Associated Production a Gaugino and a Gluino at Hadron Colliders in NLO QCD

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– Research * done with Michael Klasen and Tim Tait –

Contents:

http://gate.hep.anl.gov/berger/seminars/RADCOR.ps

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* PLB 459 (1999) 165-170, and hep-ph/0005196, PRD, in press.

1. Introduction and Motivation

- Discovery/exclusion of states predicted by Supersymmetry is a major goal of the CERN Large Hadron Collider physics program — energy and phase space to burn

- Good chance exists that some of the superpartners will be found at the Fermilab Tevatron collider prior to the LHC

- Valuable to concentrate on reaction mechanisms and production channels that make best use of the relatively restricted energy and phase space of the Tevatron where only some of the states may be excited (c.f., single top squark production PRL 83, 4472 (1999))

- Focus on associated production of a color-neutral, spin-1/2 gaugino ($\tilde{\chi}_i^0$, $\tilde{\chi}_i^\pm$) and a color-octet, spin-1/2 gluino ($\tilde{g}$):

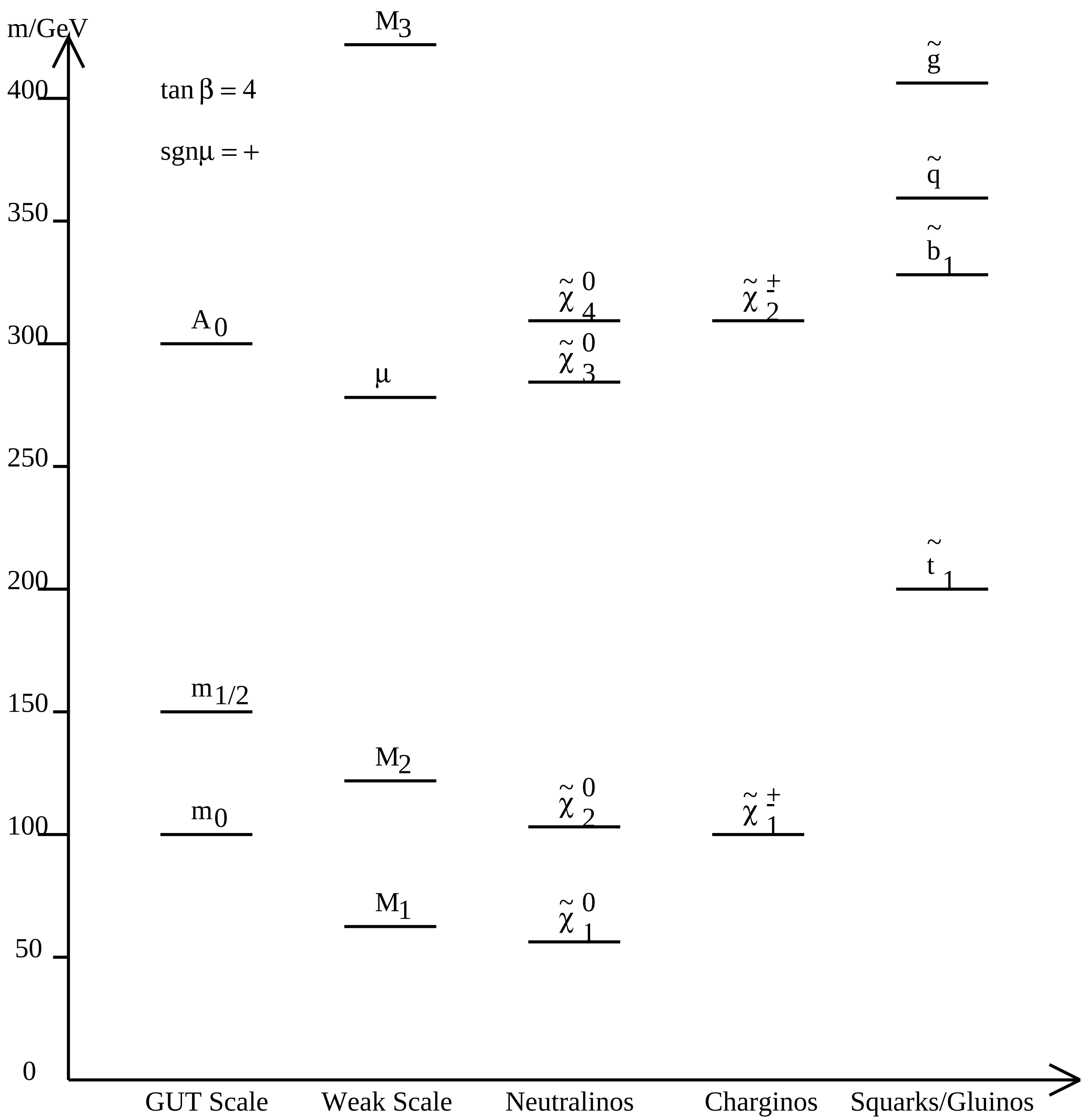
$$p + p \to \tilde{\chi}_i^0 + \tilde{g} + X,$$

$$p + p \to \tilde{\chi}_i^\pm + \tilde{g} + X$$

- Analogous Standard Model processes:
  - $p + p \to \tilde{\chi}_1^0 + \tilde{g} + X$ analog of $p + p \to \gamma + g + X$
  - $p + p \to \tilde{\chi}_2^0 + \tilde{g} + X$ analog of $p + p \to Z^o + g + X$
  - $p + p \to \tilde{\chi}_1^\pm + \tilde{g} + X$ analog of $p + p \to W^\pm + g + X$

- Why study associated production at hadron colliders?
  - Mass spectrum in typical SUGRA and gauge-mediated models favors much lighter masses for gauginos than for squarks
  $$m_{\tilde{\chi}^0_{1,2}}, m_{\tilde{\chi}^\pm_1} << m_{\tilde{q}}, m_{\tilde{g}} \simeq (1/5)\,(2TeV)$$
  - Greater phase space is available at the Tevatron, and much greater parton luminosities for
  $$\tilde{\chi}^0_{1,2}\tilde{\chi}^0_{1,2};\;\; \tilde{\chi}^0_{1,2}\tilde{\chi}^\pm_1;\; \text{and}\; \tilde{\chi}^0_{1,2}\tilde{g};\;\; \tilde{\chi}^\pm_1\tilde{g}$$
  than for
  $$\tilde{q}\tilde{q};\;\; \tilde{q}\bar{\tilde{q}};\;\; \tilde{q}\tilde{g};\;\; \tilde{g}\tilde{g}\; ....$$
  - Partially offset by the smaller couplings of the $\tilde{\chi}^0_{1,2}$ and $\tilde{\chi}^\pm_1$ (i.e., electroweak strength) at one vertex
  - Provides access to intermediate-mass gluino LSP scenarios, $m_{\tilde{g}} \simeq 30$ GeV
- Relatively simple signatures
  - $\tilde{\chi}^0_1$ is LSP (mSUGRA) or NLSP (gauge mediation)
  - $\tilde{\chi}^0_i, \tilde{\chi}^\pm_i$ decay leptonically; lepton signature plus missing $E_T \rightarrow$ clean events
  - Associated production is perhaps the best channel for measurement of the gluino mass
  - In the intermediate-mass gluino case, one might observe a gluino monojet accompanied by leptons and/or missing E_T from the gaugino decays

Mass Spectrum in a Typical SUGRA Scenario



- Experimental searches are facilitated by firm theoretical understanding of the expected sizes of cross sections and the sensitivity to parameters; next-to-leading order calculations are necessary

- Report here a full NLO calculation in SUSY-QCD of associated production of a gaugino and a gluino:

$$p + p \to \tilde{\chi}_i^0 + \tilde{g} + X,$$

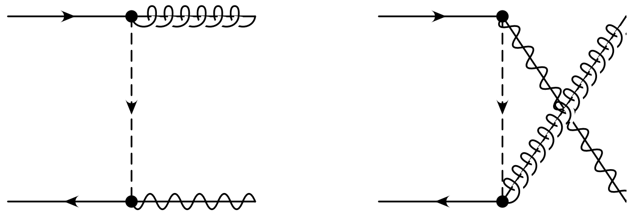
$$p + p \to \tilde{\chi}_i^\pm + \tilde{g} + X$$

- Differences relative to a pure QCD NLO calculation:
  - Majorana fermions (neutralinos are Majorana; charginos are Dirac fermions)
  - Additional diagrams associated with SUSY particle exchanges
  - Treatment of the Dirac γ_5 matrix in dimensional regularization
  - New theoretical aspects – $\tilde{g}\tilde{g}g$ vertex
  - New divergent four-point functions
  - Finite shift of the gauge relative to the Yukawa coupling to restore SUSY at one-loop
  - Extra subtraction when the intermediate squark goes on-shell

- Analysis is general, not tied to a particular SUSY breaking model. We can provide NLO cross sections for arbitrary $m_{\tilde{g}}$, $m_{\tilde{\chi}}$ and mixings
- For numerical results, we select various schemes
- Minimal SUGRA framework, specified by 5 parameters at the GUT scale
  - m_0 – common scalar mass: 100 GeV
  - $m_{1/2}$ – common gaugino mass: varied from 100 to 400 GeV
  - A_0 – common trilinear coupling: 300 GeV
  - $\tan\beta$ – ratio of v.e.v.'s: $\tan\beta = 4$
  - $sgn(\mu)$: positive
  - Value of μ fixed by EWSB (M_Z)
- $m_{\tilde{g}}$, $m_{\tilde{\chi}}$, and $m_{\tilde{q}}$ all increase with $m_{1/2}$; insensitive to m_0
- Show cross sections as a function of the physical masses $m_{\tilde{g}}$ and $m = (m_{\tilde{\chi}} + m_{\tilde{g}})/2$
- Intermediate-mass gluino LSP model,
  - A. Mafi and S. Raby, hep-ph/9912436
  - Select $m_{\tilde{g}} = 30$ GeV
  - Fix $m_{\tilde{q}} = 450$ GeV
  - Weak sector identical to SUGRA: $m_{1/2}, \tan\beta \rightarrow$ chargino and neutralino masses
- Also examined GMSB, $\tilde{g}$MSB, and AMSB cases

2. Leading Order Cross Sections

- Associated production of a gluino and a gaugino:
  - Only $q\bar{q}$ initial state at LO, $\mathcal{O}(\alpha_{EW}\alpha_s)$:



- Spin-0 $\tilde{q}_{\mathrm{L,R}}$ exchange in t and u channels; no $\tilde{q}_L/\tilde{q}_R$ interference

- Partonic cross section:

$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}t}(q\bar{q}' \to \tilde{g}\tilde{\chi}) = \frac{2\alpha_s\pi}{s^2}\frac{N_C C_F}{4N_C^2}\left[X_t\frac{(t-m_{\tilde{g}}^2)(t-m_{\tilde{\chi}}^2)}{(t-m_{\tilde{q}}^2)^2}\right.$$
$$\left.+X_u\frac{(u-m_{\tilde{g}}^2)(u-m_{\tilde{\chi}}^2)}{(u-m_{\tilde{q}}^2)^2} - 2X_{tu}\frac{m_{\tilde{g}}m_{\tilde{\chi}}s}{(t-m_{\tilde{q}}^2)(u-m_{\tilde{q}}^2)}\right]$$

  - α_s is the strong coupling strength
  - X_t, X_u, X_{tu} contain the electroweak couplings
  - Note negative (t,u) interference if $m_{\tilde{g}}m_{\tilde{\chi}} > 0$

- The couplings of the $\tilde{\chi}$ states are less than a factor of 10 smaller than the strong coupling α_s, except for the $\tilde{\chi}_2^+$, $\tilde{\chi}_3^0$, and $\tilde{\chi}_4^0$. The latter are Higgsino like, with large masses
- Second channel: associated production of a squark and a gaugino $\qquad qg \to \tilde{q}\tilde{\chi}$
- Associated production cross sections calculated in LO by Dawson, Eichten, and Quigg, PRD 31, 1581 (1985); Baer, Karatas, and Tata, PRD 42, 2259 (1990)

  [masses, parton densities, collider parameters dated]

3. Next-to-Leading Order SUSY-QCD Contributions

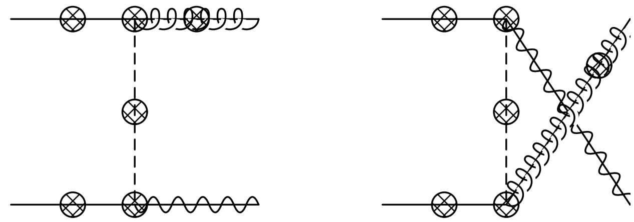
- At NLO, both $q\bar{q}$ and gq initial parton channels contribute. Indices $ij \in \{q\bar{q}, qg\}$ denote the initial channels
- Partonic cross section $\hat{\sigma}_{ij\to\tilde{g}\tilde{\chi}X}$ is obtained from fixed-order QCD calculations via an expansion in the strong coupling α_s

$$\hat{\sigma}_{ij} = \alpha_s(\mu^2)\hat{\tilde{\sigma}}_{ij}^{\mathrm{Born}} + \alpha_s^2(\mu^2)\left[\hat{\tilde{\sigma}}_{ij}^{\mathrm{V}} + \hat{\tilde{\sigma}}_{ij}^{\mathrm{R}}\right] + \mathcal{O}(\alpha_s^3)$$

- V denotes the "virtual" loop corrections. Arise from interference of the Born matrix element with the one-loop amplitudes (self-energy corrections, vertex corrections, box diagrams)
- R denotes the "real" emission contributions. Arise from three parton final-state subprocesses (extra gluon or a light quark/antiquark in the final state)
- parameter μ is the renormalization/factorization scale
- Extract UV, IR, and collinear singularities by use of dimensional regularization
- Virtues of a next-to-leading order calculation
  - Better estimate of sizes of cross sections (K-factors)
  - Greater stability of the theoretical predictions; i.e, reduced renormalization μ_R and factorization μ_F scale dependences
  - More restrictive experimental mass bounds/exclusion limits
  - More accurate p_T and y distributions
  - Improved event simulations

Loop Diagrams for Associated Production of a Gluino and a Gaugino

- Generic Diagrams:

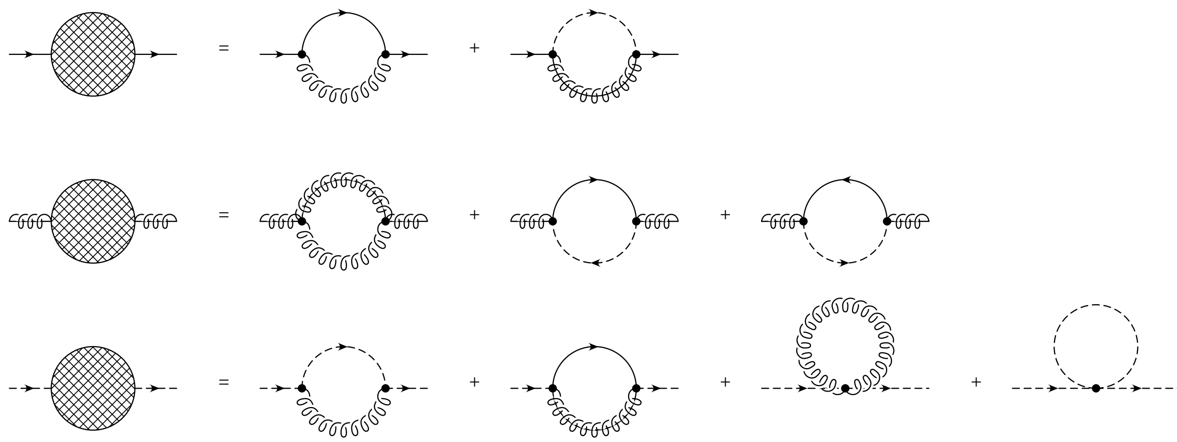


- Self-energy Corrections:

q:

$\tilde{g}$:

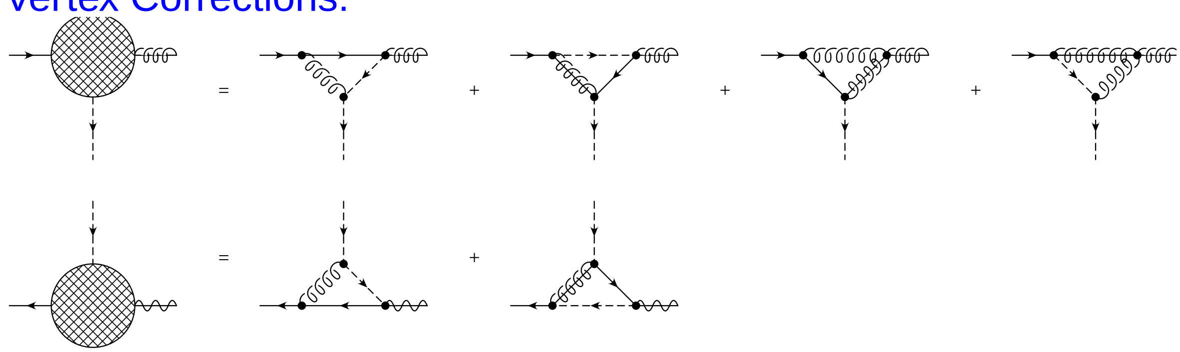
$\tilde{q}$:



- Vertex Corrections:

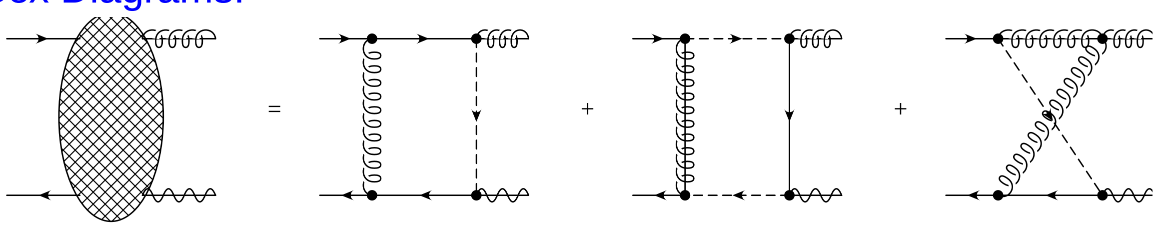
$q\tilde{q}\tilde{g}$:

$q\tilde{q}\tilde{\chi}$:



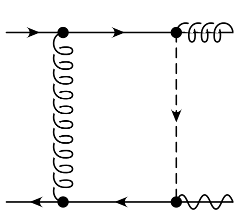
- Box Diagrams:

Boxes:

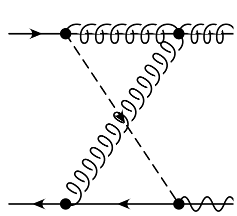


- Loop corrections (self-energy, vertex, and box terms): [→ Fig.]
  - Exchange of virtual SM and SUSY particles included
  - UV, IR, and collinear divergences are regulated by calculating matrix elements and phase space in $n = 4 - 2\epsilon$ dimensions
  - Extraction of UV, IR, and collinear singularities as poles in ϵ; $\epsilon^{(-1,-2)}$
  - Dirac γ_5 matrix enters at the $q - \tilde{q} - \tilde{g}$ and $q - \tilde{q} - \tilde{\chi}$ vertices; naive γ_5 scheme agrees with t'Hooft-Veltman scheme (no anomalies) [Chanowitz,Furman,Hinchliffe]
  - Reduction of tensor integrals to scalar [Passarino, Veltman]
  - Divergences are contained in the scalar integrals; absorptive parts obtained from Cutkosky rules in n dim.; dispersion techniques to derive the real parts. [t'Hooft, Veltman]

    2 new divergent 4-point-functions:



$$D_0(0, 0, m^2_{\tilde{\chi}}, m^2_{\tilde{g}}, s, t; 0, 0, 0, m_{\tilde{q}})$$



$$D_0(0, m^2_{\tilde{g}}, 0, m^2_{\tilde{\chi}}, t, u; m_{\tilde{q}}, m_{\tilde{g}}, 0, 0)$$

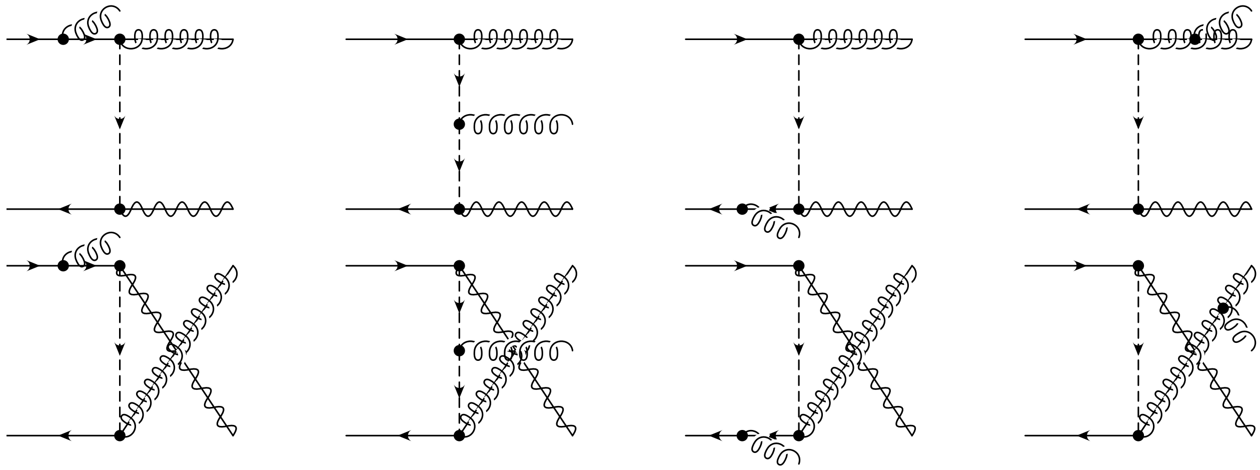
- UV singularities removed by
  - On-shell renormalization of particle masses: replace the bare masses in the LO propagators by running masses
  - $\overline{\mathrm{MS}}$ renormalization of couplings
- α_s vs. $\hat{\alpha}_s$
  - The $g - q - \bar{q}$ coupling and the $\tilde{g} - \tilde{q} - q$ coupling are guaranteed to be equal at all orders by supersymmetry
  - Standard dimensional regularization breaks SUSY at one loop – mismatch of the $n-2$ gluon transverse degrees of freedom and the 2 fermionic gluino degrees of freedom
  - Finite shift between bare Yukawa $\hat{g}$ and bare gauge coupling g to restore supersymmetry in $\overline{\mathrm{MS}}$ [Martin, Vaughn]

$$\hat{g} = g\left[1 + \frac{g^2}{32\pi^2}\left(\frac{4}{3}N_C - C_F\right)\right]$$

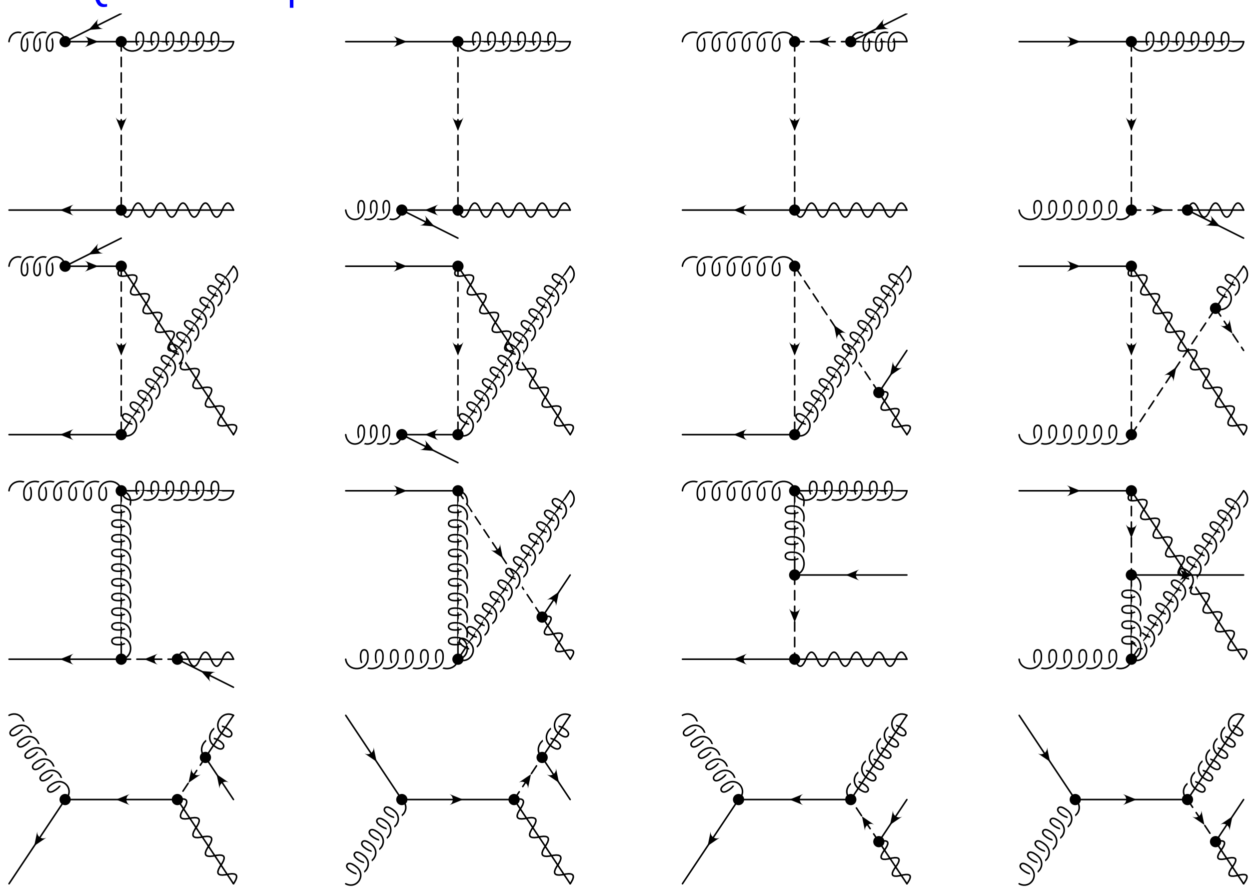
- Infrared singular terms appear as factors times parts of the Born matrix element

$2 \to 3$ Diagrams for Associated Production of a Gluino and a Gaugino

- Gluon Emission:



- Quark/Antiquark Emission :

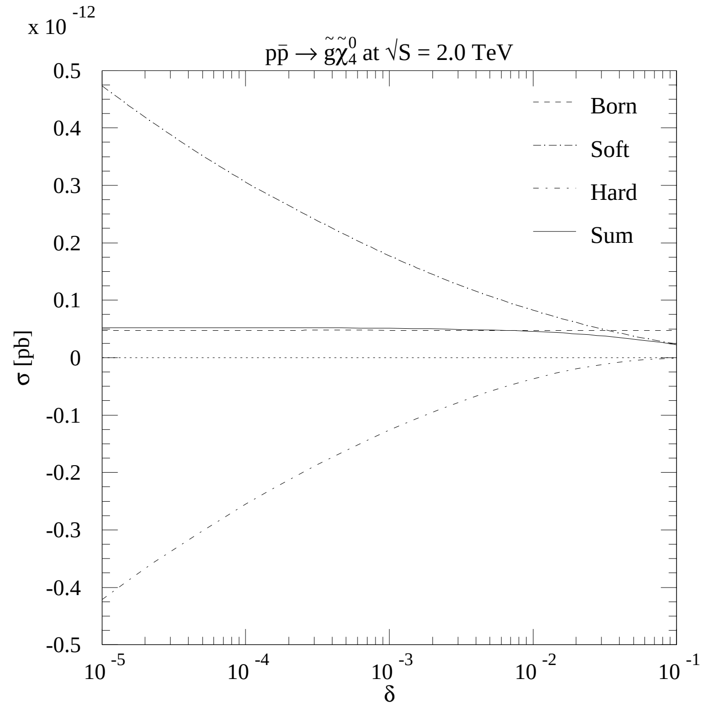


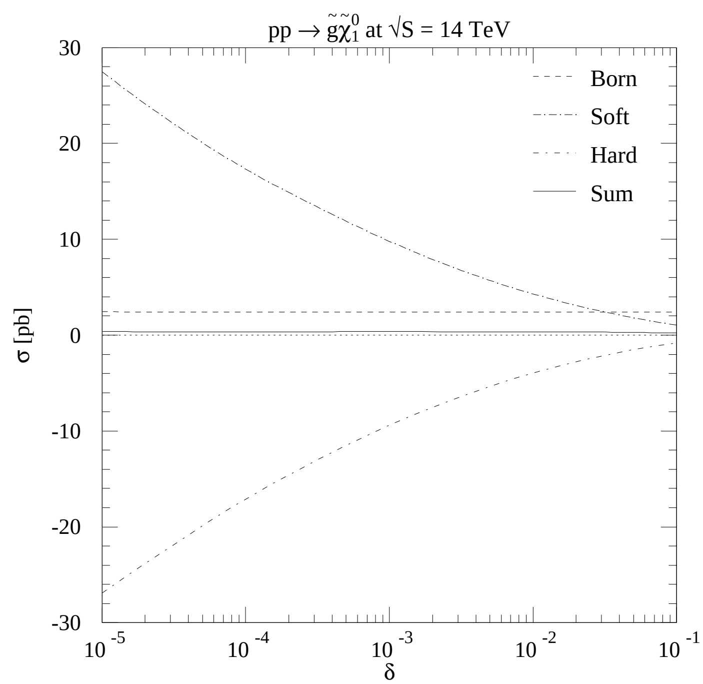
- Real emission contributions: [→ Fig.]
  - Traces calculated in $n = 4 - 2\epsilon$ dimensions
  - Phase space integration over final state partons performed in $n = 4 - 2\epsilon$ dimensions; infrared and collinear singularities extracted as poles in ϵ
  - Phase space slicing method to isolate the IR singularities

$$\frac{d\sigma^R}{dt} = \int ds_{4x} \frac{d^2\sigma^R}{dt\,du} = \int_0^{\Delta} ds_{4x} \frac{d^2\sigma^S}{dt\,du} + \int_{\Delta}^{s_{4x}^{max}} ds_{4x} \frac{d^2\sigma^H}{dt\,du}.$$

    - In the frame in which the extra final-state light parton is back-to-back with the gluino, s_4 corresponds to the energy of the light parton; IR singularity appears as $s_4 \to 0$
    - Matrix elements simplify in soft/collinear approximation
    - Analytical integration up to cut-off Δ (soft gluon region) $\to \log^{(1,2)} \Delta$ terms
    - Numerical integration above cut-off Δ (hard gluon region) $\to$ cut-off dependence cancels [→ Fig.]
  - Infrared singular terms are proportional to parts of the Born matrix element
    - C_F color and N_C color classes
    - Cancel against IR singularities from the loop diagrams
  - Collinear singularities have the universal structure of the Born cross section convoluted with an Altarelli-Parisi splitting function and are absorbed into renormalization of the parton densities at NLO
  - Quark/antiquark emission diagrams have only factorizable singularities

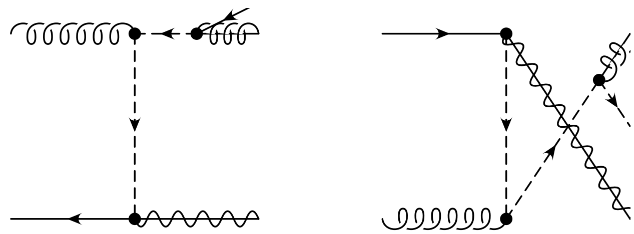
Cutoff Δ Dependence for Associated Production



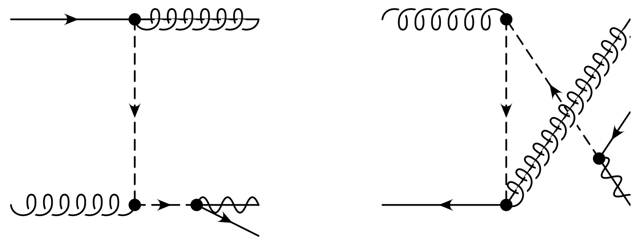


- Parameter is $\Delta/m_{\tilde{g}}^2$
- We use $\delta = 10^{-4}$

- Class of physical singularities that must be regulated, associated with intermediate on-shell squarks:
  - Squark decay to quark plus gluino if $m_{\tilde{q}} > m_{\tilde{g}}$:



  - Squark decay to quark plus gaugino if $m_{\tilde{q}} > m_{\tilde{\chi}}$:



- These contributions are included in LO squark production and subsequent squark decay
- To avoid double-counting one must subtract

$$\begin{aligned}\frac{\mathrm{d}\sigma}{\mathrm{d}M^2} &= \sigma(gq \to \tilde{q}\tilde{g})\mathrm{BR}(\tilde{q} \to q\tilde{\chi})\frac{m_{\tilde{q}}\Gamma_{\tilde{q}}/\pi}{(M^2 - m_{\tilde{q}}^2)^2 + m_{\tilde{q}}^2\Gamma_{\tilde{q}}^2} \\ &\to \sigma(gq \to \tilde{q}\tilde{g})\mathrm{BR}(\tilde{q} \to q\tilde{\chi})\delta(M^2 - m_{\tilde{q}}^2)\end{aligned}$$

- After the LO term is subtracted, the remainder is expressed as a principal-value function; well defined numerically
- For SUGRA model parameters, $m_{\tilde{g}} > m_{\tilde{q}}$ for all $m_{1/2}$ so squark to gluino plus quark does not occur. However, $m_{\tilde{q}} > m_{\tilde{\chi}}$ for all $\tilde{\chi}$ so squark to gaugino plus quark comes into play in all cases. For light gluino model, $m_{\tilde{g}} < m_{\tilde{q}}$, and squark to gluino plus quark is always active

4. Partonic Scaling Functions

- Definition:

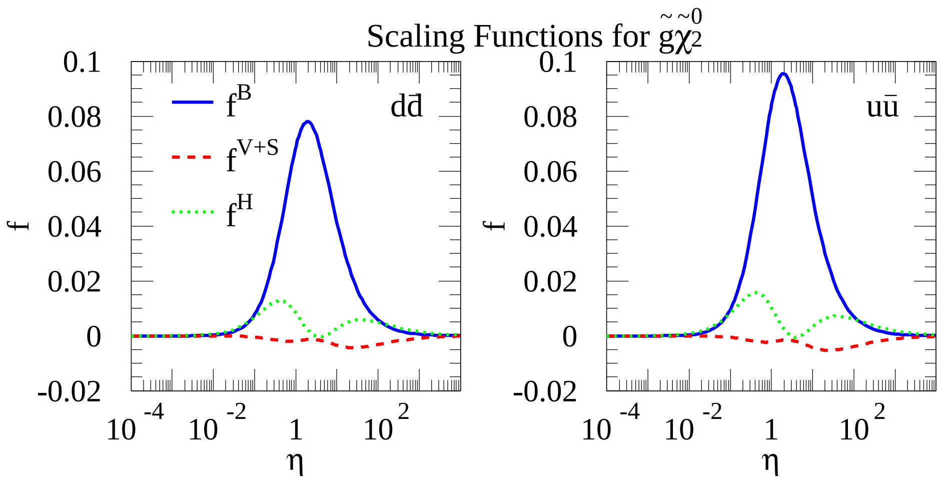
$$\hat{\sigma}_{ij} = \frac{\alpha\alpha_{(s)}(\mu)}{m^2}\left\{f_{ij}^B(\eta) + 4\pi\alpha_s(\mu)\left[f_{ij}^{V+S}(\eta,\mu) + f_{ij}^H(\eta,\mu)\right]\right\}$$

$$\eta = \frac{s}{4m^2} - 1 \quad , \quad m = \frac{m_1 + m_2}{2}$$

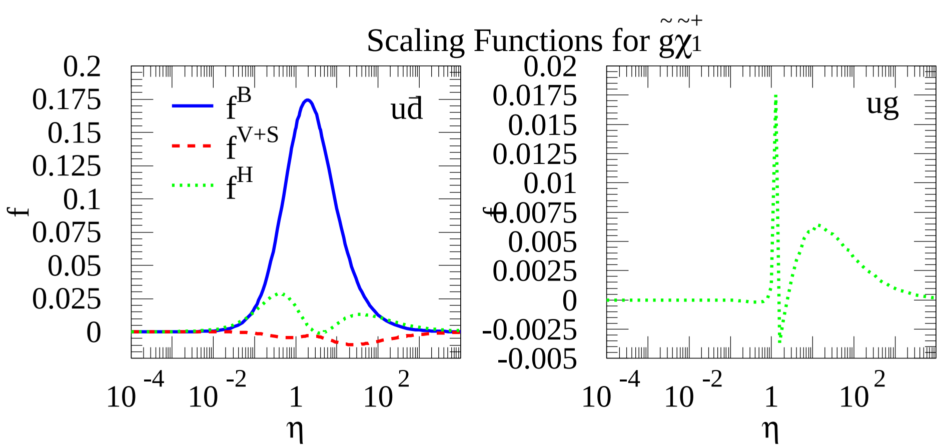
- Renormalization/factorization scale: $\mu = m$
- V+S without $\log^{(1,2)} \Delta$ terms $\rightarrow$ independent of Δ
- H with S $\log^{(1,2)} \Delta$ terms $\rightarrow$ independent of Δ
- Intermediate on-shell squarks show up as integrable singularities
  $\rightarrow$ spikes in gu, gd scaling functions
- Advantages of scaling functions:
  - Independent of couplings, parton densities, collider type and energy
  - Allow for precise numerical checks of individual contributions
  - Can study threshold, resonance, and high energy behaviors

Scaling Functions for Associated Production

- Neutralino Production:



- Chargino Production:



5. Hadronic Cross Sections

- Hadronic cross section obtained as a convolution of the partonic cross section with parton densities:

$$\sigma^{h_1 h_2}(S,\mu) =$$

$$\sum_{i,j=g,q,\overline{q}} \int_{\tau}^{1} \mathrm{d}x_1 \int_{\tau/x_1}^{1} \mathrm{d}x_2 f_i^{h_1}(x_1,\mu) f_j^{h_2}(x_2,\mu) \hat{\sigma}_{ij}(x_1 x_2 S,\mu)$$

$$\tau = \frac{4m^2}{S}, m = \frac{m_{\tilde{\chi}} + m_{\tilde{g}}}{2}$$

  - LO: 1-loop α_s, CTEQ5L, $\Lambda^{(5)} = 146$ MeV
  - NLO: 2-loop α_s, CTEQ5M, $\Lambda^{(5)} = 226$ MeV

- Hadronic cross sections for Tevatron Run II and LHC

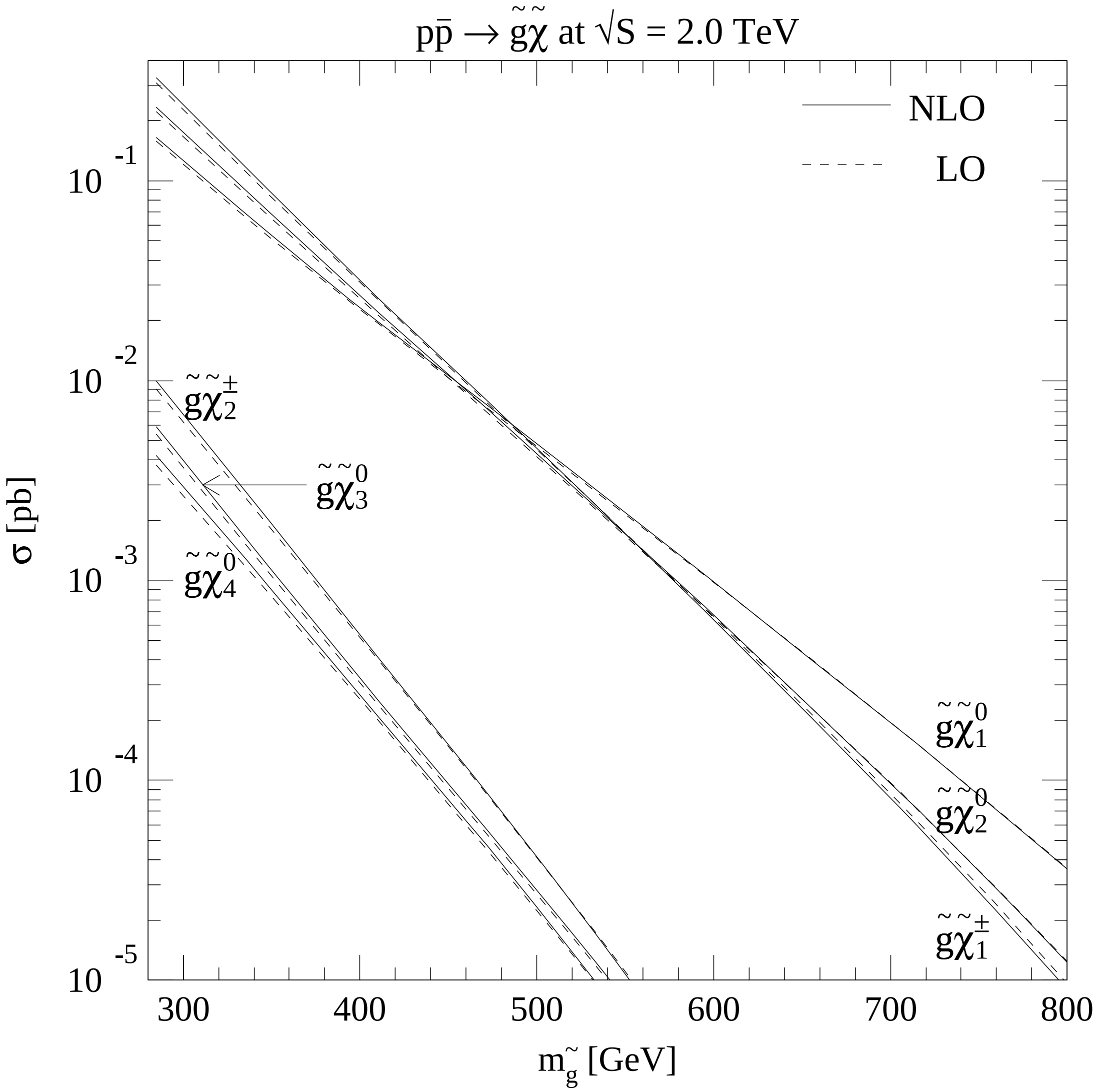
- K factor $= \sigma_{\mathrm{NLO}}/\sigma_{\mathrm{LO}}$
  - K factors decreased after the change from CTEQ4 $\rightarrow$ CTEQ5
    - Tevatron: -12 %
    - LHC: -4 %

- Renormalization/factorization scale (μ) dependence

- Differential cross sections in rapidity and transverse momentum

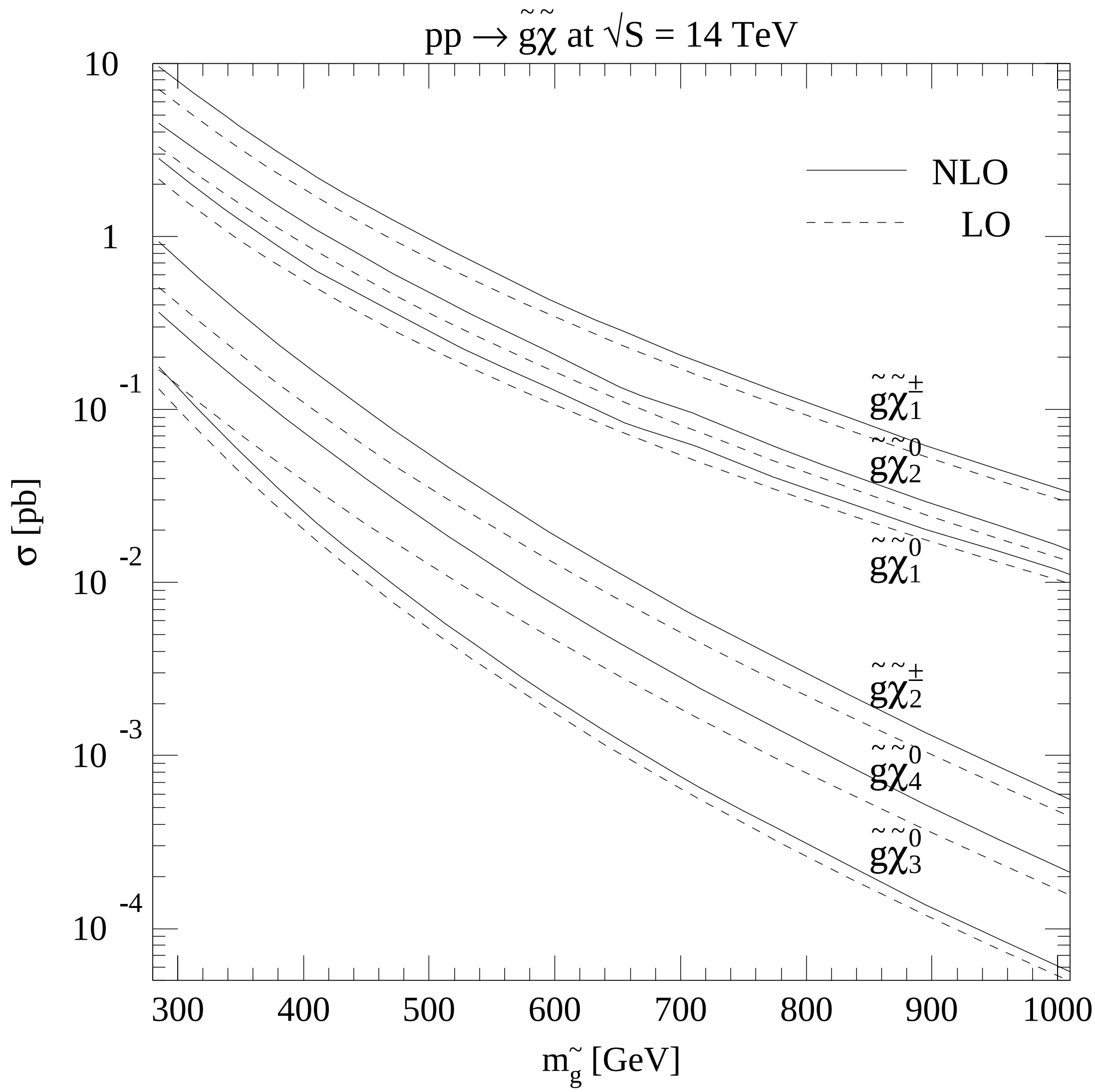
Total Cross Sections for Associated Production

of a Gluino and a Gaugino vs. $m_{\tilde{g}}$ – SUGRA case



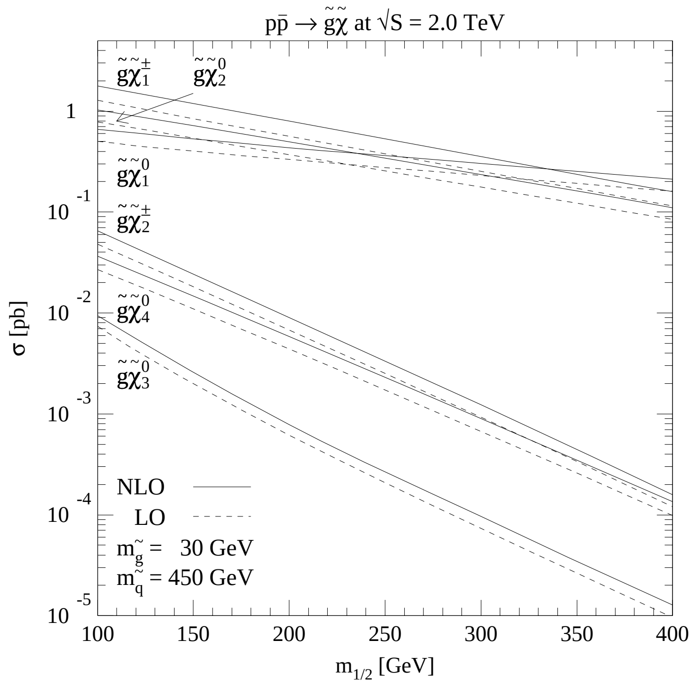
- $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ have similar cross sections and masses
- $\tilde{\chi}_1^0$ cross section is suppressed at small mass despite $m_{\tilde{\chi}_1^0} < m_{\tilde{\chi}_2^0}$; photon like coupling
- $\sigma(\tilde{g}\tilde{\chi}_2^0) \simeq 0.10$ pb for masses corresponding to the chosen SUGRA scenario
- For 2 fb^{-1}, 10 or more events could be produced in each of the lighter gaugino channels of the SUGRA model, if $m_{\tilde{g}} <$ 450 GeV.

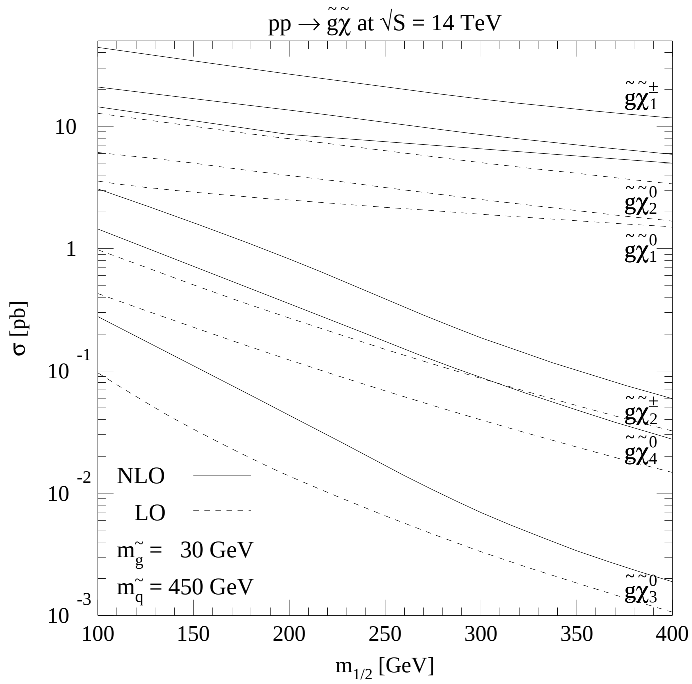
Total Cross Sections at the LHC - SUGRA case



- At the LHC the $\tilde{\chi}_1^{\pm}$ cross section is the largest
- At small $m_{\tilde{g}}$ there is a 30 fold increase over FNAL
- At large $m_{\tilde{g}}$ the increase is of order 10^4
- Parton density uncertainty estimated roughly: for $\tilde{\chi}_2^0$, 12% drop of the NLO cross section from CTEQ4M to CTEQ5M at the Tevatron and 4% drop at the LHC energy

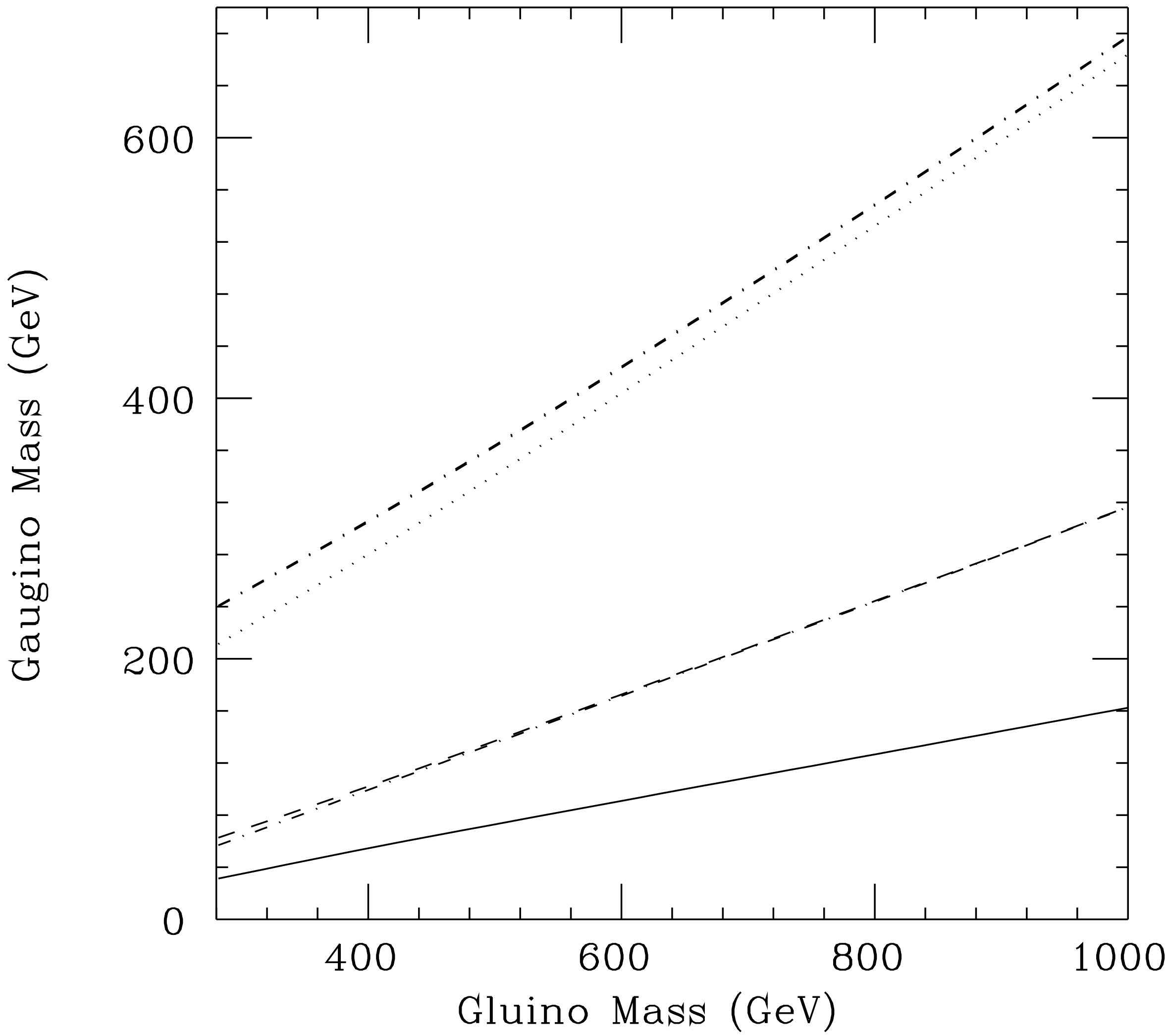
Total Cross Sections for Associated Production – Light $\tilde{g}$ case





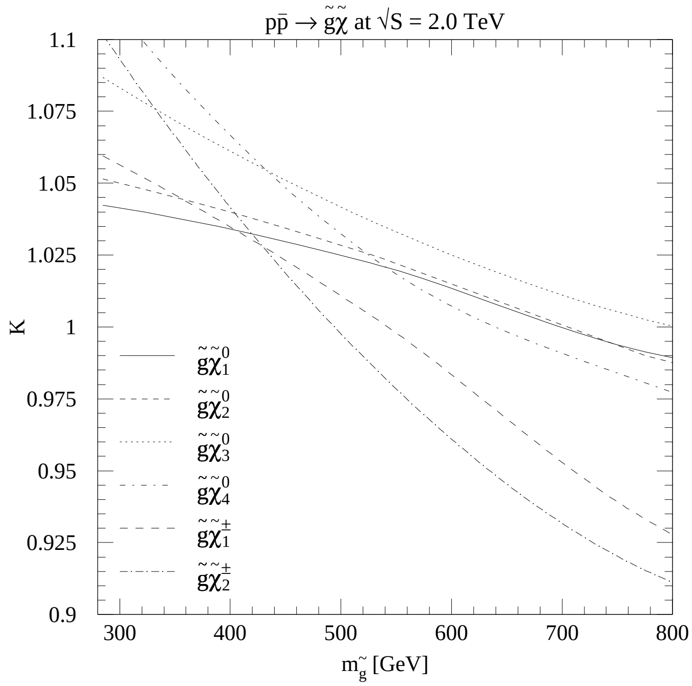
- $m_{\tilde{g}} = 30$ GeV; $m_{\tilde{q}} = 450$ GeV; cross sections vs. $m_{1/2}$
- K factors in the range 1.3 to 1.4 at Tevatron and 2 to 4 at the LHC
- At Tevatron, for 2 fb^{-1}, > 100 events could be produced in the three lighter gaugino channels if $m_{1/2} <$ 400 GeV

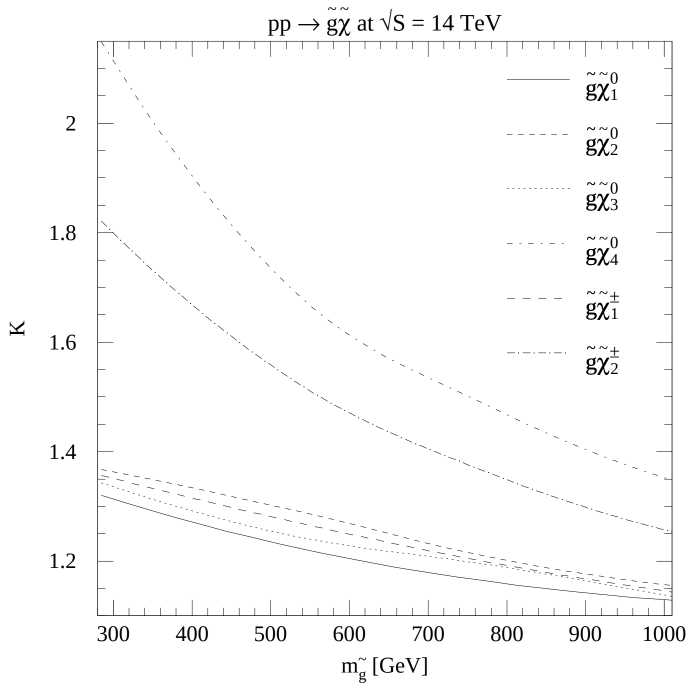
Gaugino Mass as a Function of the Gluino Mass



Solid line denotes the $\tilde{\chi}_1^0$ mass; dashed line is the $\tilde{\chi}_2^0$ mass; lower dot-dashed line is the $\tilde{\chi}_1^+$ mass; dotted line is the $\tilde{\chi}_3^0$ mass; and the upper dot-dashed line denotes the $\tilde{\chi}_4^0$ and $\tilde{\chi}_2^+$ masses.

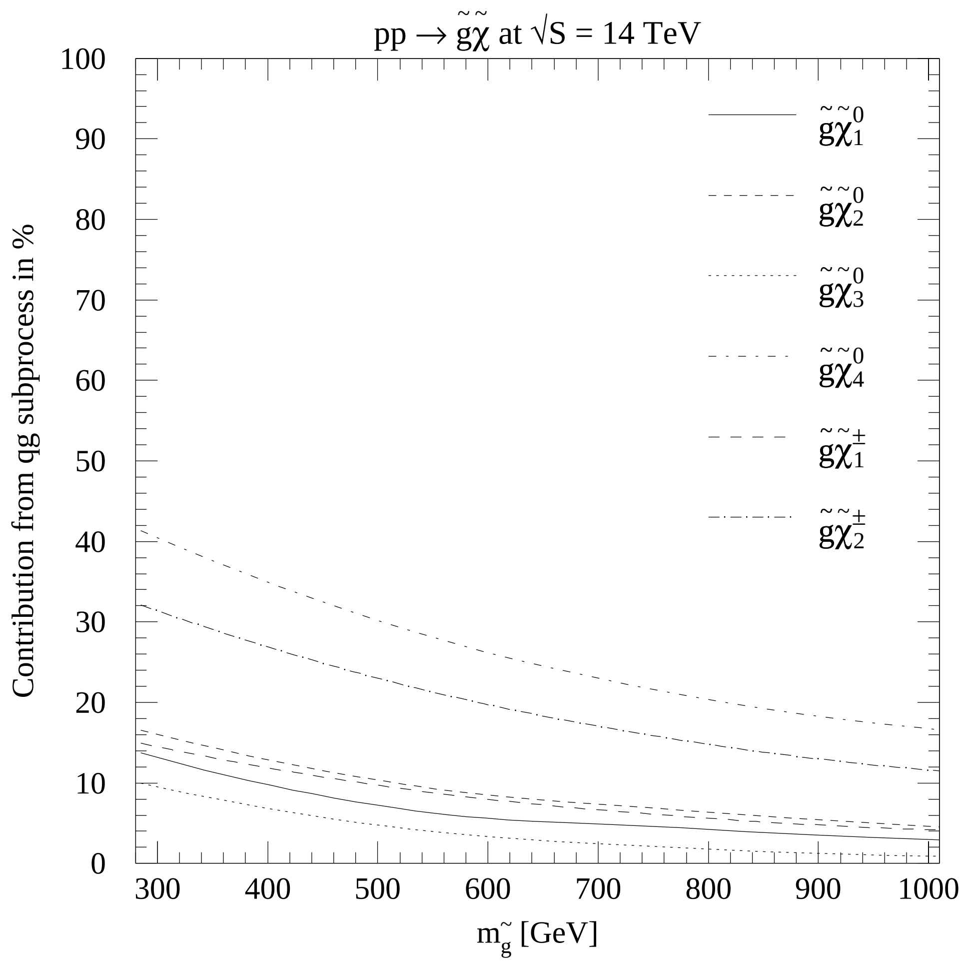
K factors for Associated Production – SUGRA case



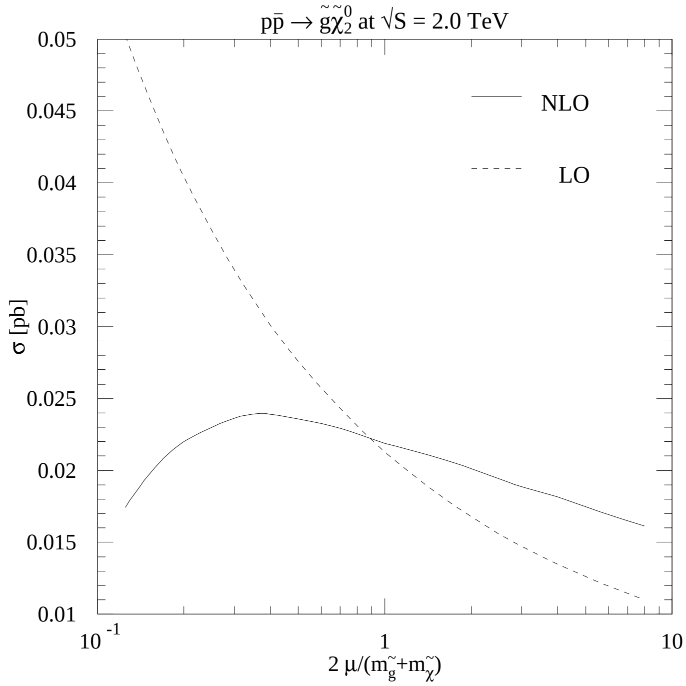


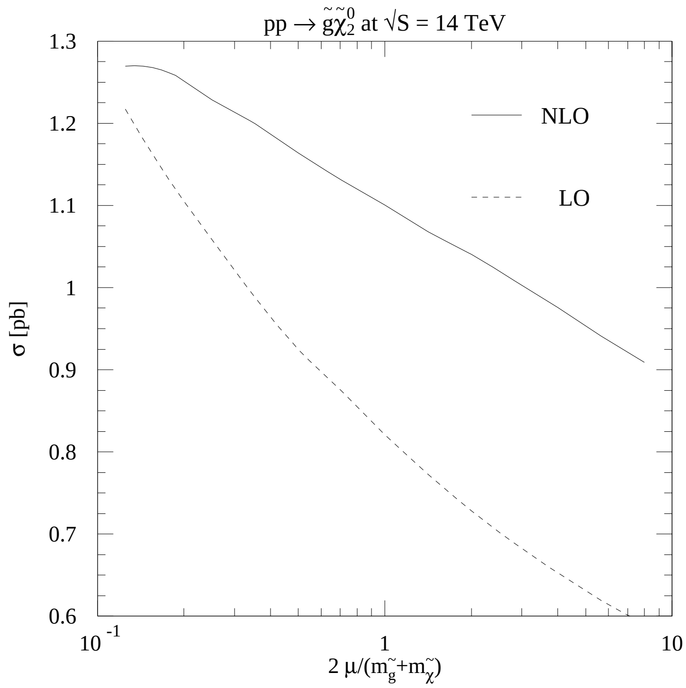
- $K = \sigma_{\rm NLO}/\sigma_{\rm LO}$; evaluated at $\mu = (m_{\tilde{g}} + m_{\tilde{\chi}})/2$
- Enhancements of at most 10% at the Tevatron; generally in the range 20% to 40% at the LHC, but x2 for $\tilde{\chi}_4^0$ and $\tilde{\chi}_2^\pm$
- qg initial state is significant at the energy of the LHC; from 10% of the final answer for the light $\tilde{\chi}$ channels up to 40% for $\tilde{\chi}_4^0$

gq initial state fraction for Associated Production – SUGRA case



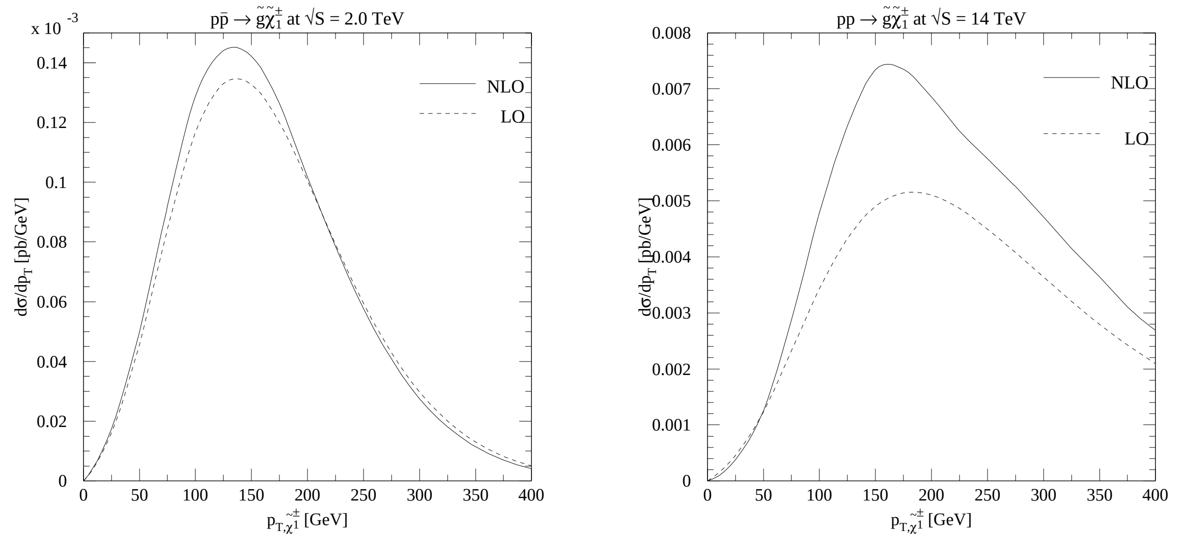
Renormalization/Factorization Scale Dependence - SUGRA Case





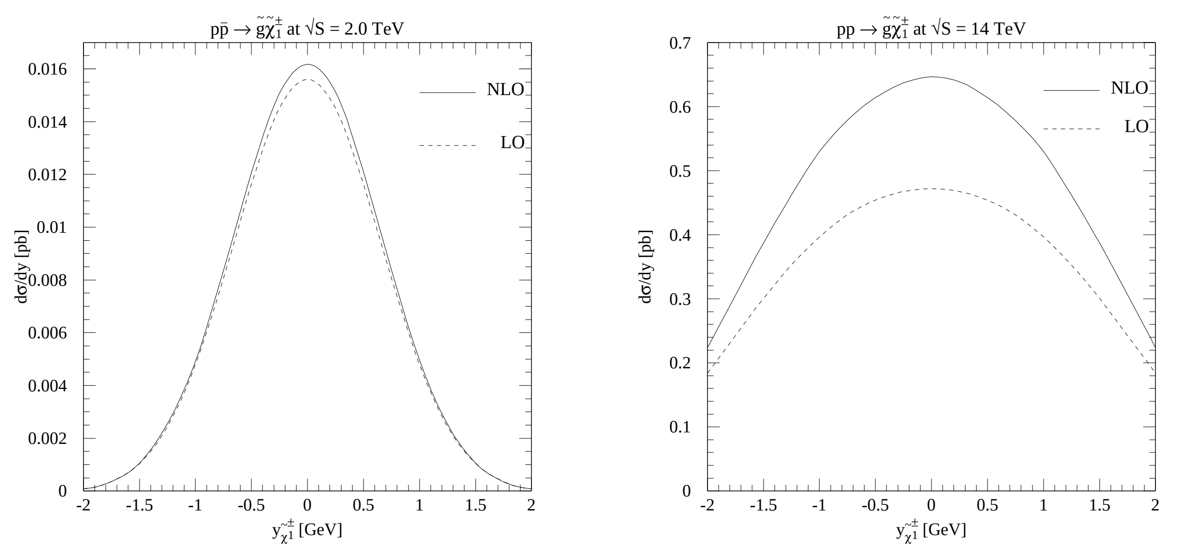
- Scale factor is μ/μ_o; $\mu_o = (m_{\tilde{\chi}} + m_{\tilde{g}})/2$; evaluated at the ”default” value $m_{\tilde{\chi}_2^0} = 104$ GeV, $m_{\tilde{g}} = 410$ GeV
- Reduction from LO ($\pm 23\%$) to NLO ($\pm 8\%$) at FNAL and from LO ($\pm 12\%$) to NLO ($\pm 4.5\%$) at LHC for $\mu/\mu_o \in \{0.5, 2\}$

p_T Distributions for Associated Production – SUGRA Scenario



- Distribution is integrated over all y
- Shift of the spectrum to smaller p_T – modest effect at the Tevatron but more important at the LHC where the gq channel contributes significantly – K is not independent of p_T

y Distributions for Associated Production – SUGRA Scenario



- Distribution is integrated over all p_T
- Shape of the y distribution is not appreciably affected by NLO contributions; normalization increased

6. Summary

- Associated production offers chance to study parameters of soft SUSY-breaking Lagrangian – rates are controlled by phases of $\tilde{\chi}$ and $\tilde{g}$ masses and mixings in the $\tilde{q}$ and $\tilde{\chi}$ sectors
- Full NLO SUSY-QCD calculation reported here of associated production of a gluino and a gaugino
- Quantitative results shown for SUGRA and light gluino cases; GMSB and $\tilde{g}$MSB have similar spectra and σ's to SUGRA case; AMSB has heavy gluino ($m_{\tilde{g}} < 0$), smaller σ's
- Cross section for associated production of a gluino and a gaugino is of hadronic size at the Tevatron
- Next-to-leading order enhancements are largest for small m, large S; generally modest in the SUGRA case — up to 10% at the Tevatron and 20% to 100% at the LHC — larger in the light gluino case ($\simeq 1.3$ at FNAL; 2 to 3 at LHC) where gq initial state plays a more significant role.
- Renormalization/factorization scale uncertainties are reduced by about a factor of 2 – greater reliability
- NLO p_T distribution shifted wrt LO – shifts are greater at the LHC and when gq channel is important; shapes of y distributions at NLO are similar to LO
- Signals for associated production are relatively simple since gauginos decay leptonically – discovery channel?
- Large cross section for the light gluino $\rightarrow$ associated production is a good channel for discovery at the Tevatron, closing window on this possibility, and/or setting limits on light $\tilde{\chi}$ masses