Squark Pair Production at Next-to-Leading Order

Ryan Gavin
Paul Scherrer Institute

with C Hangst, M Krämer, M Mühlleitner, M Pellen, E Popenda, M Spira

Theory Seminar, Fermilab
March 21, 2013

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Bracket Update - Winners
Michigan St
Butler

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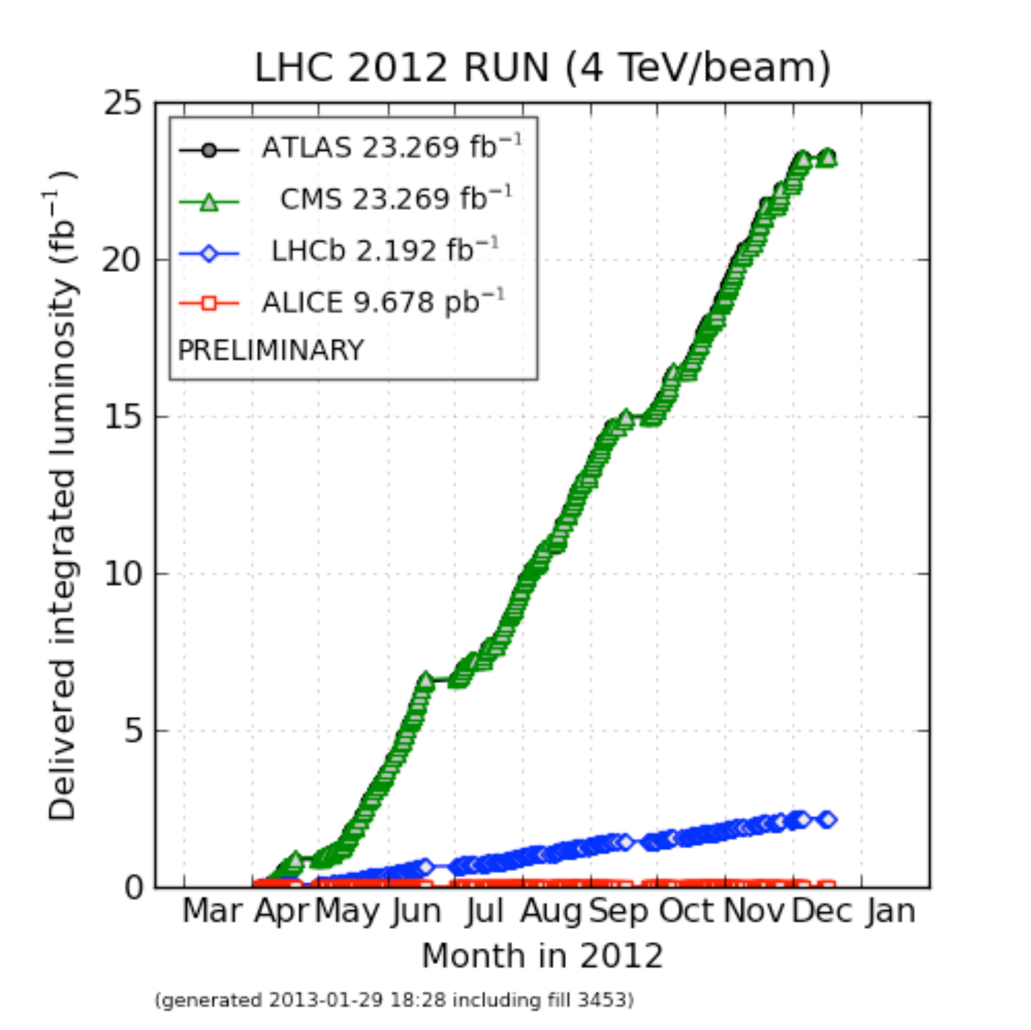
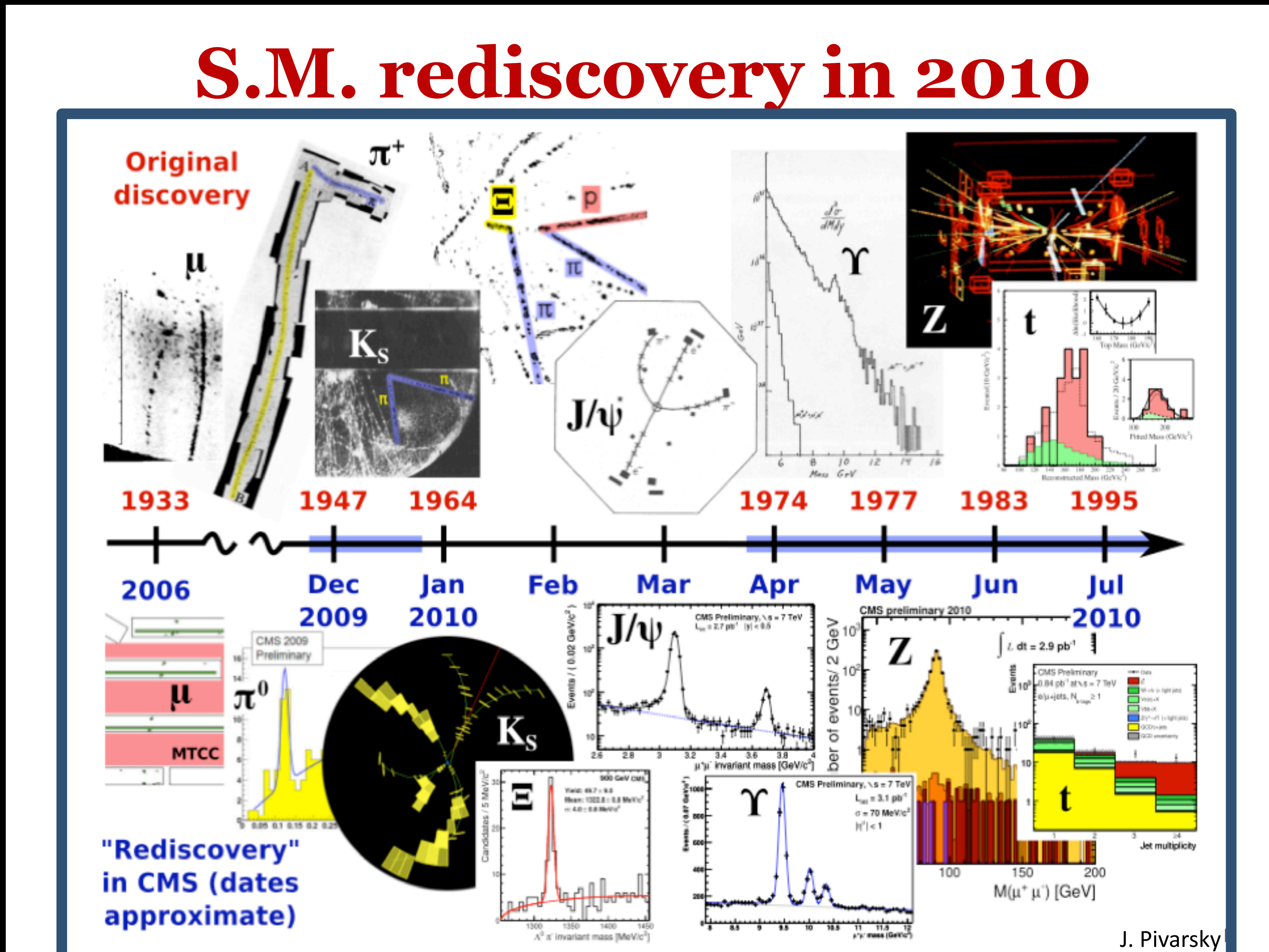
The Large Hadron Collider

- LHC ushering in new era of particle physics



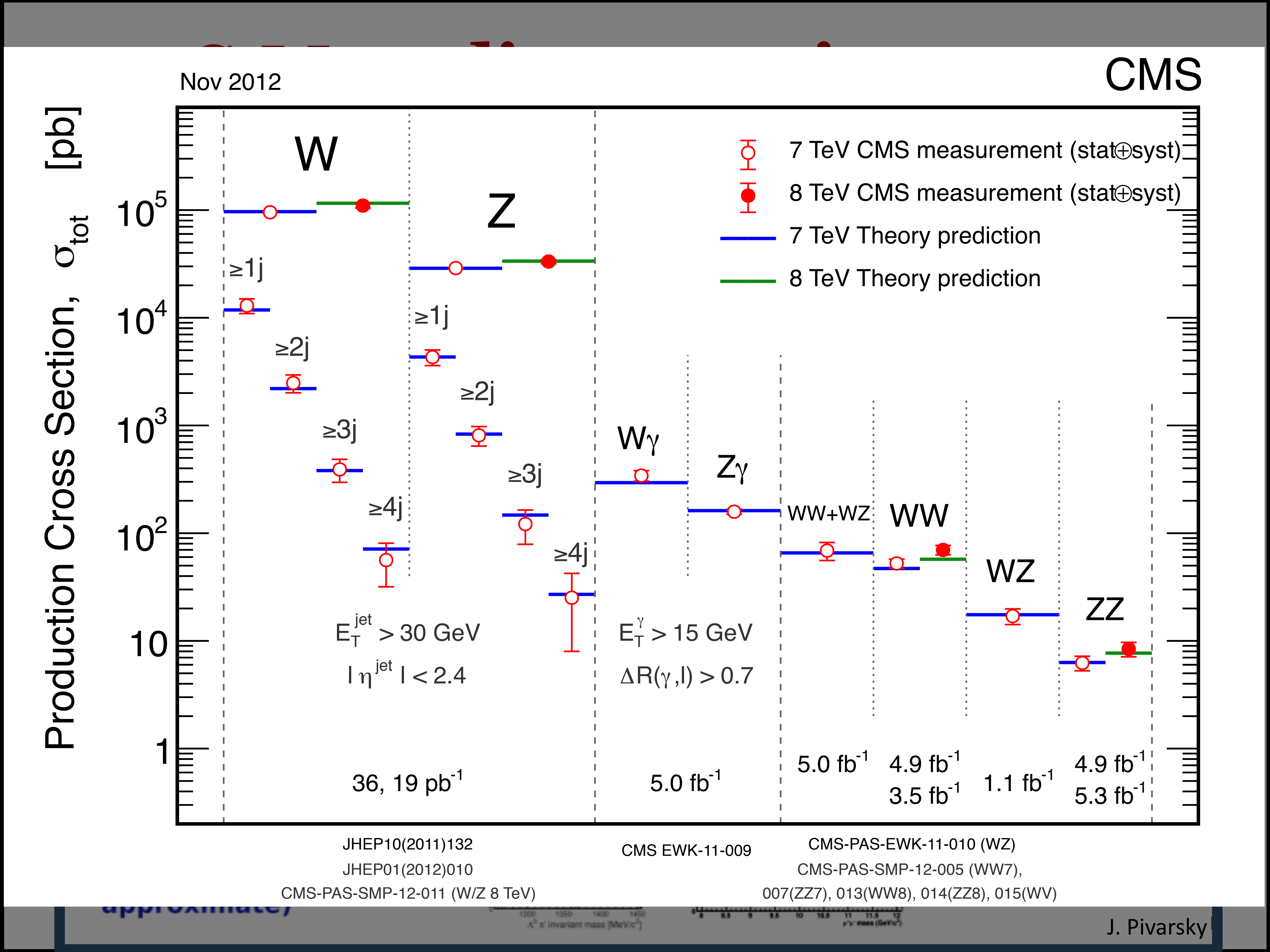
- Energy frontier - ~23 fb^{-1} in 2012 @ 8 TeV

The SM @ the LHC



slide taken from C. Mariotti

The SM @ the LHC



03/2013

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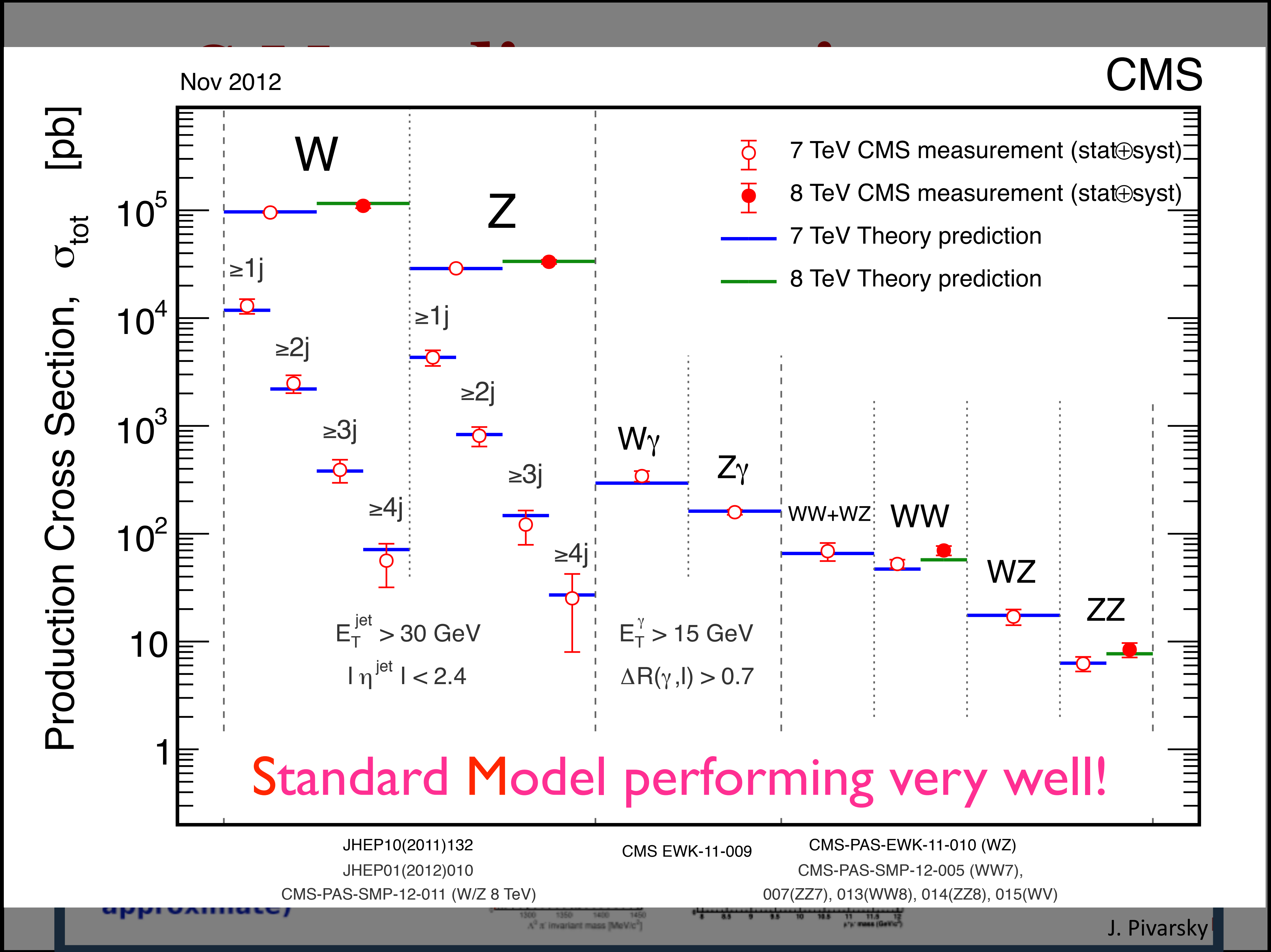

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The LHC

- Not built to rediscover Standard Model
  - new energy frontier (7, 8, and soon to be 13 TeV)
  - directly probe TeV scale physics

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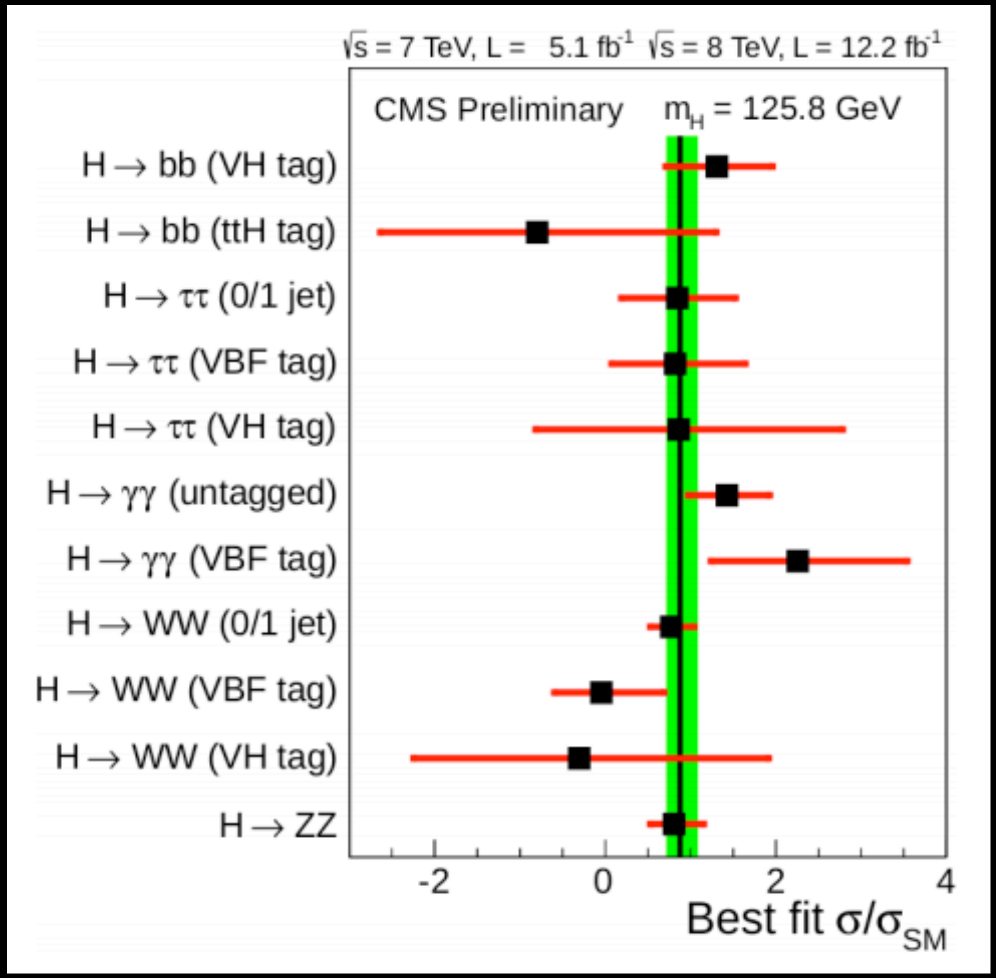
- Not built to rediscover Standard Model
  - new energy frontier (7, 8, and soon to be 13 TeV)
  - directly probe TeV scale physics
- Investigate Electroweak Symmetry Breaking
  - give mass to EW gauge bosons
  - from unitarity, $M_H \leq 1$ TeV
  - expect to find Higgs, or something like it, at LHC

EWSB & the Higgs

- July 4th, 2012 - CERN announces discovery of new particle, $M_H \approx 125$ GeV
  - consistent with SM Higgs

Updated results 03/2013



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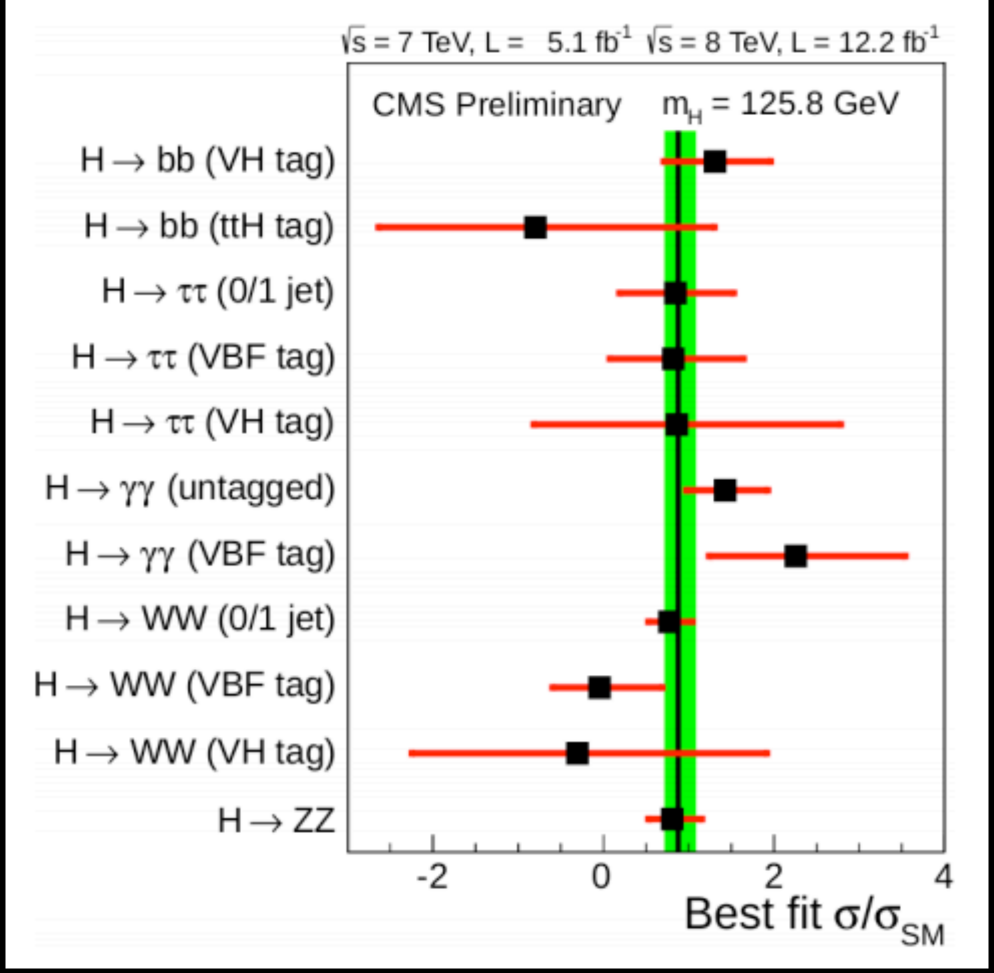

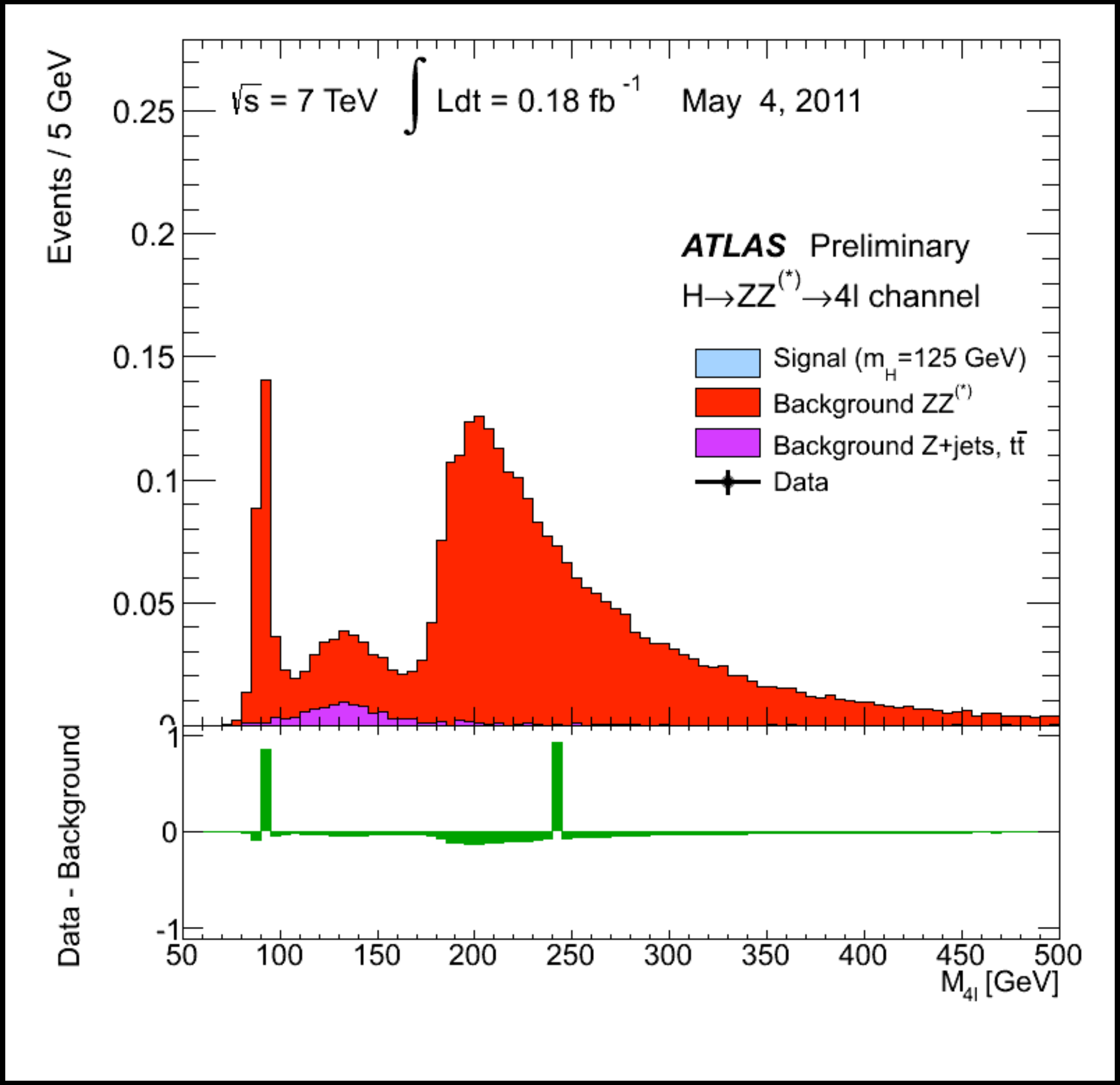

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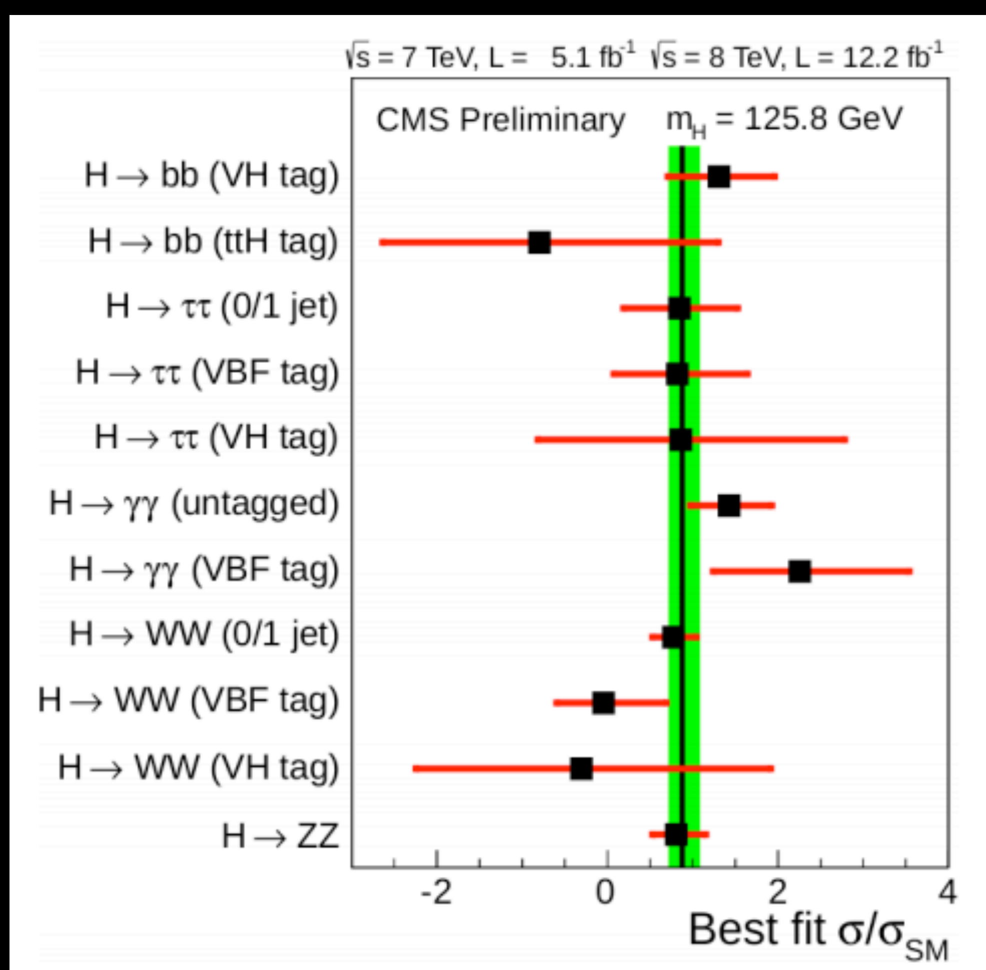

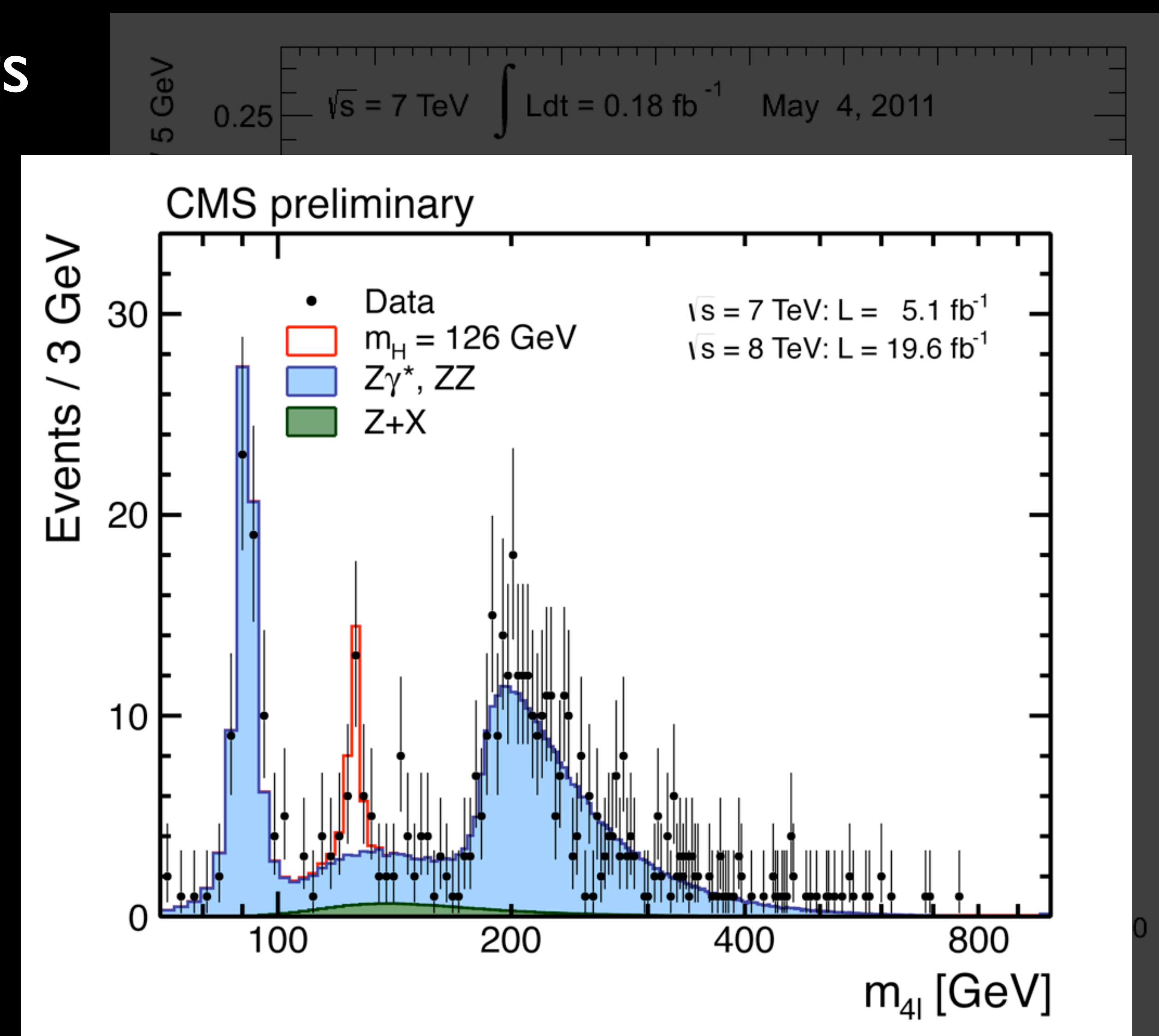

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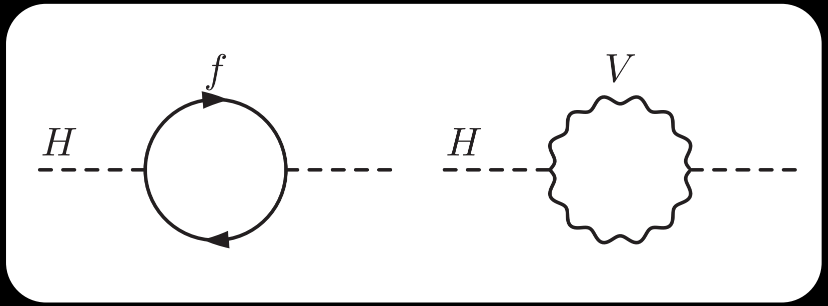
EWSB & the Higgs

- Masses receive quantum corrections

$$M^2_{H,phys} = M^2_{H,0} + \delta M^2_H$$

- Corrections are quadratically divergent



- Physical mass requires fine tuning

$$\delta M^2_H \sim \frac{\alpha}{\pi}(m^2_f + \Lambda^2)$$

- Λ (UV cutoff), typically scale to which SM is valid
- Hierarchy/naturalness problem is unsettling
  - why $M_{Pl} >> M_H$?

New Physics?

- Besides hierarchy problem, there is also the issue of dark matter
  - SM doesn't provide a dark matter candidate
- Many models for physics beyond the SM
  - Supersymmetry, Extra Dimensions, Little Higgs, Compositeness, ...
- Here, search for new physics will be motivated by Supersymmetry

Supersymmetry

- Symmetry relating fermions and bosons

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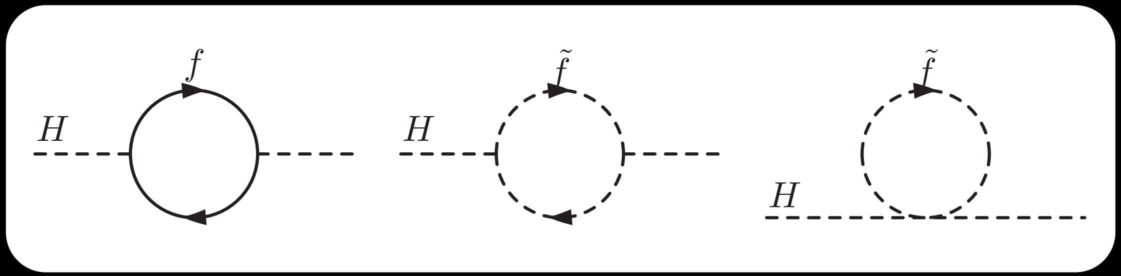

$$\delta M_H^2 \sim \frac{\alpha}{\pi}(m_f^2 - m_{\tilde{f}}^2)$$

Supersymmetry

- Symmetry relating fermions and bosons
- Solution to hierarchy problem
  - SM quadratic corrections to Higgs mass cancel against corrections from supersymmetric partners
- Gauge coupling unification (weak scale soft SUSY breaking)
- Dark matter candidate with *R*-parity conservation

$$P_R = (-1)^{3(B-L)+2s}$$

B - baryon #
L - lepton #
s - spin

SM particle: $P_R = 1$ SUSY particle: $P_R = -1$

The MSSM

- Minimal Supersymmetric extension of the Standard Model (MSSM)
  - only 1 superpartner for each SM particle
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- Minimal Supersymmetric extension of the Standard Model (MSSM)
  - only 1 superpartner for each SM particle
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  - *R*-parity conserved
- How can we look for the MSSM at the LHC?
  - proton-proton machine → QCD

MSSM Particle Content

chiral superfields

Names		spin 0	spin 1/2	$SU(3)_C, SU(2)_L, U(1)_Y$
squarks, quarks	Q	$(\tilde{u}_L, \tilde{d}_L)$	(u_L, d_L)	$(\mathbf{3}, \mathbf{2}, +\frac{1}{6})$
(× 3 families)	$\bar{u}$	$\tilde{u}_R^*$	$u_R^\dagger$	$(\bar{\mathbf{3}}, \mathbf{1}, -\frac{2}{3})$
	$\bar{d}$	$\tilde{d}_R^*$	$d_R^\dagger$	$(\bar{\mathbf{3}}, \mathbf{1}, +\frac{1}{3})$
sleptons, leptons	L	$(\tilde{\nu}, \tilde{e}_L)$	(ν, e_L)	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$
(× 3 families)	$\bar{e}$	$\tilde{e}_R^*$	$e_R^\dagger$	$(\bar{\mathbf{1}}, \mathbf{1}, +1)$
Higgs, higgsinos	H_u	(H_u^+, H_u^0)	$(\tilde{H}_u^+, \tilde{H}_u^0)$	$(\mathbf{1}, \mathbf{2}, +\frac{1}{2})$
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vector superfields

Names	spin 1/2	spin 1	$SU(3)_C, SU(2)_L, U(1)_Y$
gluino, gluon	$\tilde{g}$	g	$(\mathbf{8}, \mathbf{1}, 0)$
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what's charged under $SU(3)_C$?

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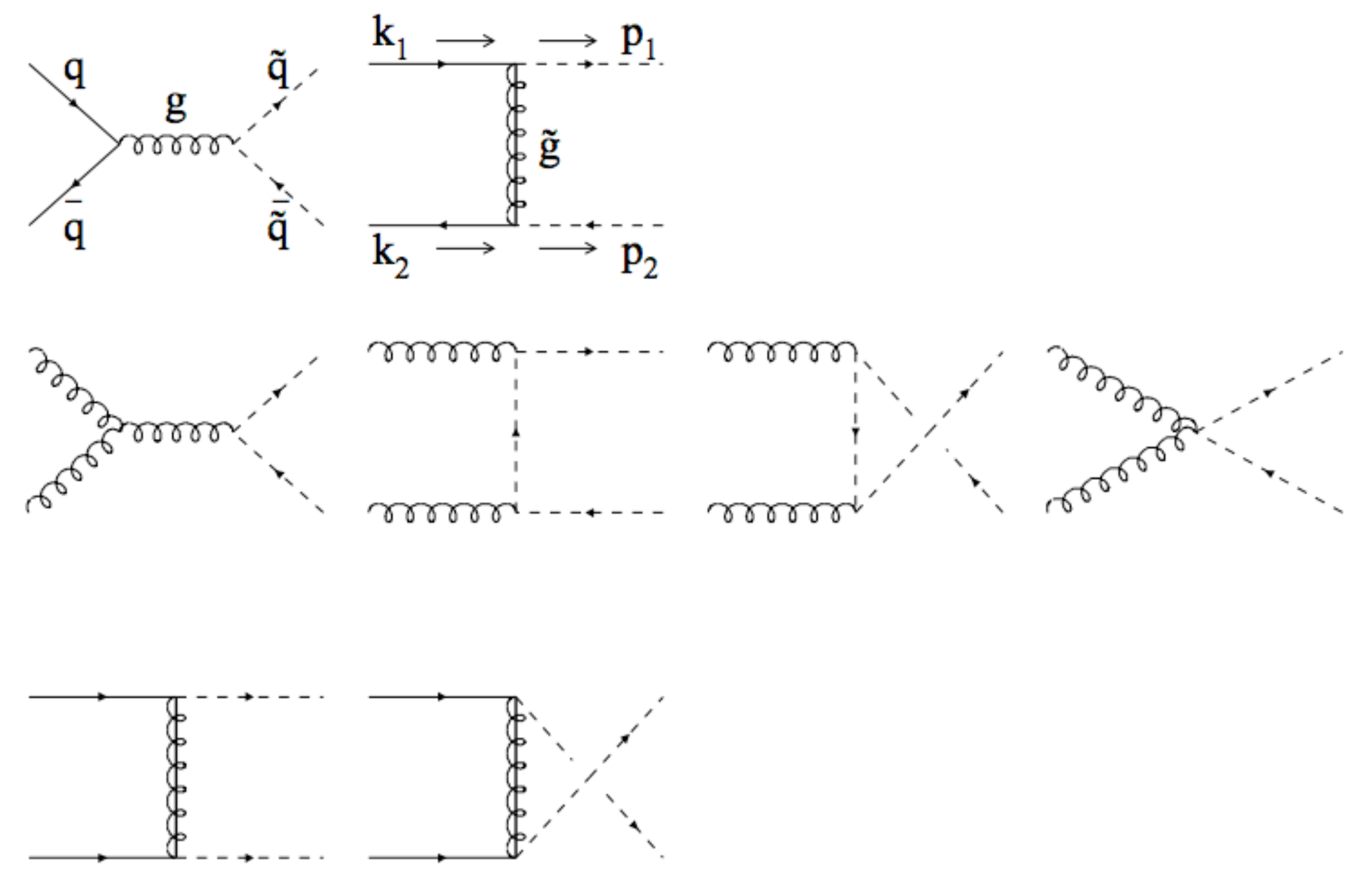
Squarks & Gluinos



Squark Pairs

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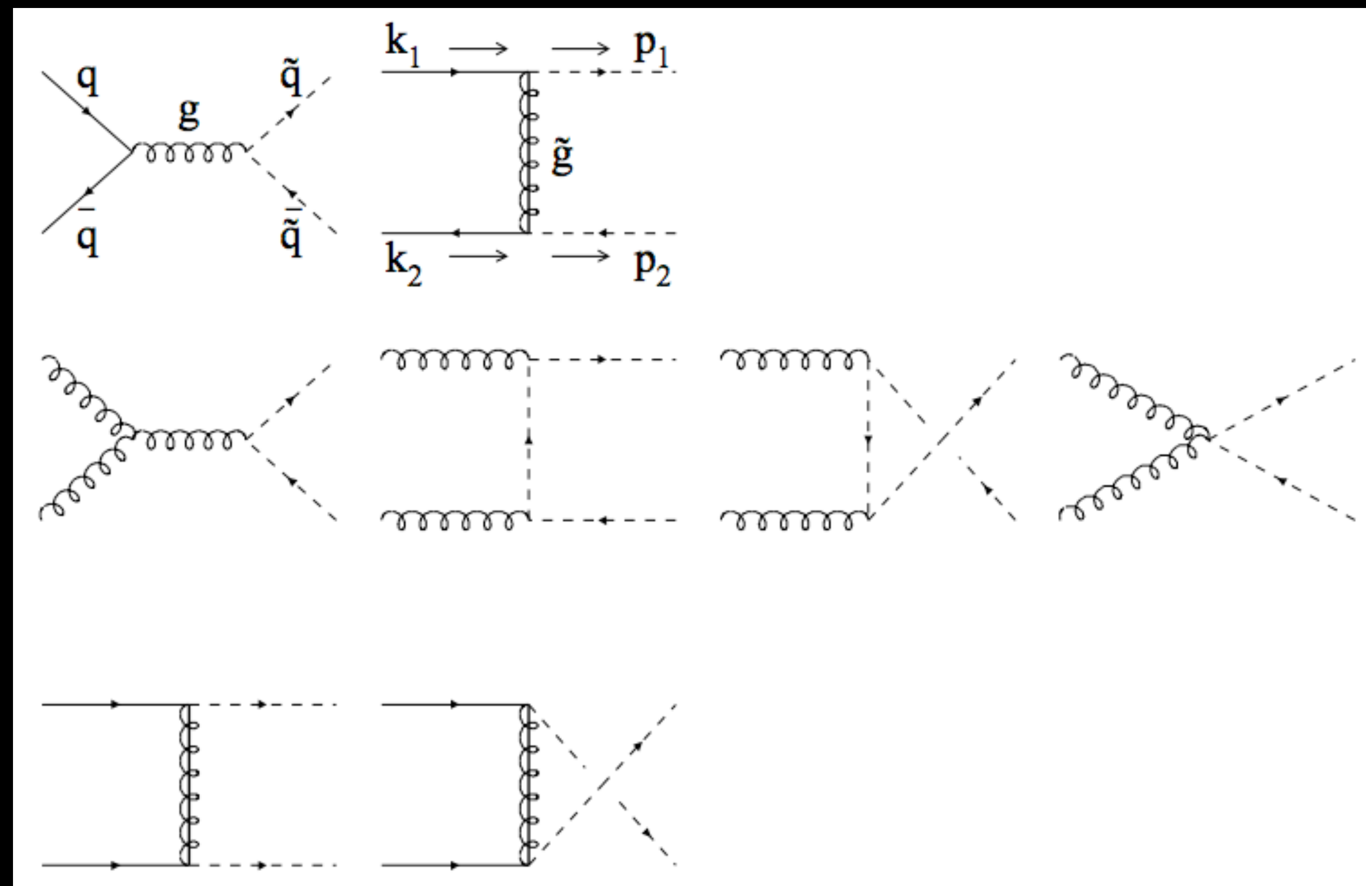

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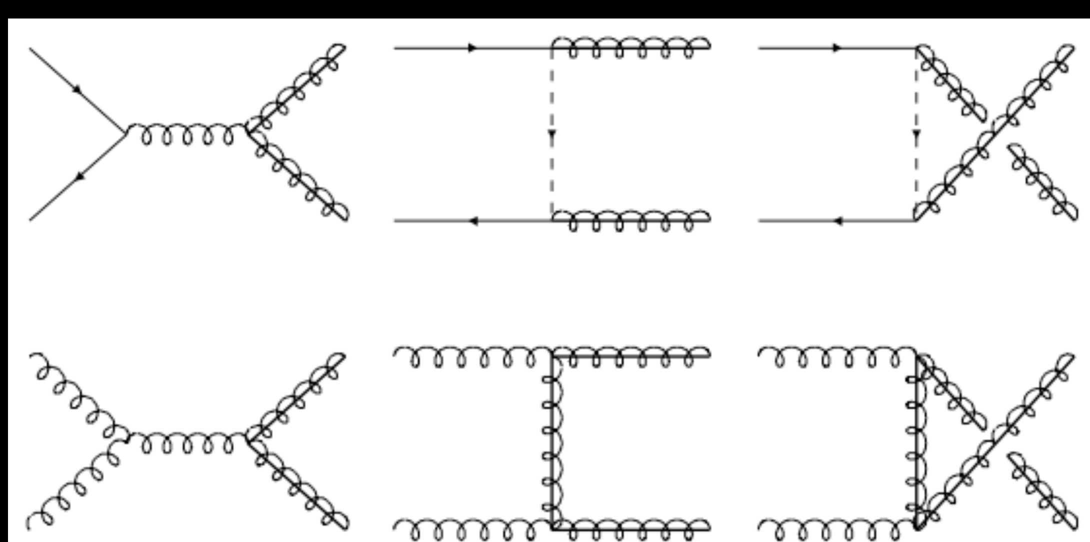

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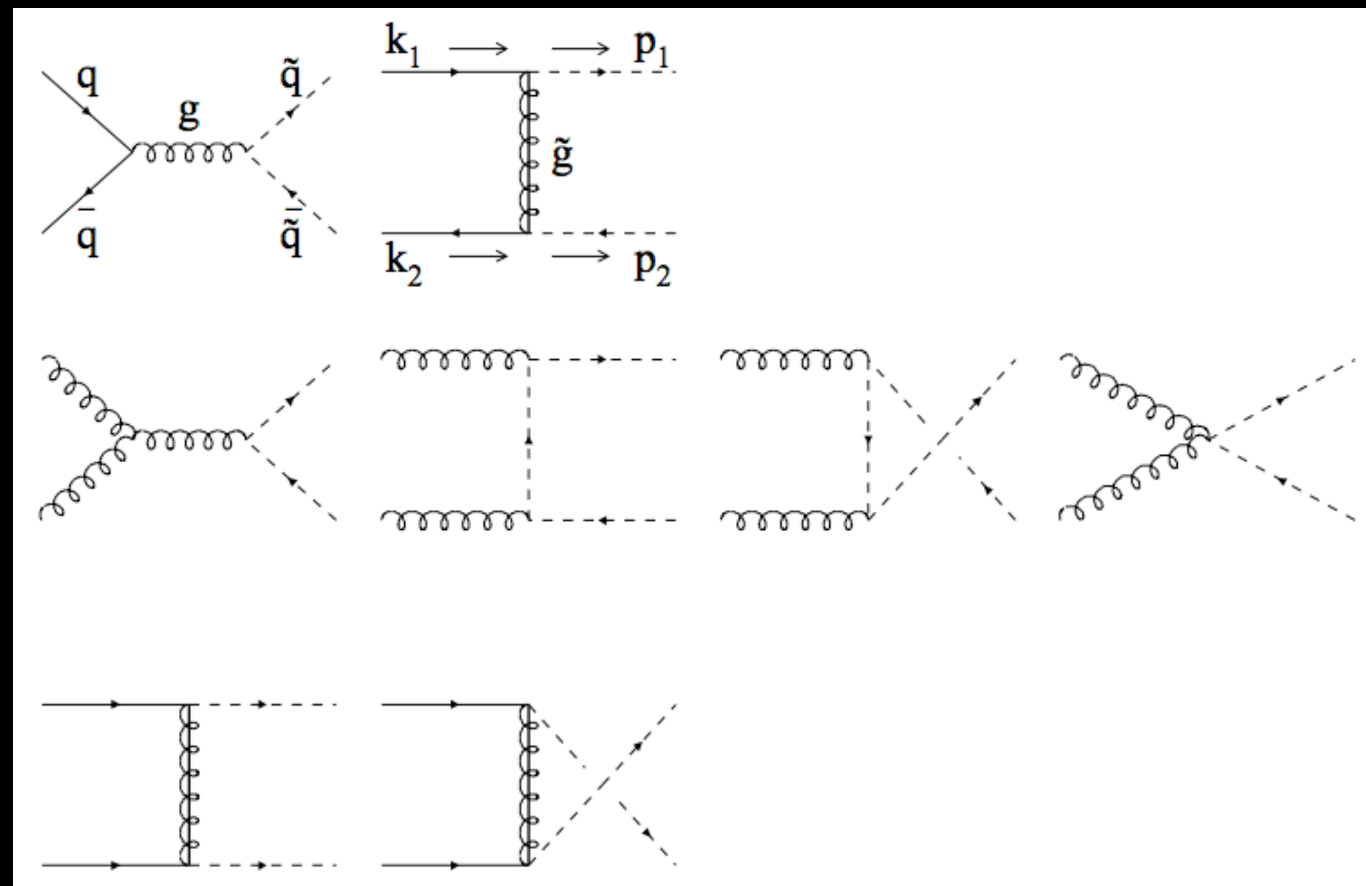

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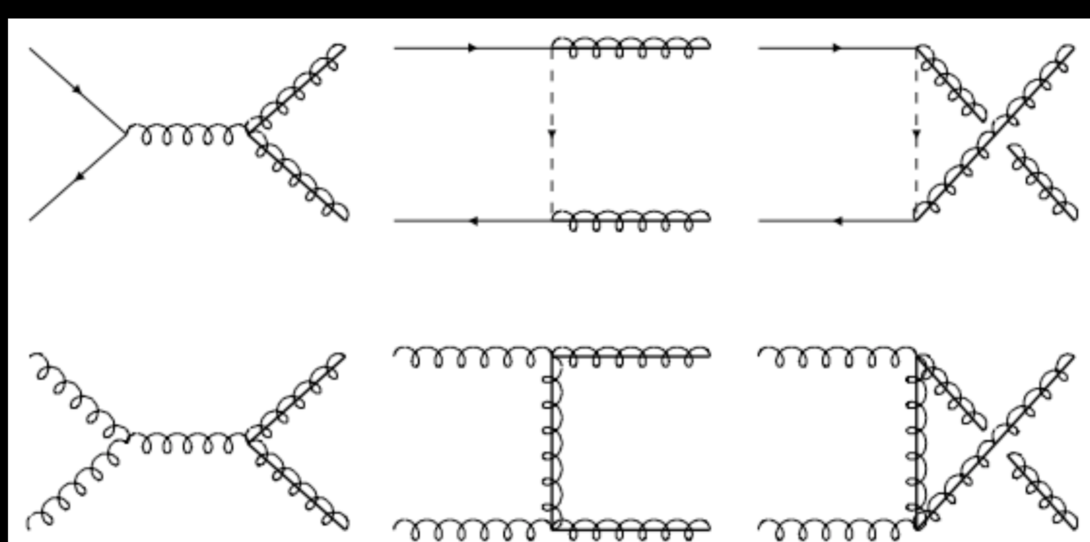
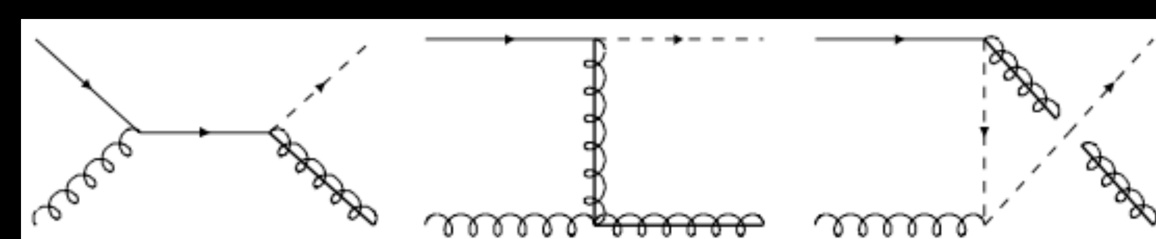


Squark-Gluino



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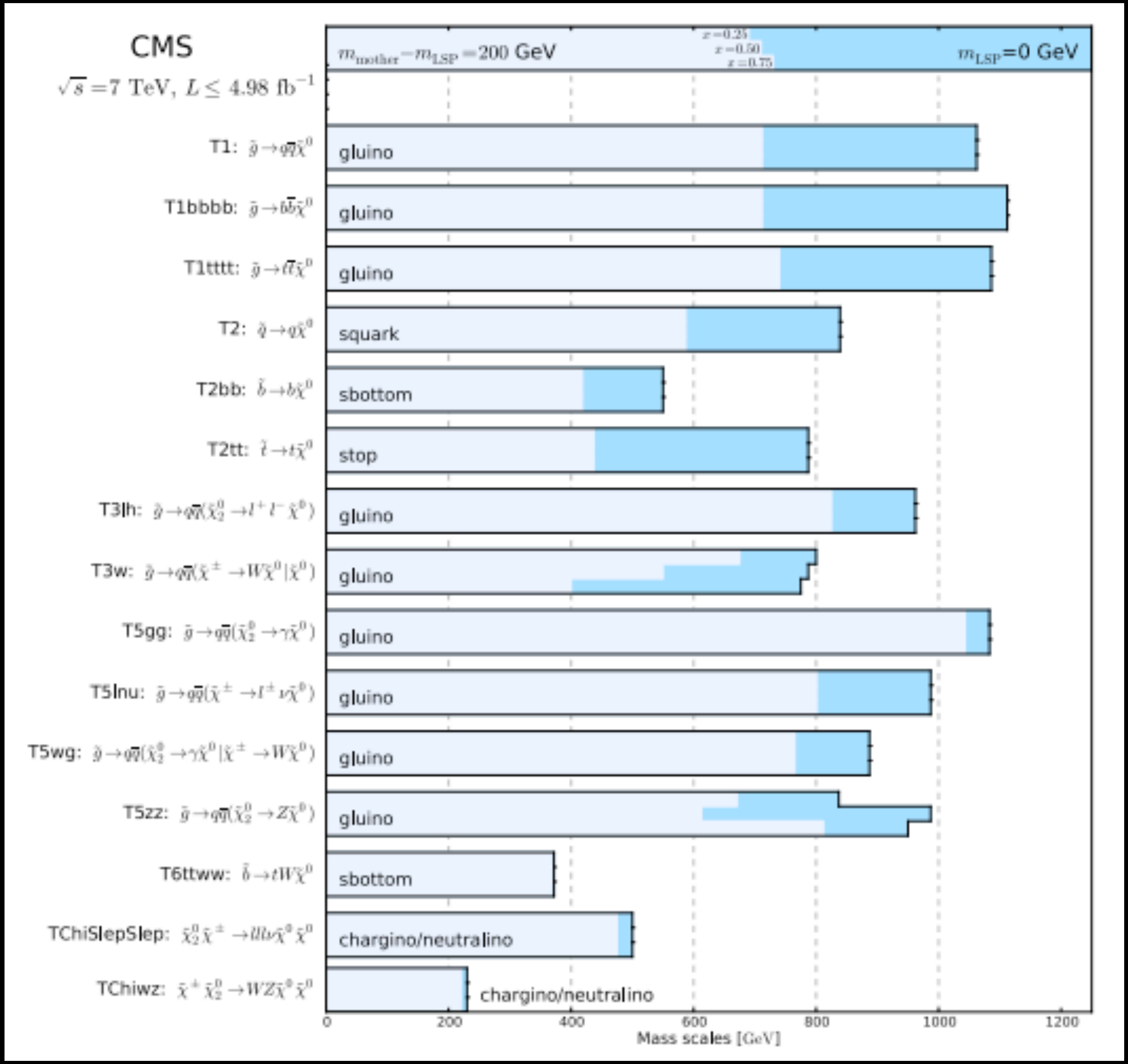

arXiv:1301.2175

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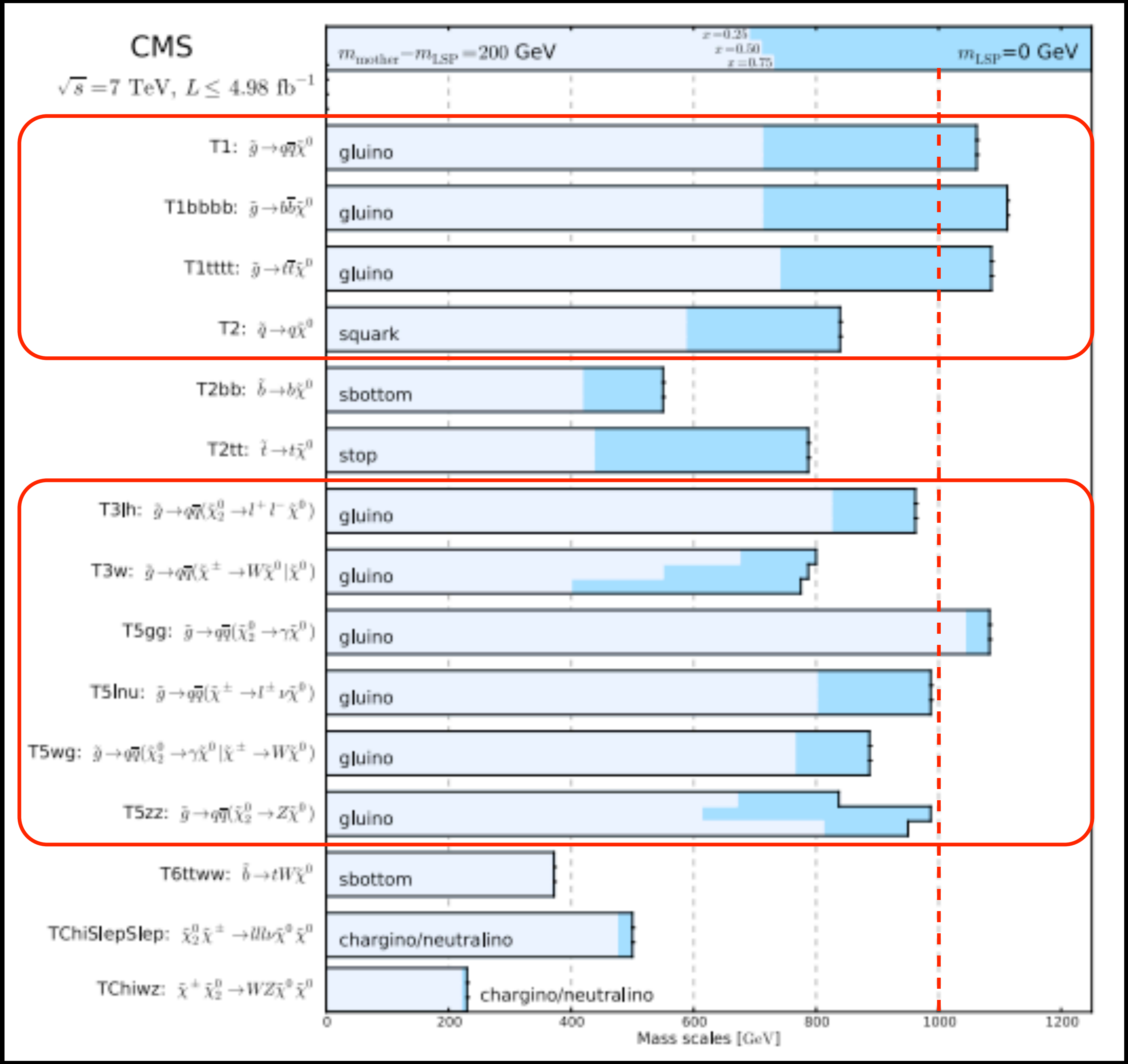

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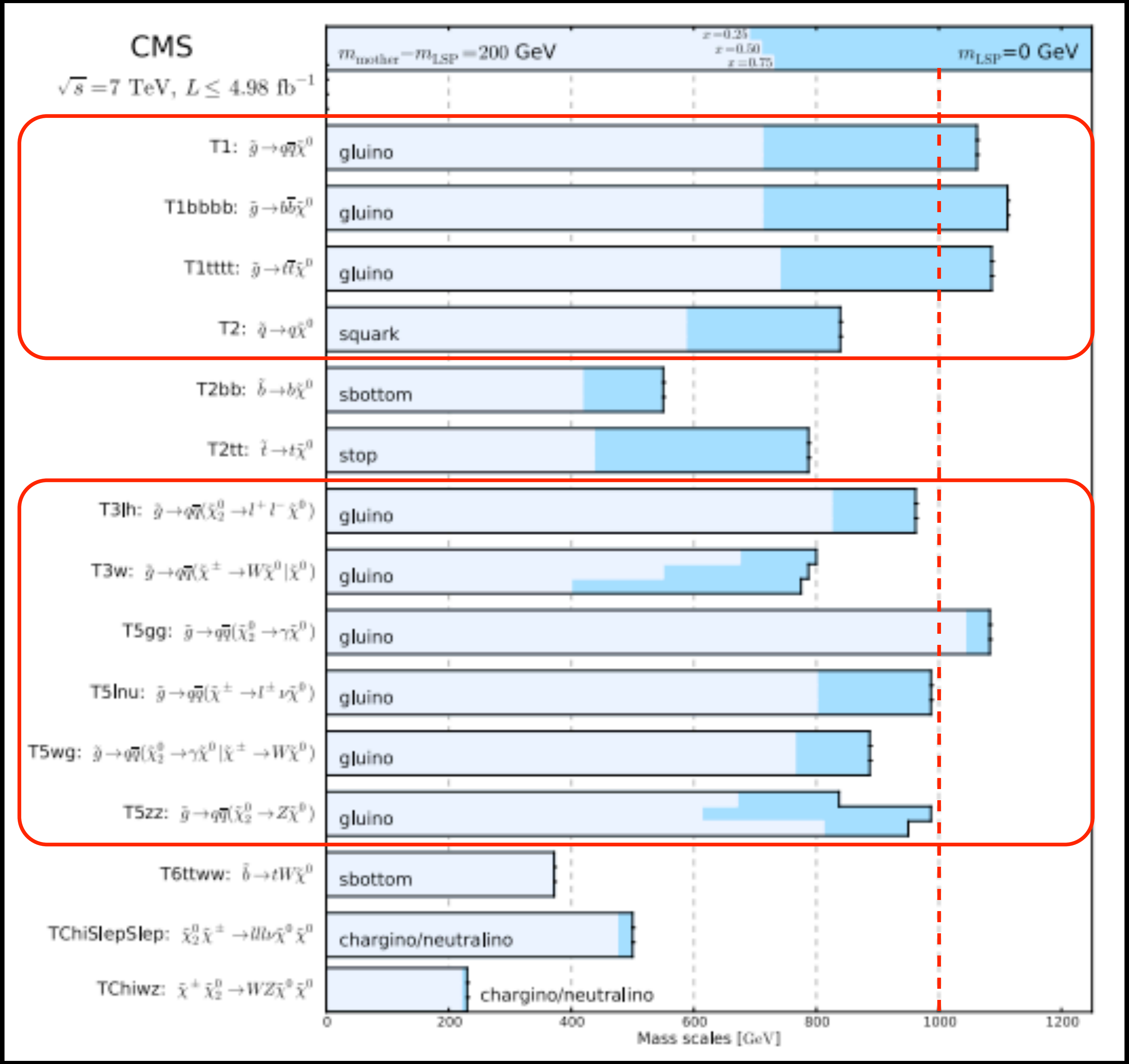

limits
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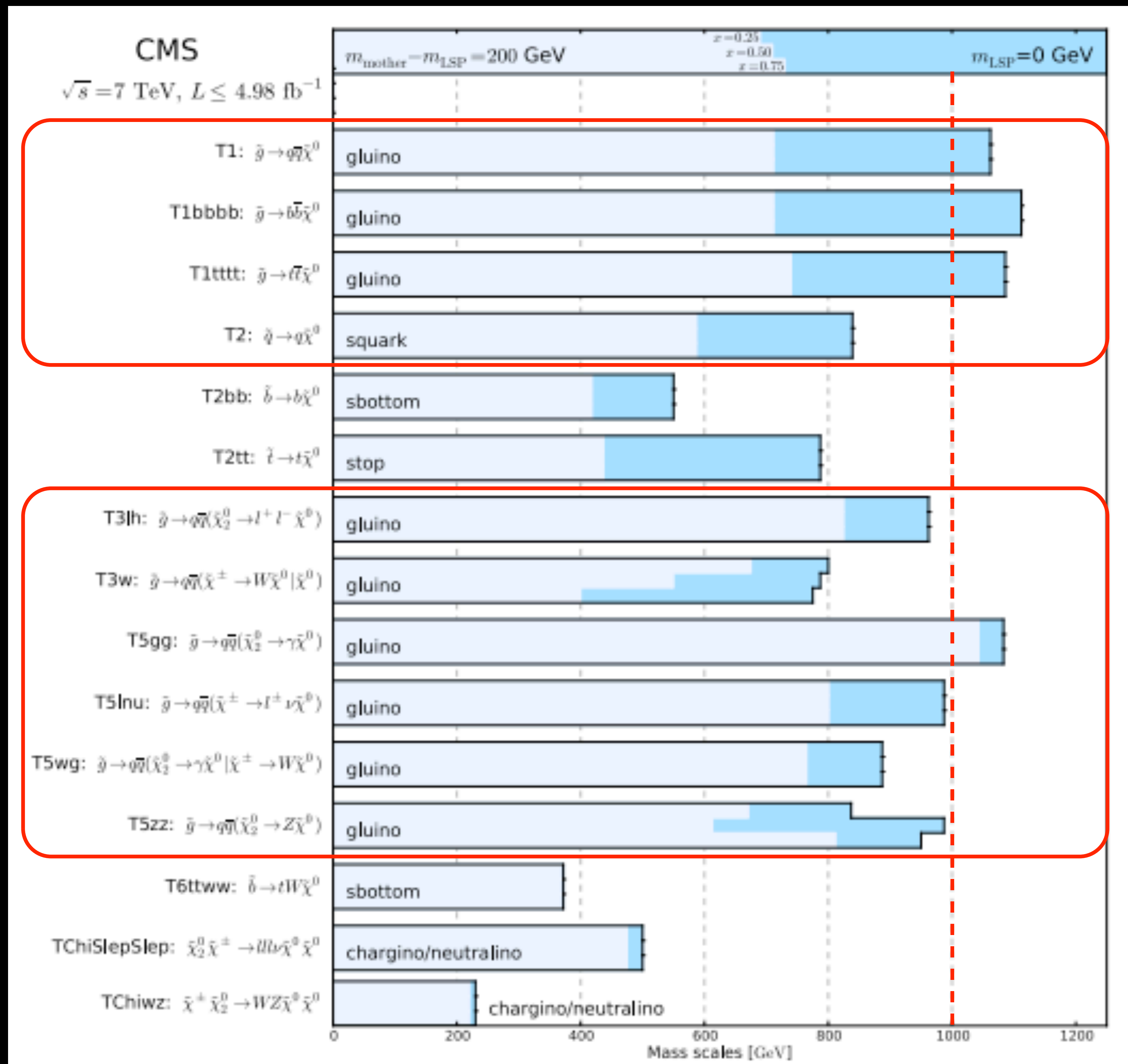

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However, simple models, often degenerate sparticle masses

125 GeV Higgs from MSSM?

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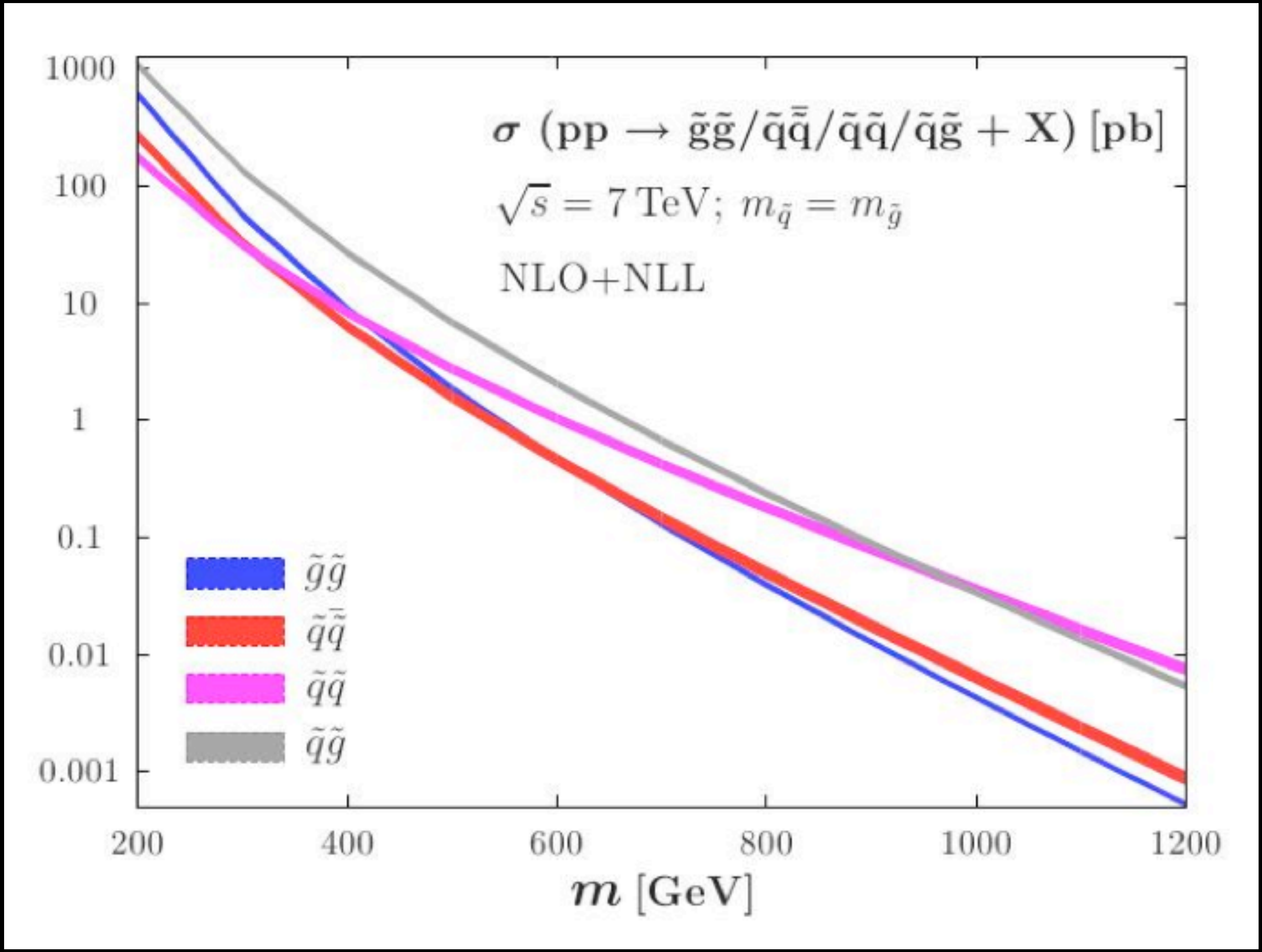
  - $m_h \leq \sim 135$ GeV
- MSSM still consistent with 125 GeV Higgs-like particle found at LHC

SUSY Production



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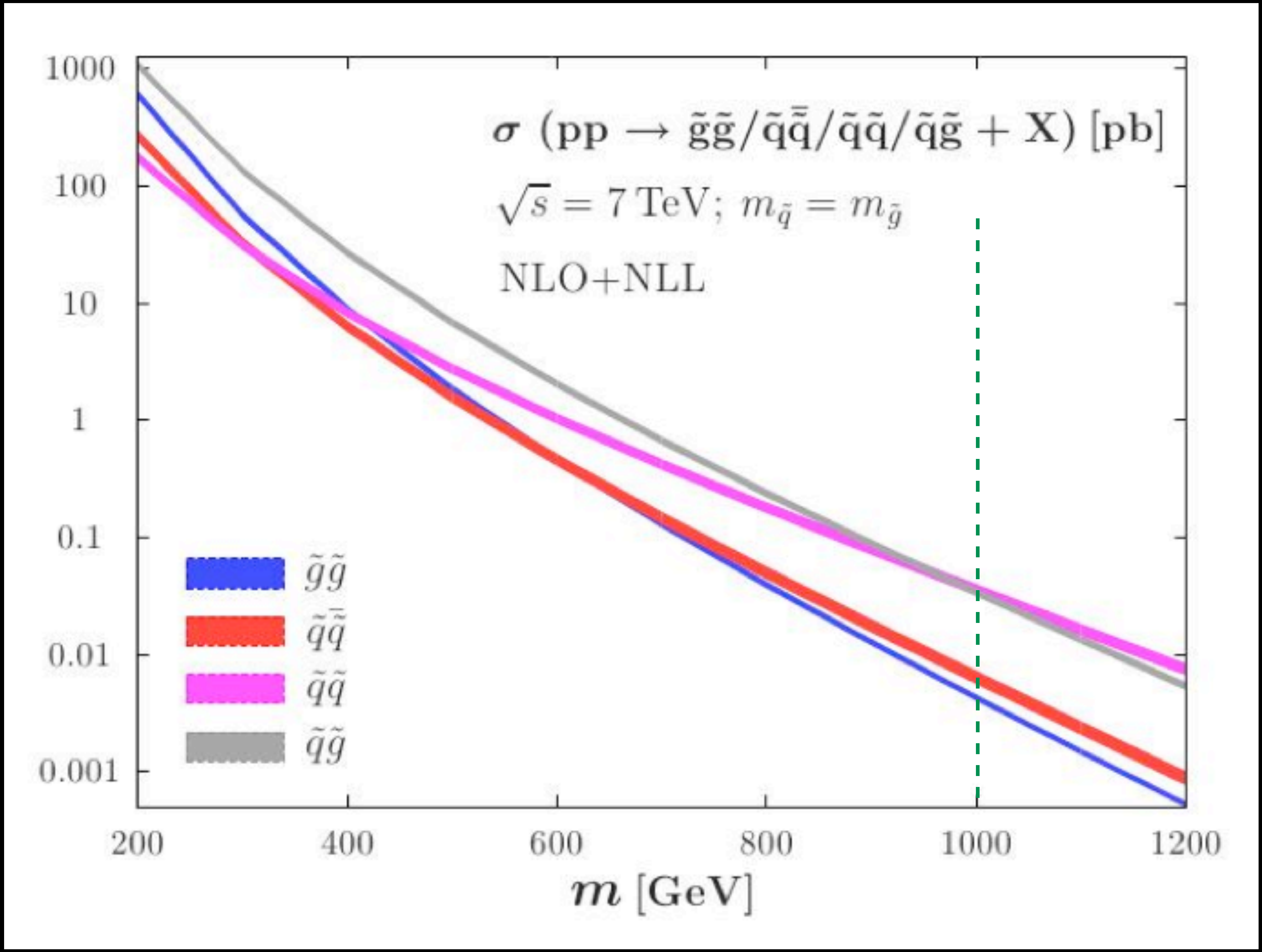

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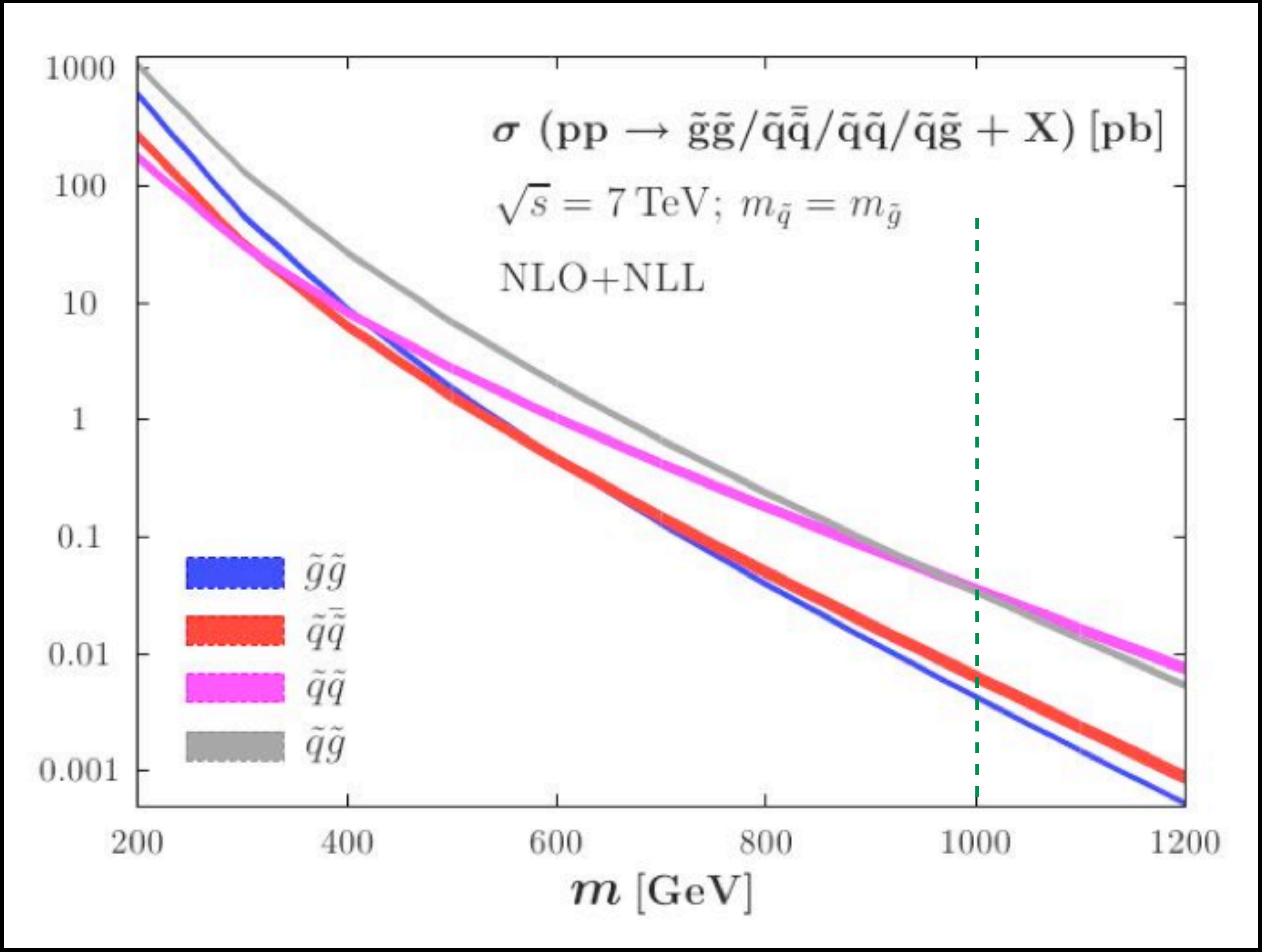

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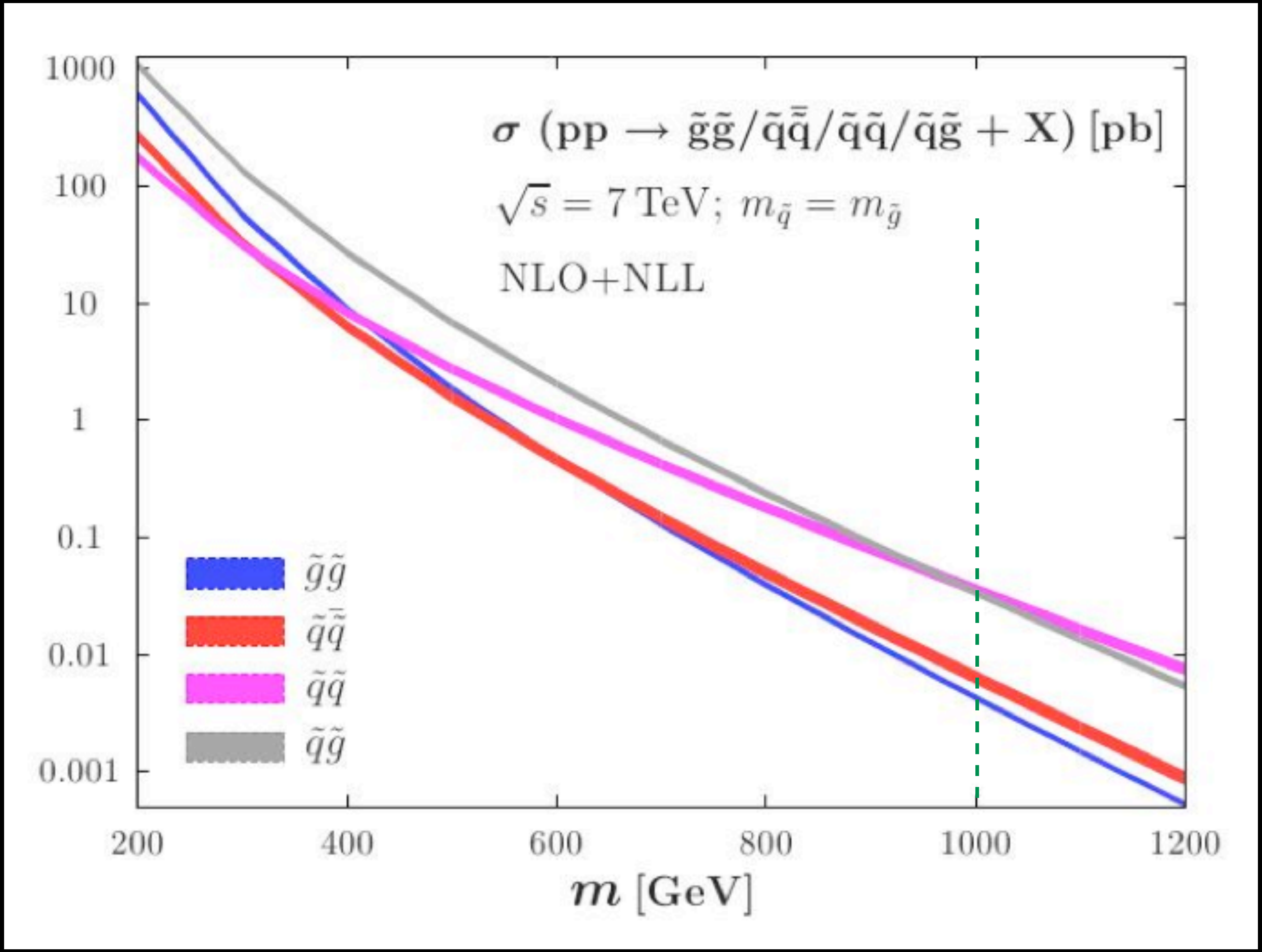

$\tilde{q}\tilde{q}$ & $\tilde{g}\tilde{g}$ production are dominant processes at m ~ 1 TeV

focus on $\tilde{q}\tilde{q}$

Higher Orders

- Quantitative predictive power begins at NLO
  improvement of normalization
  reduction of uncertainties
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- Acceptances derived from calculation and simulation

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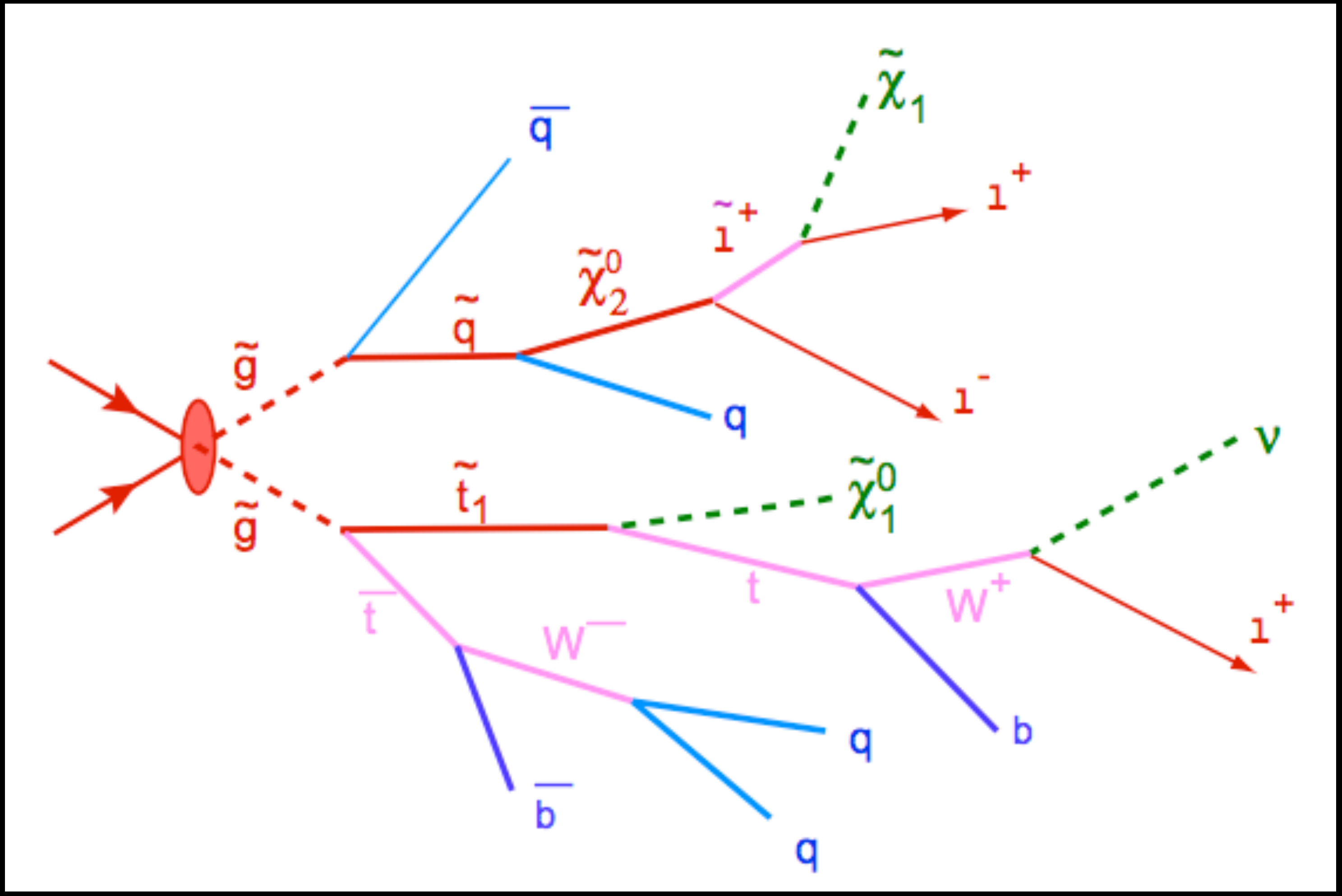
    - can be model dependent
- Excess
  - discriminate between BSM models
  - investigate model parameters, measure properties
    - particle masses, widths, couplings
    - quantum numbers (spin, charges, etc.)

Precise Predictions for BSM?

BSM physics can be quite messy!



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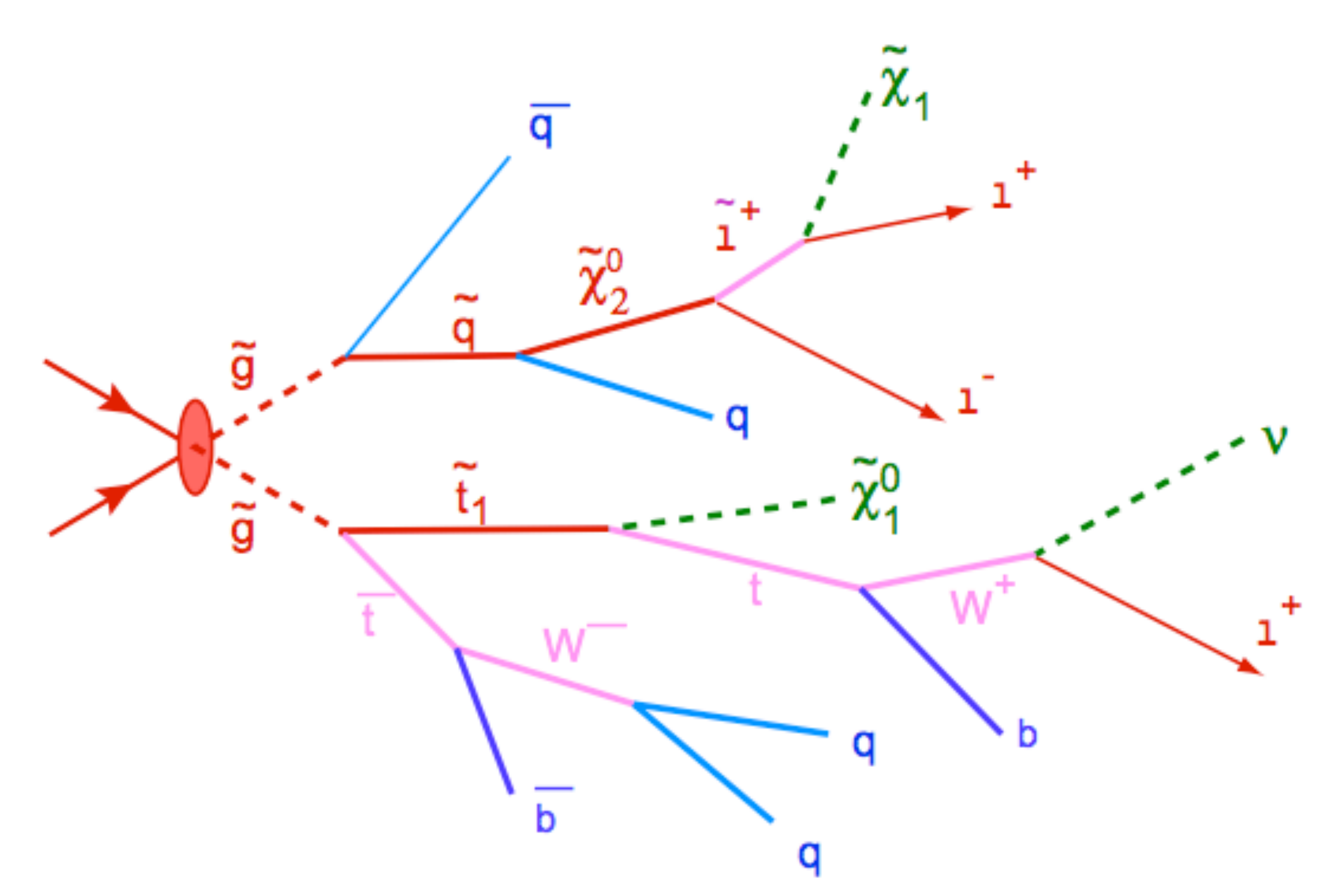


Need best predictions to untangle these mysteries!

Current Status of Calculations

- Leading order since the early 80's

Kane & Leveille '82
Harrison & Smith '83
Reya & Roy '85
Dawson, Eichten, Quigg '85
Baer & Tata '85

- NLO QCD
  - Prospino: public code — Beenakker, Höpker, Krämer, Plehn, Spira, Zerwas
    - squark masses assumed to be degenerate
    - various subchannels not treated individually
    - differential K-factors assumed to be flat
- Threshold summation — Bozzi, Fuks, Klasen; Kulesza, Motyka; Langenfeld, Moch; Beneke, Falgari, Schwinn; Beenakker, Brensing, Krämer, Kulesza, Laenen, Niessen
- Electroweak Corrections — Hollik, Kollar, Mirabella, Trenkel; Bornhauser, Drees, Dreiner, Kim; Beccaria, Macorini, Panizzi, Renard, Verzegnassi

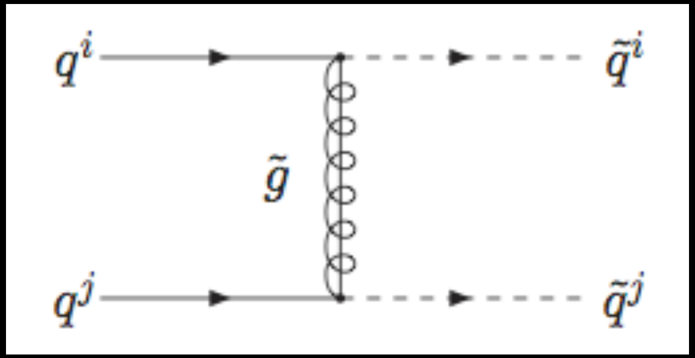
Squark Pair Production

- Consider squark pair production
  - doesn't include $\tilde{q}\tilde{q}^*$
- Goals
  - make no assumptions on mass spectrum
  - embed squark pair production in a fully differential partonic Monte Carlo

* Note: similar calculation by Hollik, Lindert & Pagani, '12

Squark Pair Production

- Tree level



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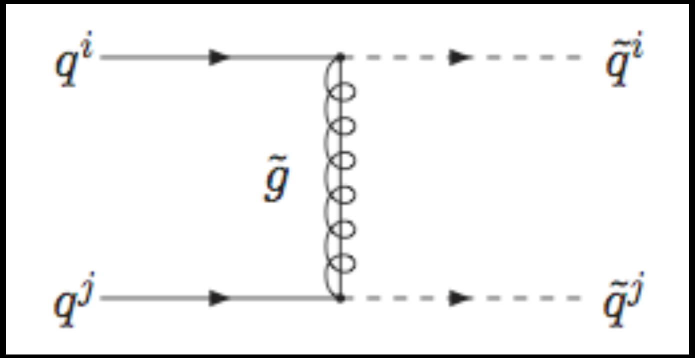

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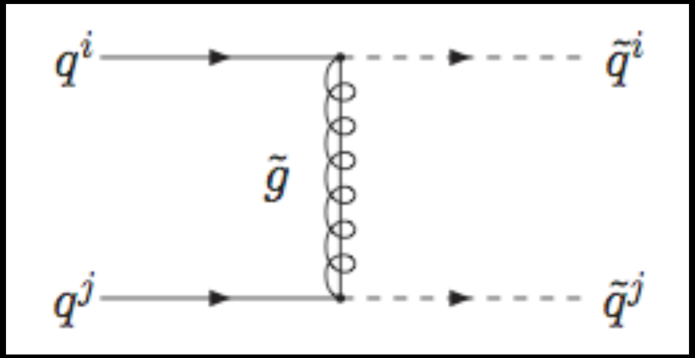
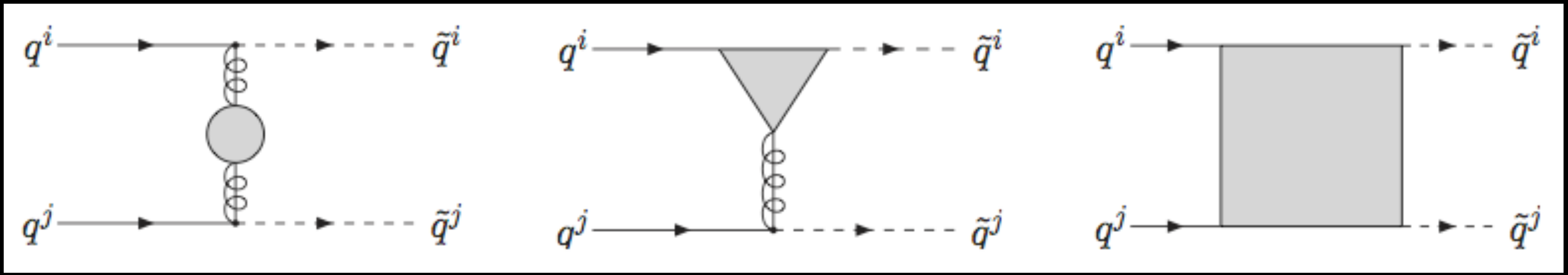


- Virtual Corrections

u-channel processes not shown



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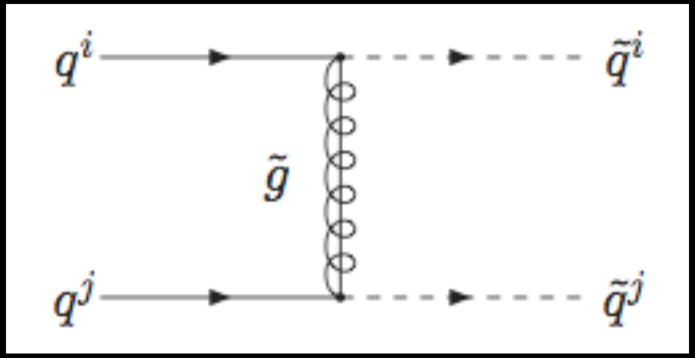

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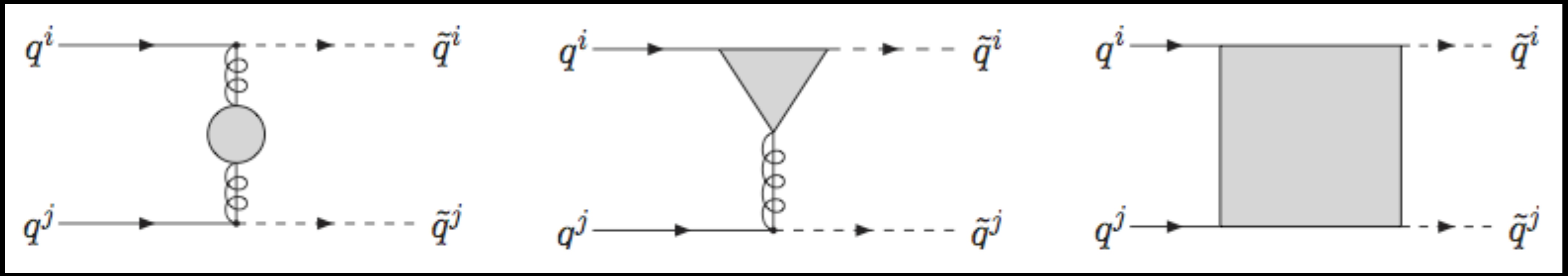

  - gluino propagator, vertex, & box corrections
  - quarks, gluons, squarks, & gluinos propagating in loops

Virtual Corrections

- Virtual corrections performed using FeynArts, FormCalc, and LoopTools
  - using dimensional regularization - $d=4-2\varepsilon$

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- Virtual corrections performed using FeynArts, FormCalc, and LoopTools
  - using dimensional regularization - $d=4-2\varepsilon$
- Dim. reg. creates a mismatch in the degrees of freedom in gluinos (2) and gluons (d-2)
  - breaks supersymmetry
  - mismatch manifests itself in the difference between g_s and $\hat{g}_s$ at one-loop level
  - finite shift is added to restore this supersymmetric relation

$$\hat{g}_s = g_s(1 + \frac{\alpha_s}{3\pi})$$

Renormalization

- Virtual corrections, loop integrals, result in singularities
  - UV and IR divergences

Renormalization

- Virtual corrections, loop integrals, result in singularities
  - UV and IR divergences
- UV poles cancel against redefinitions of particle fields and masses - renormalization
  - fields and masses renormalized in on-shell scheme
  - strong coupling renormalized in $\overline{\text{MS}}$ scheme
    - however, heavy particles are decoupled to match experimental value of α_S

$$\delta g_s = \frac{\alpha_s}{8\pi}\left(\beta_0\left(-\Delta + \log\frac{Q^2}{\mu^2}\right) - 2\log\frac{m_{\tilde{g}}^2}{Q^2} - \frac{2}{3}\log\frac{m_t^2}{Q^2} - \sum_{i=1,12}\frac{1}{6}\log\frac{m_{\tilde{q}_j}^2}{Q^2}\right)$$

Real Radiation

- IR virtual poles cancel against soft and collinear emission in real radiation

- MadGraph used for generation of real radiation

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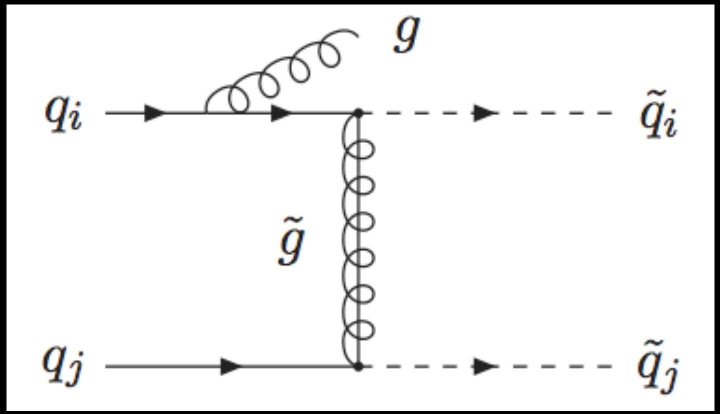
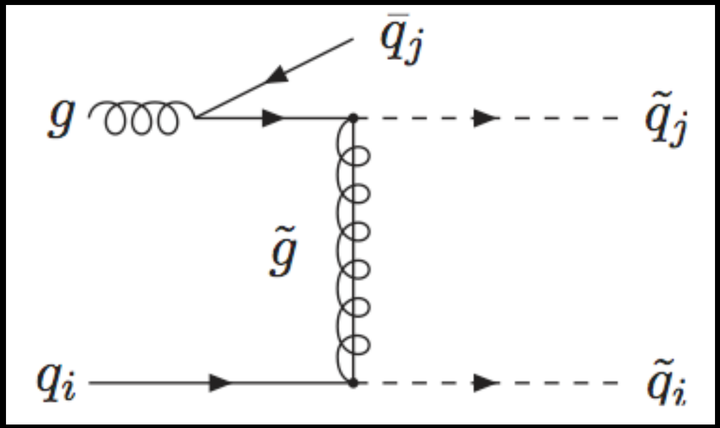


soft & collinear



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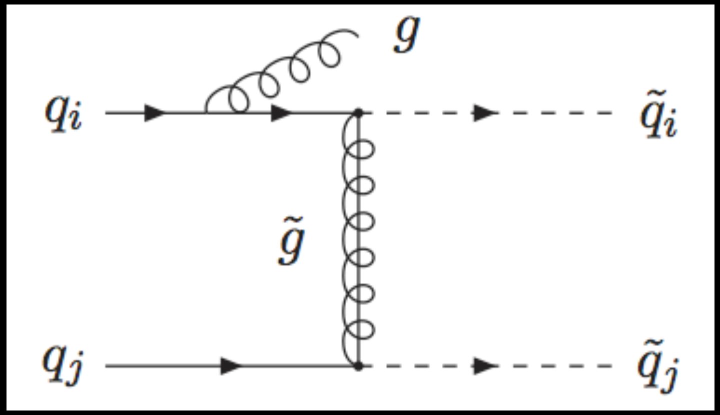

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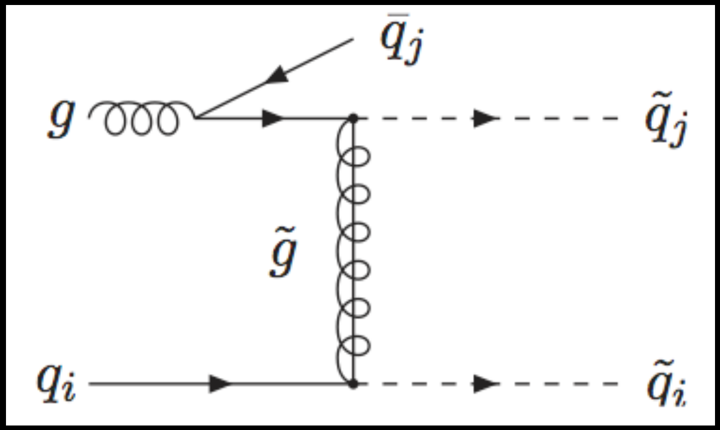

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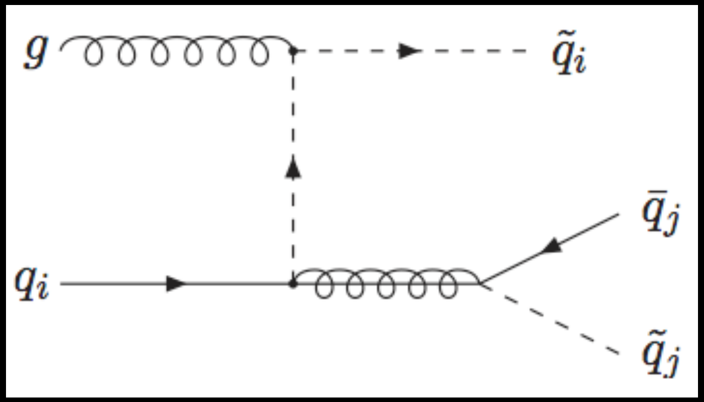
$$\sigma_{NLO} = \int d\Phi_2 d\sigma_V + \int d\Phi_3 d\sigma_R = \int d\Phi_2 \left[d\sigma_V + \int d\Phi_1 d\sigma_A \right] + \int d\Phi_3 \left[d\sigma_R - d\sigma_A \right]$$

On-Shell Subtraction

- Problems occur when intermediate gluino goes on-shell in quark-gluon initial state real emission process



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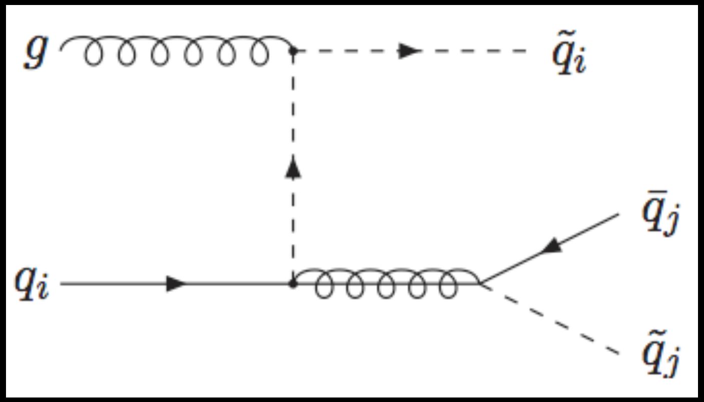

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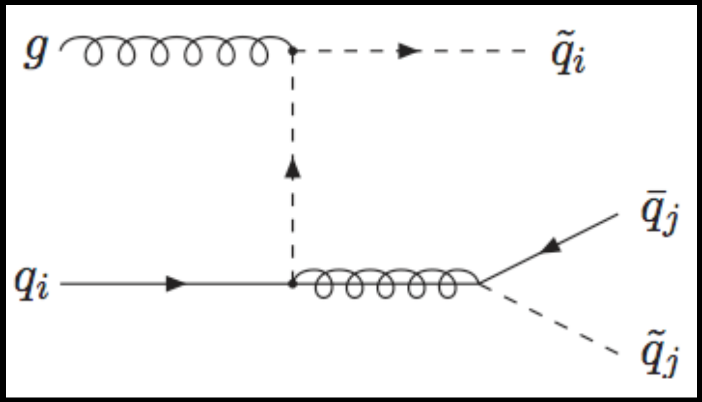

  - occurs when, $m_{\tilde{q}} < m_{\tilde{g}}$, regulated by inserting $\Gamma_{\tilde{g}}$

- In qg→q̃q̃q, separate diagrams into M_{res} & M_{non}

$$|M_{gq}|^2 = |M_{res}|^2 + 2\text{Re}(M^*_{non} M_{res}) + |M_{non}|^2$$

- When on-shell, resonant piece equivalent to squark-gluino Born level process multiplied by $\Gamma(\tilde{g}\rightarrow q\tilde{q}) / \Gamma_{\tilde{g}}$

On-Shell Subtraction

- Subtraction Methods
  - diagram removal I (DR-I): set $M_{res} = 0$
  - diagram removal II (DR-II): set $|M_{res}|^2 = 0$, (keep interference terms) Hollik, Lindert, & Pagani, '12
  - diagram subtraction (DS): construct local 'counterterm' to substract on-shell contributions for every phase space point

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Hollik, Lindert, & Pagani, '12

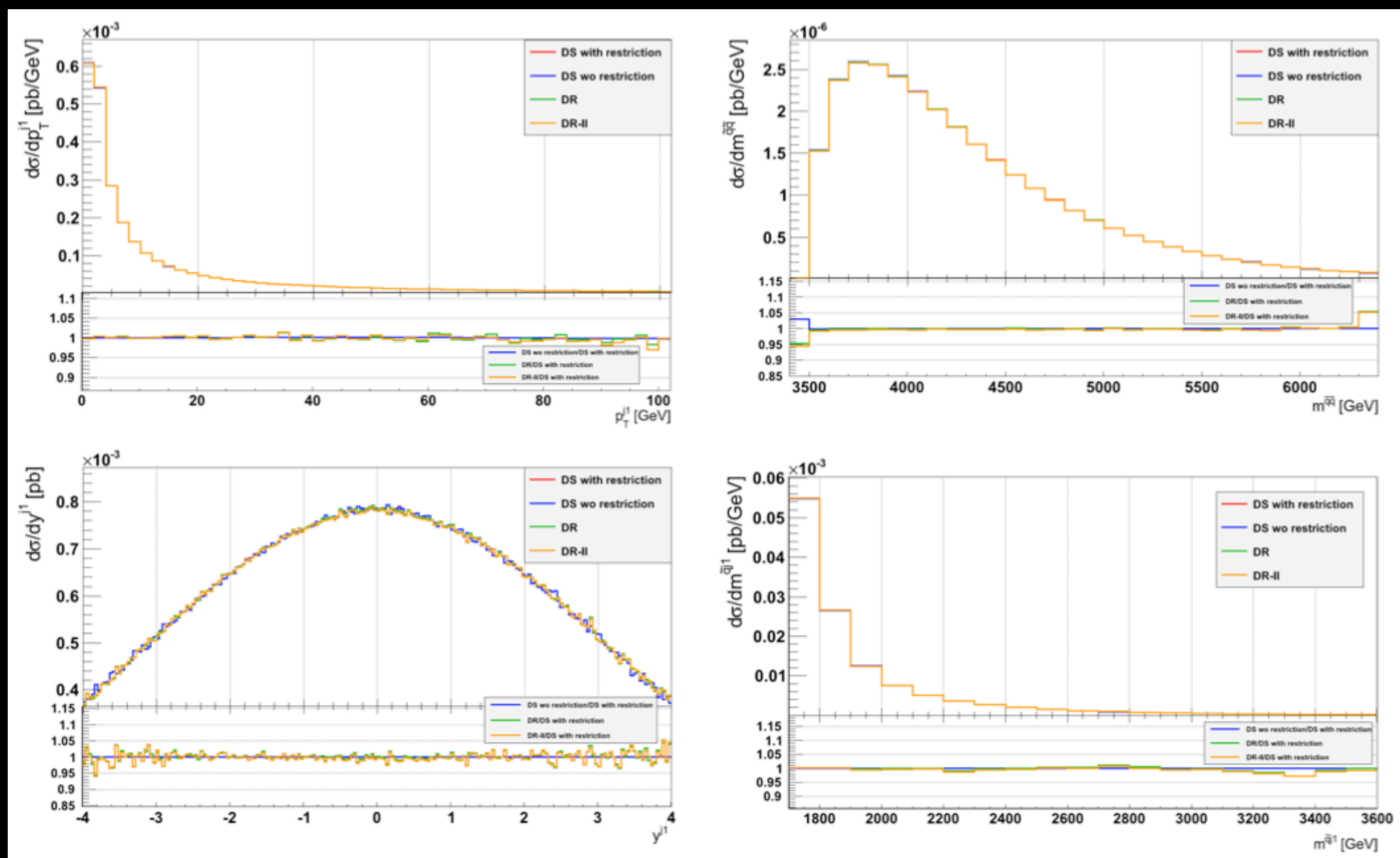
- DR-I & DR-II break gauge invariance → arbitrary results
- Requirements for 'counterterm'
  - match exactly the contribution of the resonant terms when $(p_{\tilde{q}} + p_q)^2 = m_{\tilde{g}}^2$
  - fall off quickly when away from resonant region in phase space - Breit-Wigner
  - preserves gauge invariance as $\Gamma \rightarrow 0$

$$d\sigma_{\text{sub}} = \Theta(\sqrt{\hat{s}} - m_{\tilde{g}} - m_{\tilde{q}_i}) \cdot \Theta(m_{\tilde{g}} - m_{\tilde{q}_j}) \cdot |M_r(\tilde{\Phi}_3)|^2 \cdot \frac{m_{\tilde{g}}^2 \Gamma_{\tilde{g}}^2}{(m_{\bar{q}_j \bar{q}_j}^2 - m_{\tilde{g}}^2)^2 + m_{\tilde{g}}^2 \Gamma_{\tilde{g}}^2} \cdot d\tilde{\Phi}_3$$

On-Shell Subtraction

NLO distributions - $\tilde{u}_L\tilde{u}_L$ production

$m_{\tilde{u}_L}$	$m_{\tilde{u}_R}$	$m_{\tilde{d}_L}$	$m_{\tilde{d}_R}$	$m_{\tilde{g}}$
1746.63	1684.31	1748.25	1677.82	1840.58



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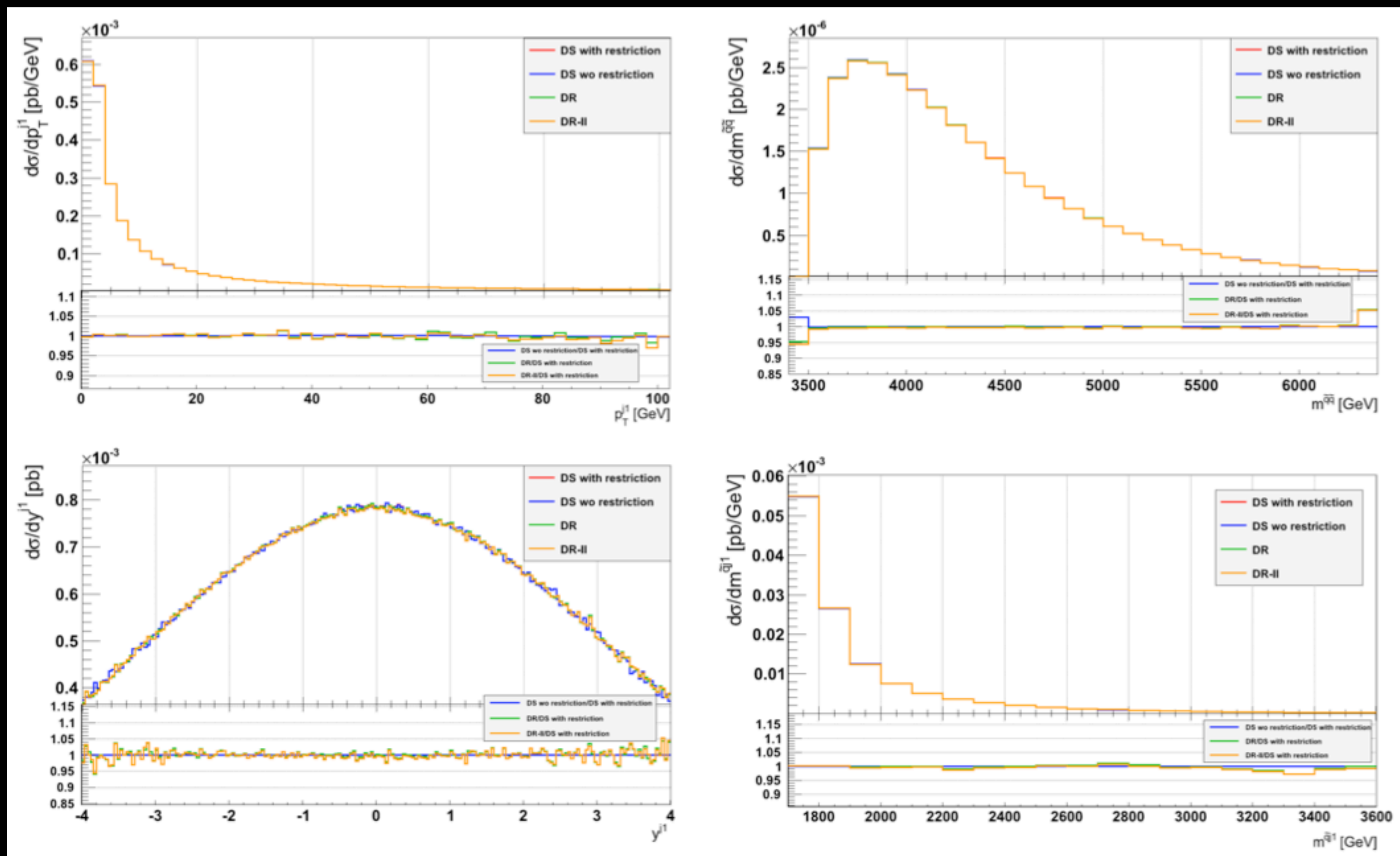

sub-percent level effect

Phenomenology

$$K = \frac{\sigma_{NLO}}{\sigma_{LO}}$$

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K-Factor	1,10	1,17	1,21	1,22	1,19	1,30	1,16

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- 20% variation in *K*-factors
- Independent treatment is reasonable

Phenomenology

Consider

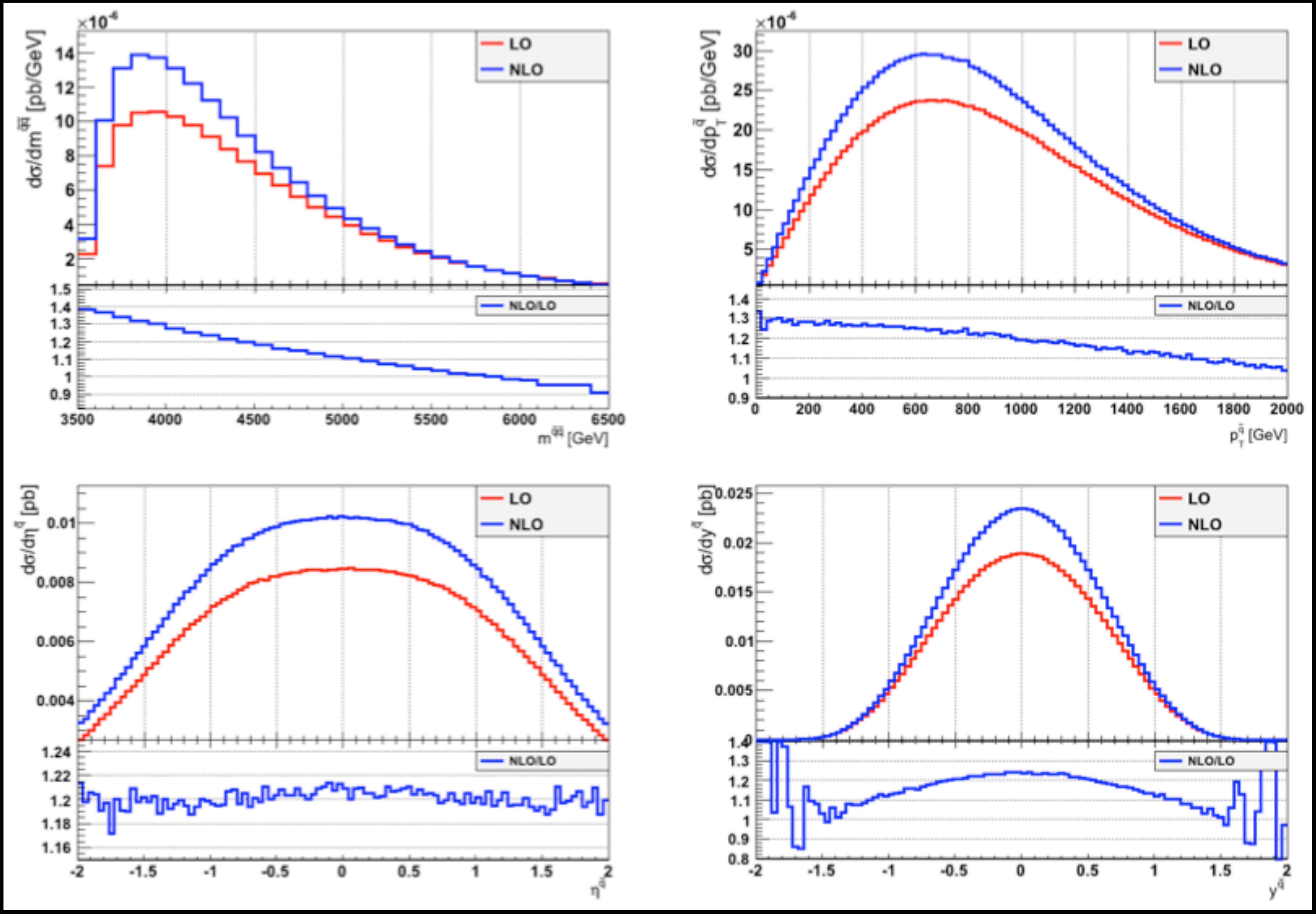
$m_{\tilde{u}_L}$	$m_{\tilde{u}_R}$	$m_{\tilde{d}_L}$	$m_{\tilde{d}_R}$	$m_{\tilde{g}}$
1799.53GeV	1769.21GeV	1801.08GeV	1756.40GeV	1602.91GeV

First two squark generations are degenerate

- $\sqrt{s}$ = 14 TeV
- CT10nlo & CTEQ6L1 PDFs
- $\mu_R = \mu_F = m_{squark,avg}$
- Cross section includes all combination of flavor/chiralities and their charge conjugated processes

LO	NLO	K-factor
14.491(2)fb	17.415(2)fb	1.202

Phenomenology



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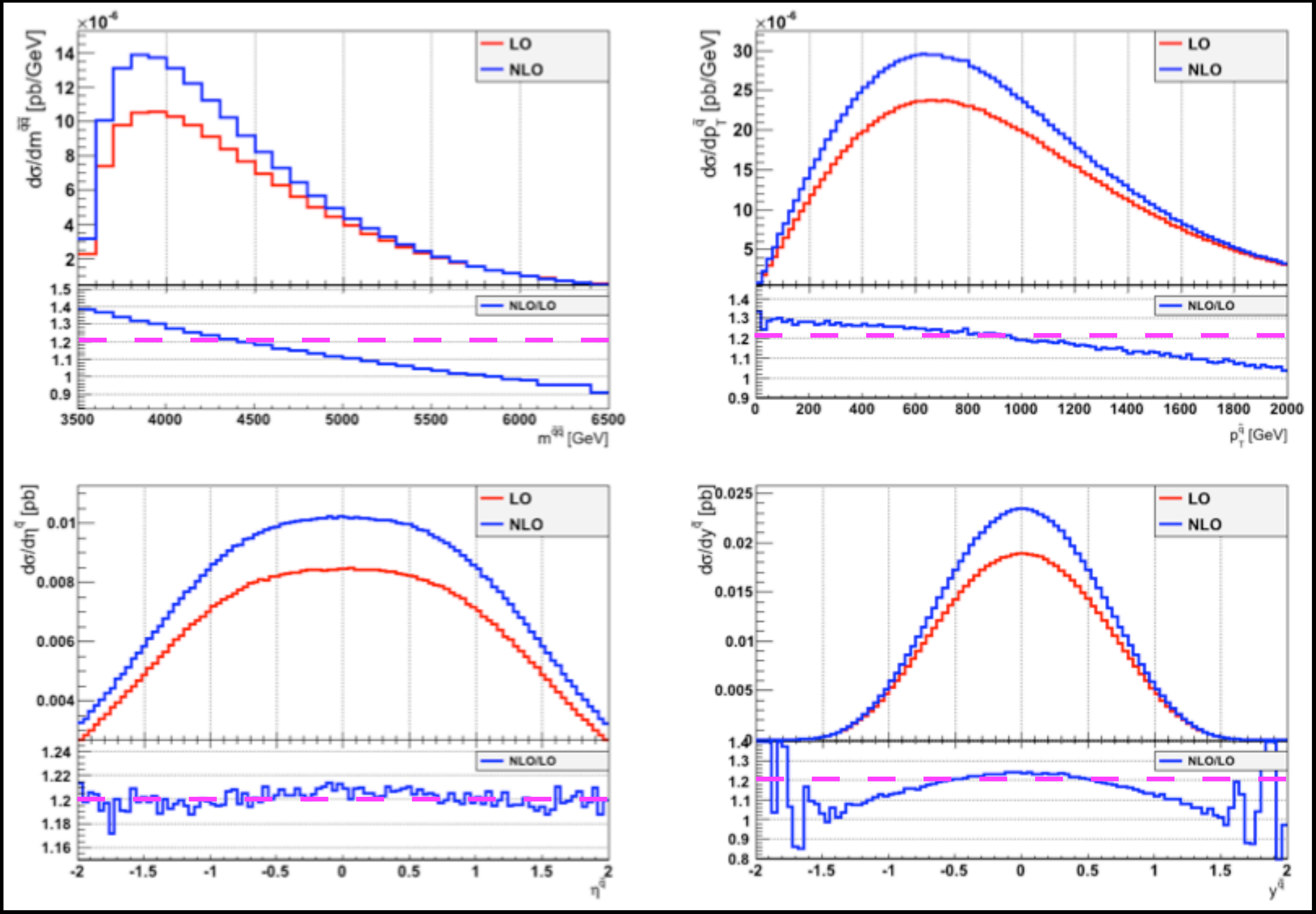

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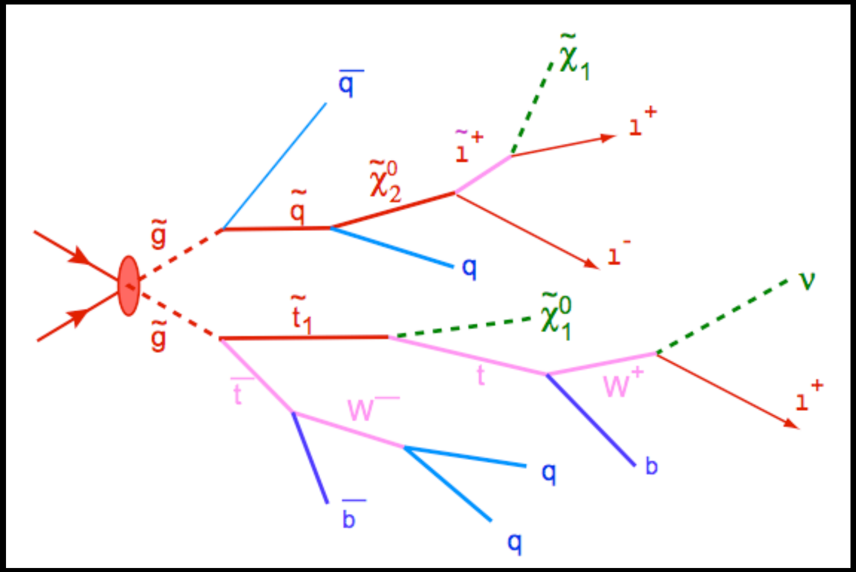
  - properly care for intermediate on-shell gluino
- Question: How would a flexible Monte Carlo like this affect LHC SUSY searches?

Can We Go Further?

- SUSY particles decay in the detector until they reach LSP

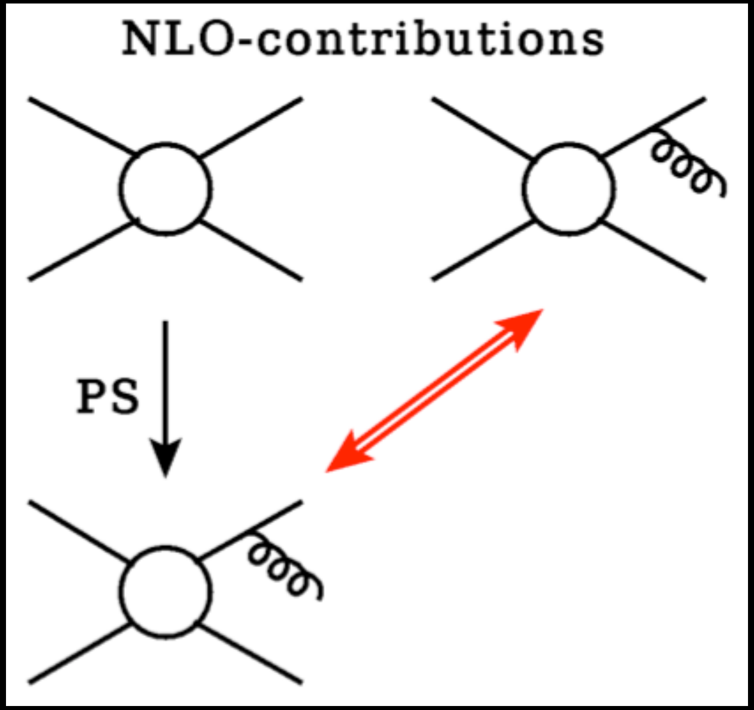


- 6 quarks
- 3 leptons
- missing energy
- LSP

- Particles charged under $SU(3)_C$ radiate gluons, eventually hadronize and form jets
- Showering, simulated using parton showers
- Producing colored SUSY pairs → parton shower?

Parton Shower

- Showering a LO process is straight forward
- More complicated with NLO
- Need to avoid double counting
- Two popular NLO-matching schemes
  - MC@NLO Frixione & Webber `02
  - POWHEG Nason `04



The POWHEG Method

- Basic Idea
  - generate the hardest emission first
  - shower with a p_T-veto → subsequent radiation guaranteed to be softer
  - works directly for p_T-ordered showers
    - for angular-ordered showers, need to introduce truncated shower
  - NLO accuracy for infrared-safe observables - not ‘sensitive’ to radiation
  - LL accuracy in soft/collinear region

The POWHEG Box

- Provides process independent ingredients for a POWHEG implementation of arbitrary processes
  - Automated FKS subtraction scheme
  - generation of radiation phase space
  - hardest radiation according to POWHEG-Sudakov
  - NLO distributions as by-product
  - LHE-output: unweighted events, can be passed to parton shower
- User needs to implement process specific parts
  - flavor structures for Real and Born channels
  - Born phase space
  - Born, Virtual, and Real amplitudes squared
- First process implemented with strongly interacting BSM particles
  - required small changes to the main code

Implementation in POWHEG

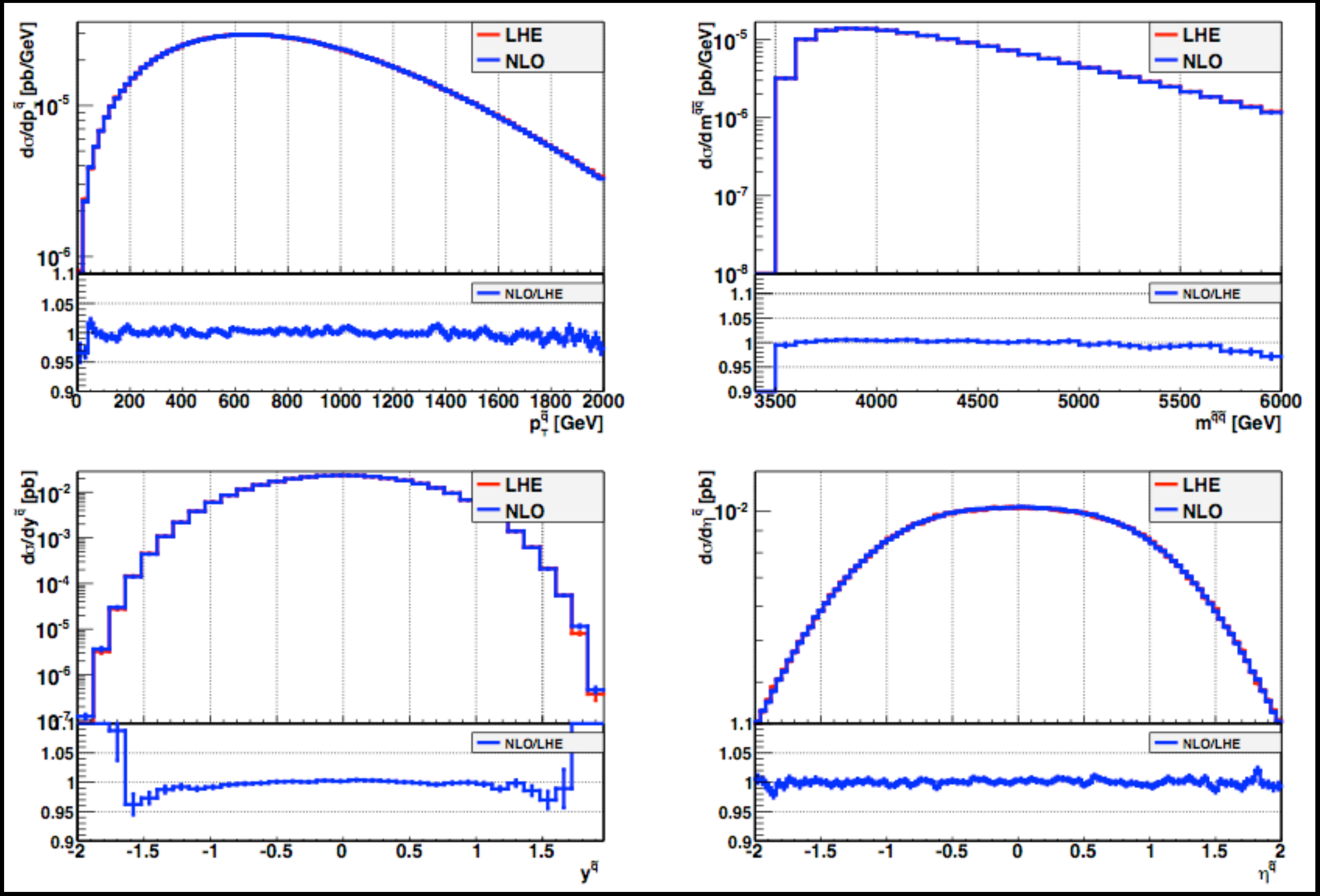
As before consider

$m_{\tilde{u}_L}$	$m_{\tilde{u}_R}$	$m_{\tilde{d}_L}$	$m_{\tilde{d}_R}$	$m_{\tilde{g}}$
1799.53GeV	1769.21GeV	1801.08GeV	1756.40GeV	1602.91GeV

First two squark generations are degenerate

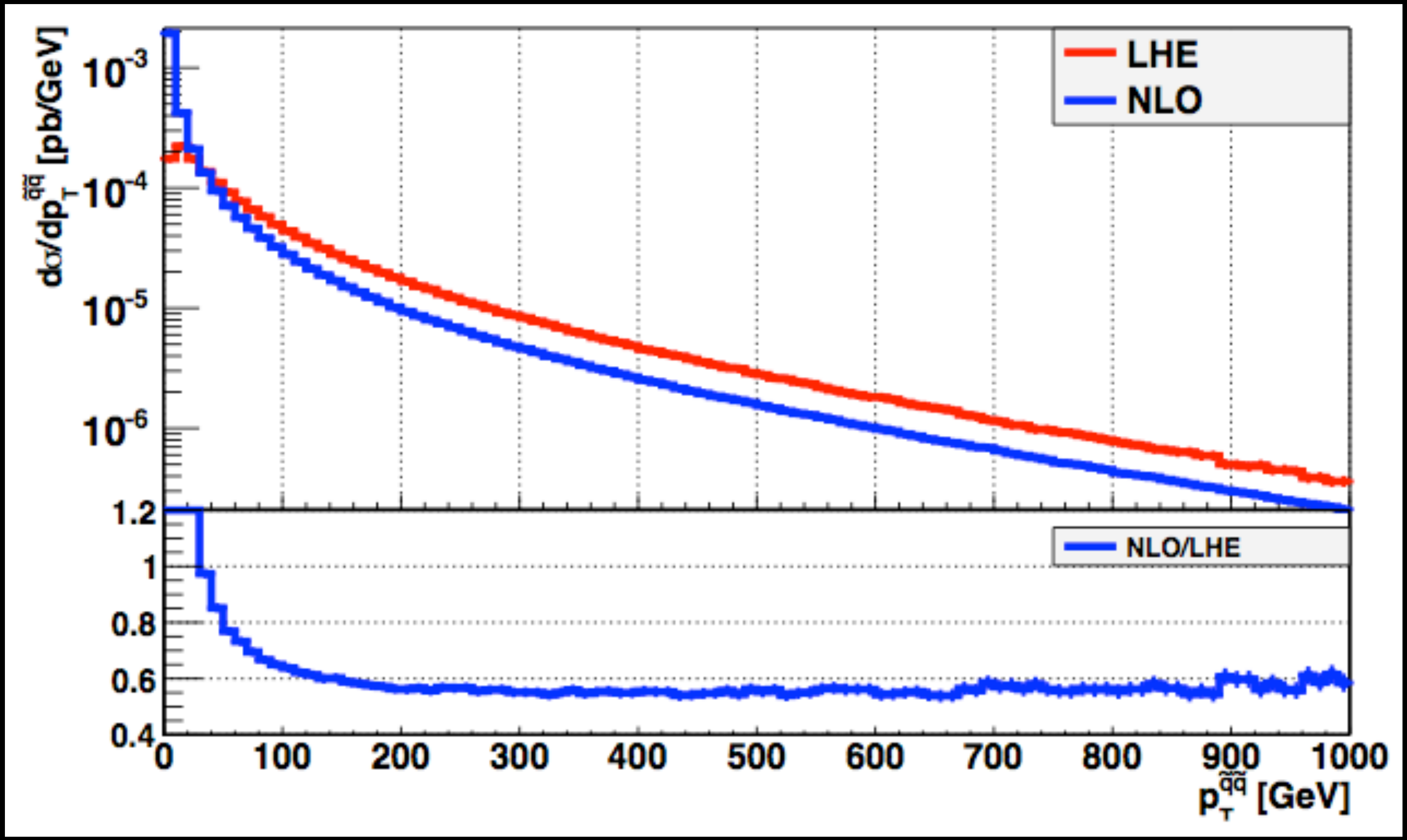
- $\sqrt{s}$ = 14 TeV
- CT10nlo PDF
- $\mu_R = \mu_F = m_{squark,avg}$
- Parton showers used
  - PYTHIA 6.4.26: p_T-ordered Sjostrand, Mrenna, Skands `06
  - HERWIG++ 2.6.1: angular-ordered (default) Arnold, d'Errico, Gieseke et al. `12
  - Dipole shower: HERWIG with p_T-ordered Platzer & Gieseke `11
- cluster partons with FastJet 3.0.3 with anti-k_T algorithm and R=0.4
- no cuts, hadronization, or multiple particle interactions

Inclusive (IR-safe) Observables



NLO accuracy preserved

Exclusive Observable



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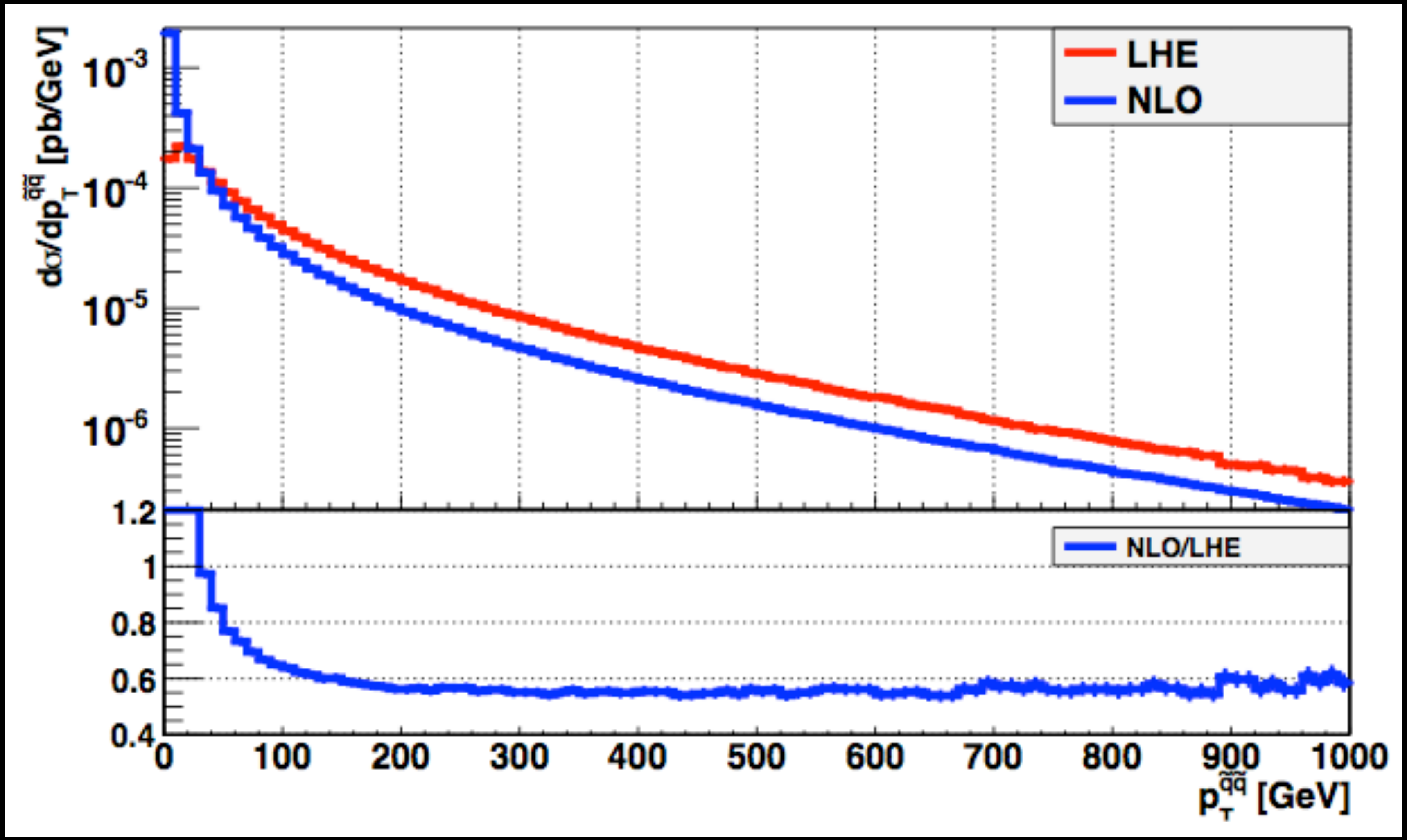


- p_T of squark pair is the p_T of radiated parton
- low pT: Sudakov damping (NLO diverges)
- high pT: NLO/PWG ≈ 60%

Exclusive Observable

- Discrepancies come from large K-factors at NLO: ~ 1.2
  - present in gg→H and VV production

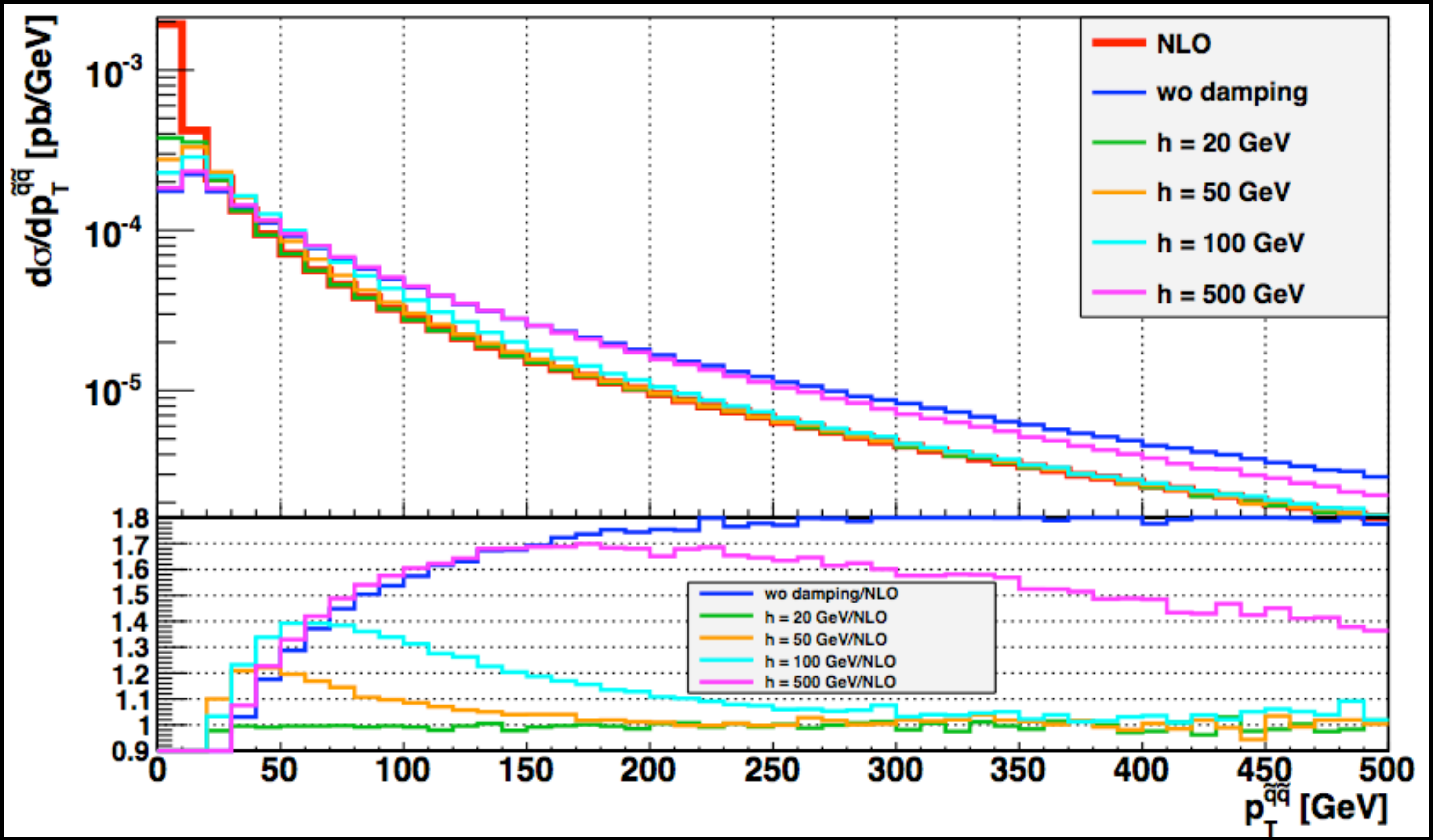
Alioli, Nason, Oleari, Re `09
& Melia, Nason, Rontsch, Zanderighi `11

- ‘Split’ real contribution into hard and singular parts

$$\mathcal{R} = \mathcal{R}_s + \mathcal{R}_r = \mathcal{F}\mathcal{R} + (1 - \mathcal{F})\mathcal{R}; \quad \mathcal{F} = \frac{h^2}{p_T^2 + h^2}$$

- Use IR singular part for radiation generation

Exclusive Observable



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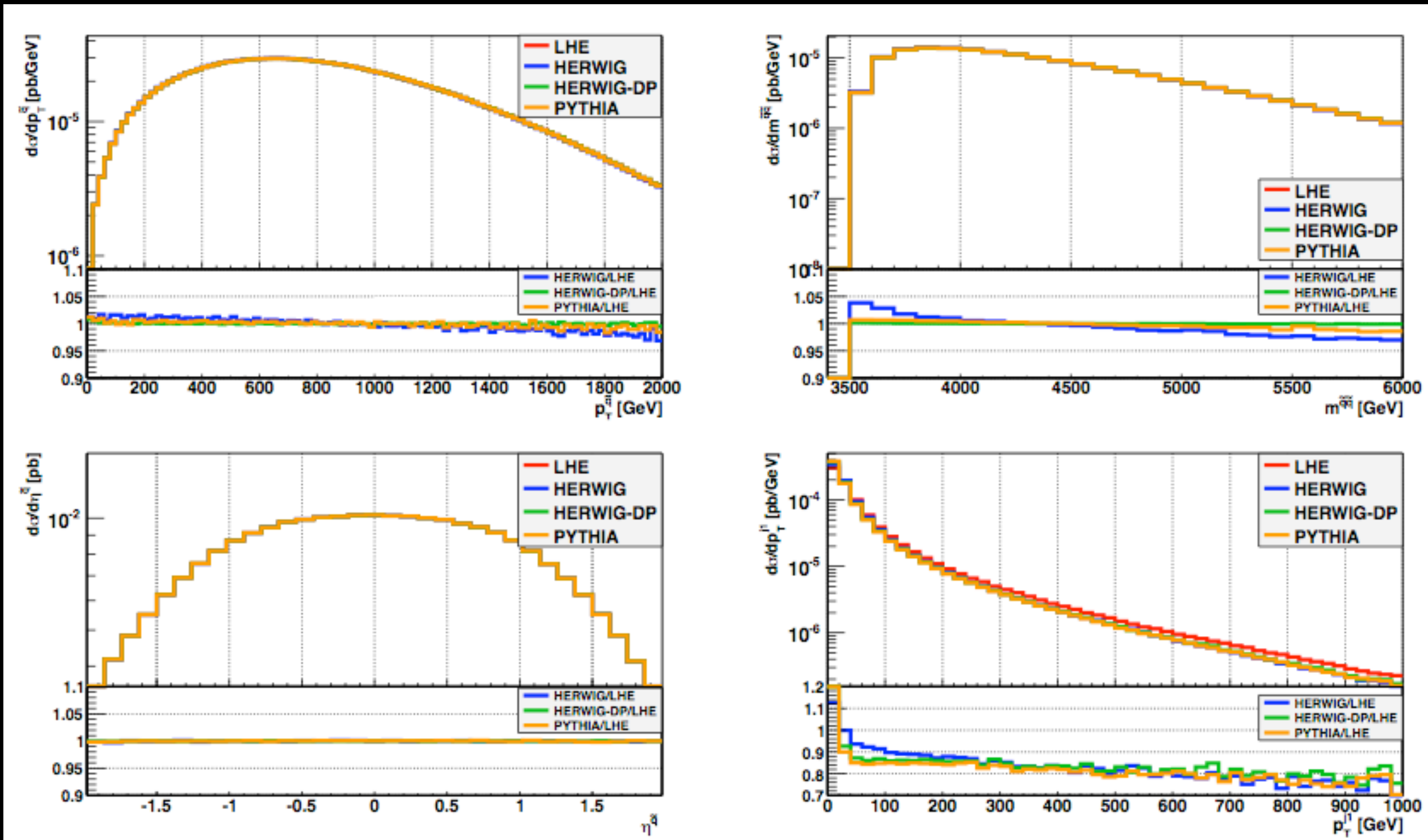
Effects of Parton Shower



POWHEG Overview

- Squark-pair production implemented in POWHEG-Box
- Inclusive observables behave as expected
- Discrepancies in exclusive observables can be explained by NLO enhancement
    - aid by ‘splitting’ real contributions - using IR singular piece in radiation generation
- Investigate more fully the effects of parton showers in SUSY pair production

Further Still?

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  - can't directly 'see' sparticles, only their decay products

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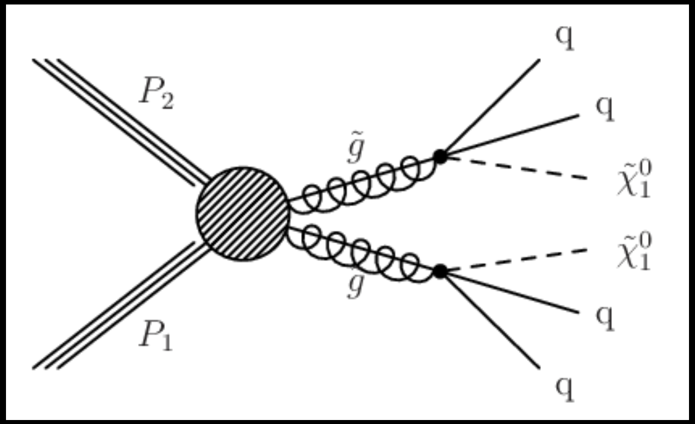

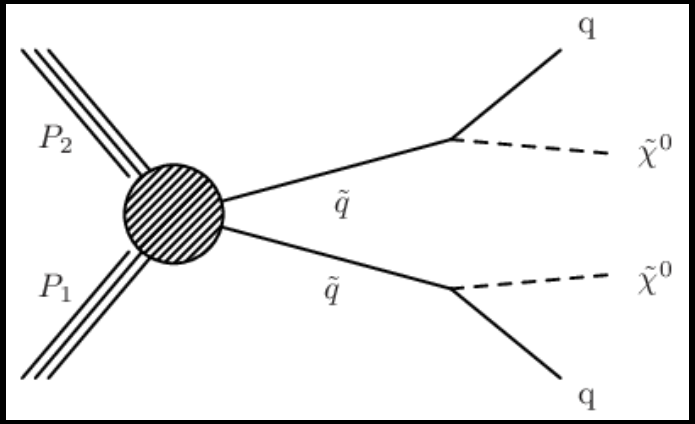

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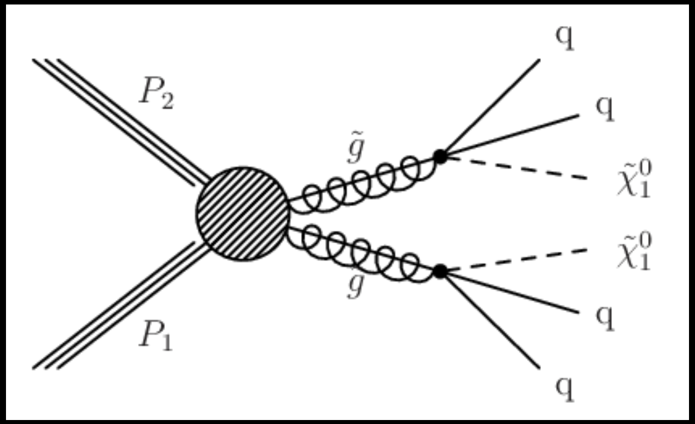

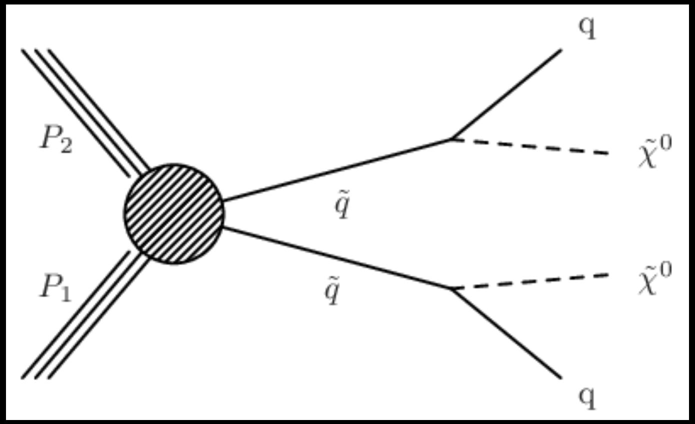

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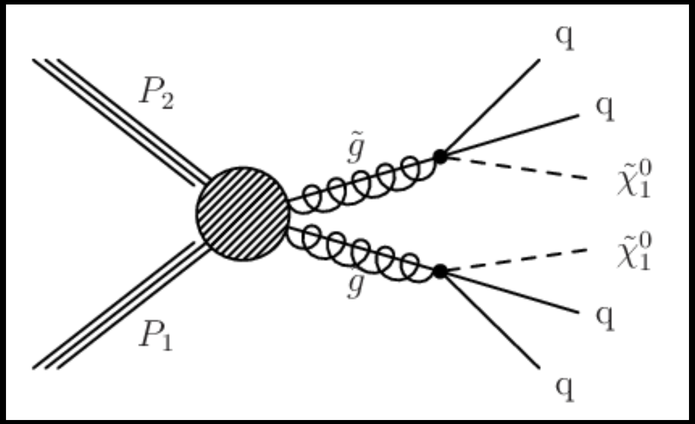

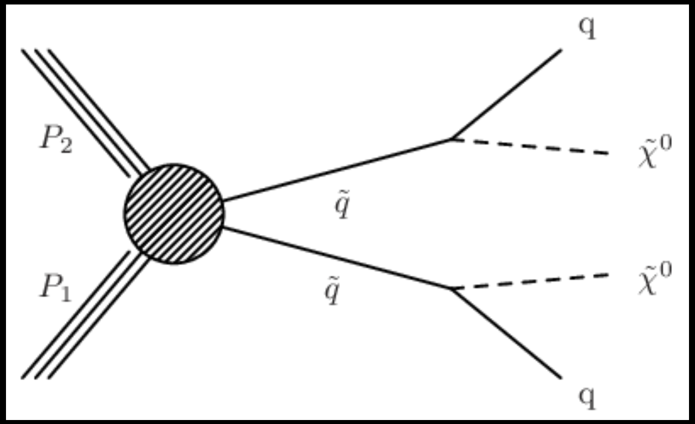

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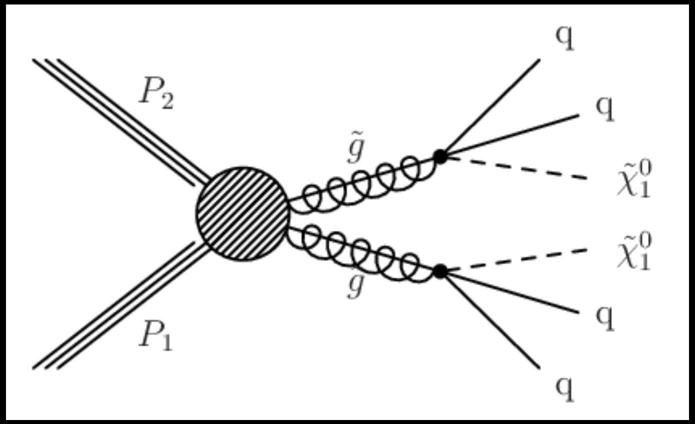
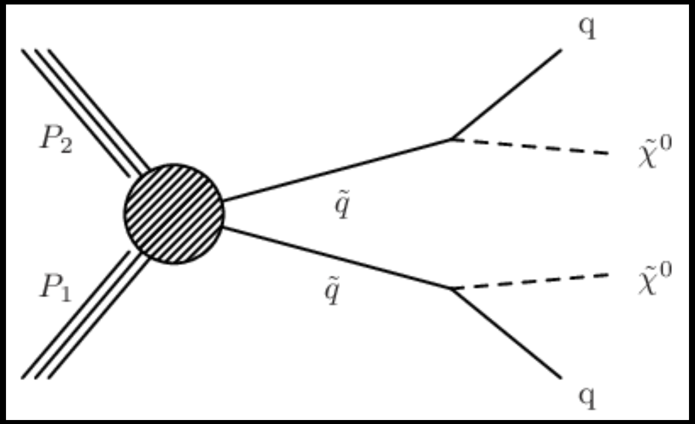
  - gross simplification of analysis





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- Gluinos are fermions - carry spin information
  - squarks are scalar, so multiplying by decay is okay

Squark Decay

- Full squark decay at NLO known since mid 90's

  Djouadi, et. al. `96

  - inclusive only

- Goal: to calculate squark decay to quark-neutralino and embed it in a flexible partonic Monte Carlo

  - eventually combine with squark production at NLO

- When squarks are produced on-shell and decay

  - non-factorizable corrections are assumed to be small

  - only consider factorizable corrections

Squark Pair Prod @ NLO

- Factorizable corrections

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Squark Pair Prod @ NLO

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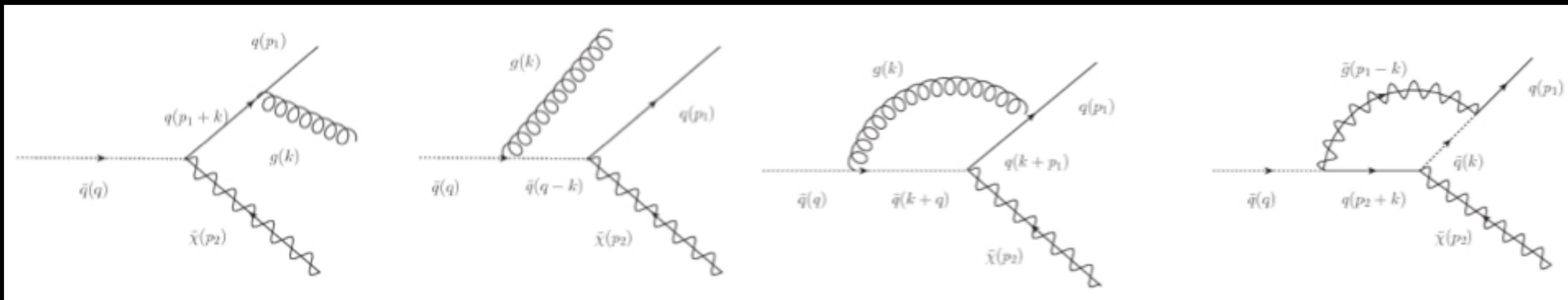
Squark Pair Prod @ NLO

- Factorizable corrections

$$d\sigma_{@nlo} = d\sigma_{production@NLO} \times d\sigma_{decay@LO} + d\sigma_{production@LO} \times d\sigma_{decay@NLO}$$

- Fully differential cross section of production and decay at NLO in QCD

Squark Decay at NLO



- Calculation proceeds in the same manner as squark production
- Nearly finished....

Big Picture

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  - eventually, match production and decay to a parton shower

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  - on-shell production, factorizable corrections only
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  - eventually, match production and decay to a parton shower
  - release in a public code

Conclusions

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- Squark decay, fully differential at NLO - improves predictions, measurements, and limits