqrt{s}$ [TeV]	$\sigma_{\rm tot}$ [fb]	$\sigma_{\rm ONS}$	$\sigma_{\rm OFS}$	$\sigma_{\rm OFS}/\sigma_{\rm ONS}$
1.0	482	50.5	49.7	0.98
2.0	574	60.2	64.4	1.07
4.0	203	21.3	24.1	1.13
10	36.7	3.85	4.65	1.21
20	9.37	0.983	1.24	1.26
40	2.36	0.248	0.329	1.33
100	0.378	0.0397	0.0558	1.41
200	0.0946	0.00993	0.0146	1.47
400	0.0237	0.00248	0.00376	1.52
1000	0.00379	0.000397	0.000618	1.56

$\sigma_{\rm tot}$ & $\sigma_{\rm ONS}$ fall off as 1/s as expected

$\sigma_{\rm OFS}/\sigma_{\rm ONS}$ grows as $Li_2(s)$, but with $m_{\tilde{b}_1}$ coefficient: $\sim m_{\tilde{b}_1} Li_2(s)$

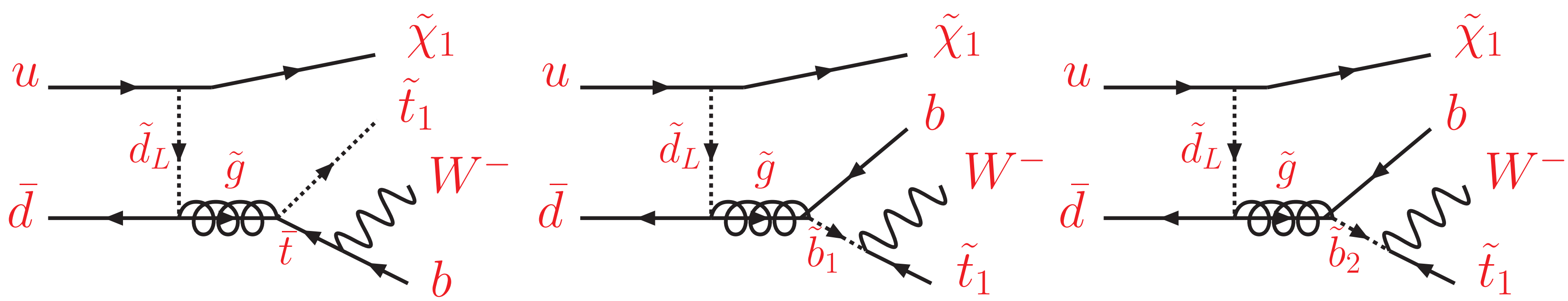
This result is found analytically as well as numerically.

Sanity Checks

1. $\Gamma_{\tilde{g}} = 0$ in M.E., multiply by $\frac{(q^2-m^2)^2}{(q^2-m^2)^2+(m\Gamma)^2}$ outside $\longrightarrow$ same result.

2. What if $\tilde{b}$ decays?

Slightly more complicated, due to additional diagrams:



- $Li_2(s)$ growth still present, although with scale shift.

(more on the $\tilde{b} \longrightarrow W\tilde{t}$ decay later...)

3. What if W decays? $\longrightarrow$ no change

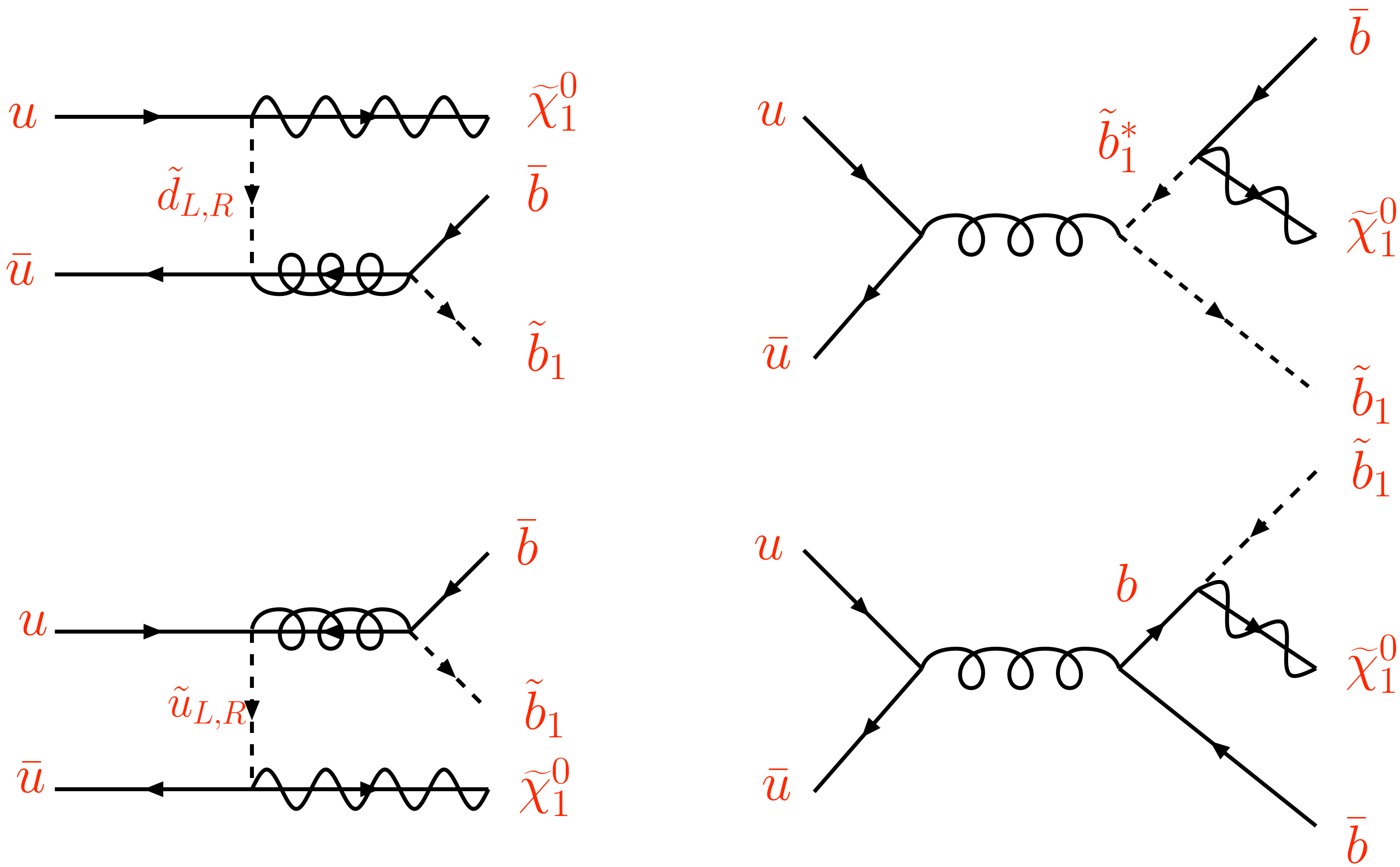
More complicated processes

Some salient results:

- Enhancements present for variety of initial/final states
- Need interactions with fermions or vector bosons
- Need significant $\left(\frac{m_{daughter}}{m_{parent}}\right)$
- Cascade decays sometimes complicate: effect is unpredictable
- Interference effects can become important
- PDFs tend to smear and hide but not remove
- Kinematics mostly unaffected, but not always
- Basically: Everything you might expect to cause complications, does

Potentially Observable Process at the LHC

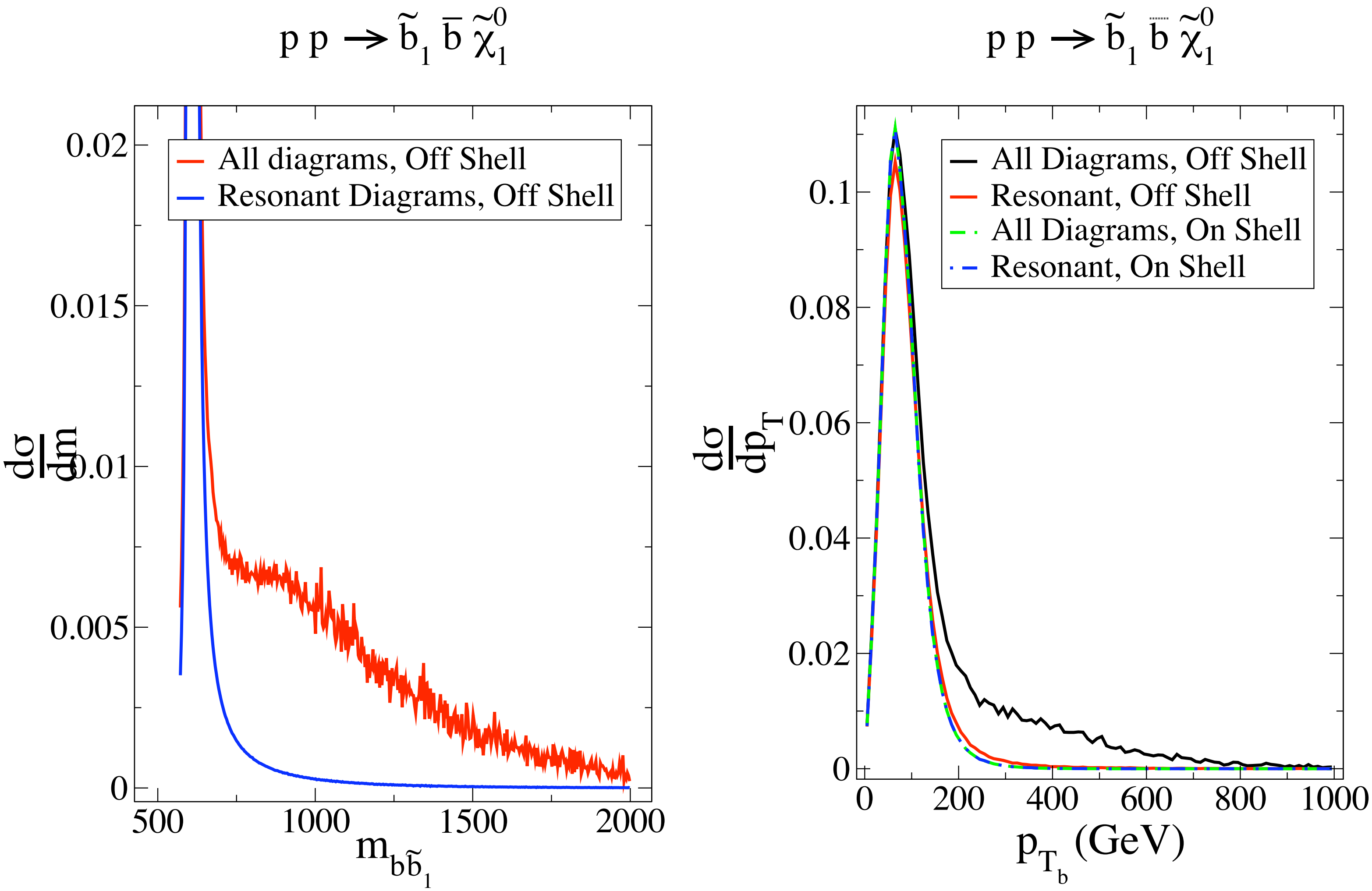
Consider $pp \longrightarrow \tilde{\chi}_1^0 \tilde{g} \longrightarrow \tilde{\chi}_1^0 \bar{b} \tilde{b}_1$:



$\longrightarrow$ Two more diagrams appear; one is $\tilde{b}_1$-resonant

$\longrightarrow$ Produce effects beyond those of resonant diagrams taken off-shell

$pp \to \tilde{g}\tilde{\chi}_1^0 \to \bar{b}\tilde{b}_1\tilde{\chi}_1^0$ off-shell   +50% correction to rate!



spreads... reason: no interference, but new $\tilde{b}_1$ pole

(separable by jet/lepton edges? probably , but need to check)

Conclusions

- interesting theoretical feature for off-shell SUSY processes:
  $\sigma_{\rm OFS}$ can grow as $Li_2(s)$ relative to $\sigma_{\rm ONS}$
  1. always occurs for gluino
  2. occurs for $\tilde{Q} \to V\tilde{Q}$
  3. ... ?
- off-shell SUSY @ LHC has large non-res. corrections
  $\longrightarrow$ most processes have same kinematics as on-shell,
  but not always true
  (slightly smeared-out, but same pole & invariants)
- Each decay in cascades potentially has off shell effects: this must be checked for each process
- ... but effect mitigated at (V)LHC by PDF's
- rather insidious implications for Linear Colliders