SUSY at the LHC with $\sqrt{s} = 7$ TeV and ~ 1 fb^{-1}

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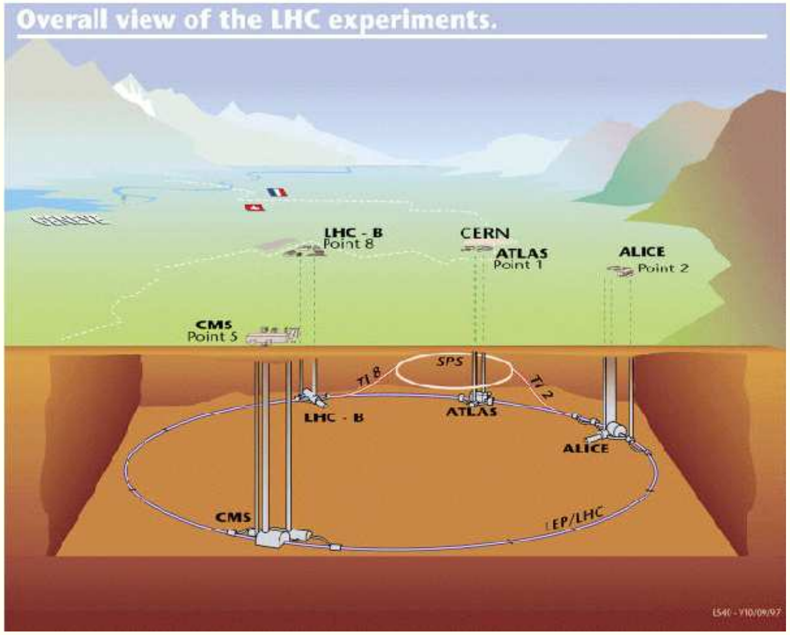
OUTLINE

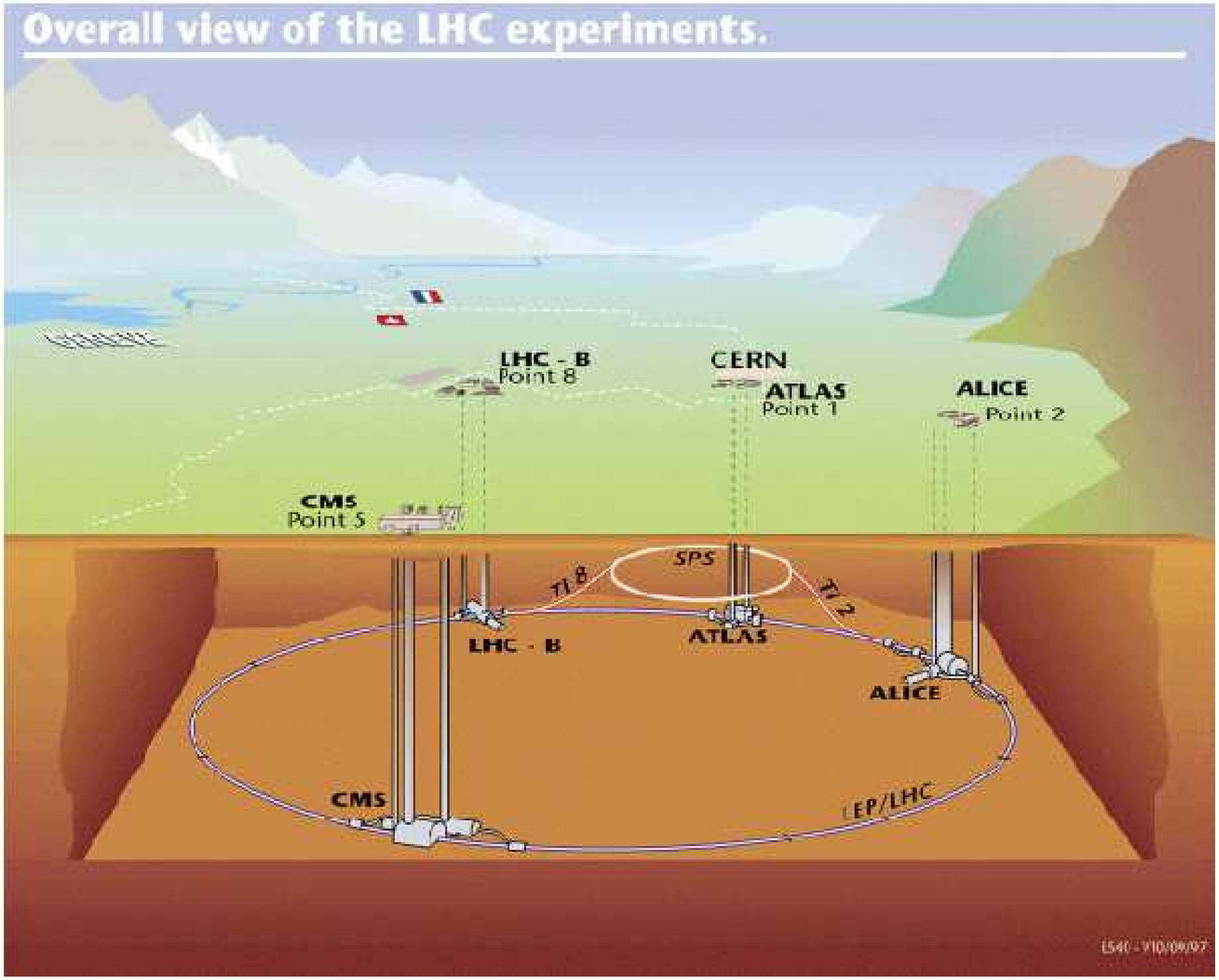
- ⋆ LHC details
- ⋆ Sparticle production
- ⋆ Sparticle decay
- ⋆ Event generation
- ⋆ LHC reach during Run 1
- ⋆ my prediction for LHC
  - Yukawa unified SUSY
  - $m_{\tilde{g}} \lesssim 500$ GeV!



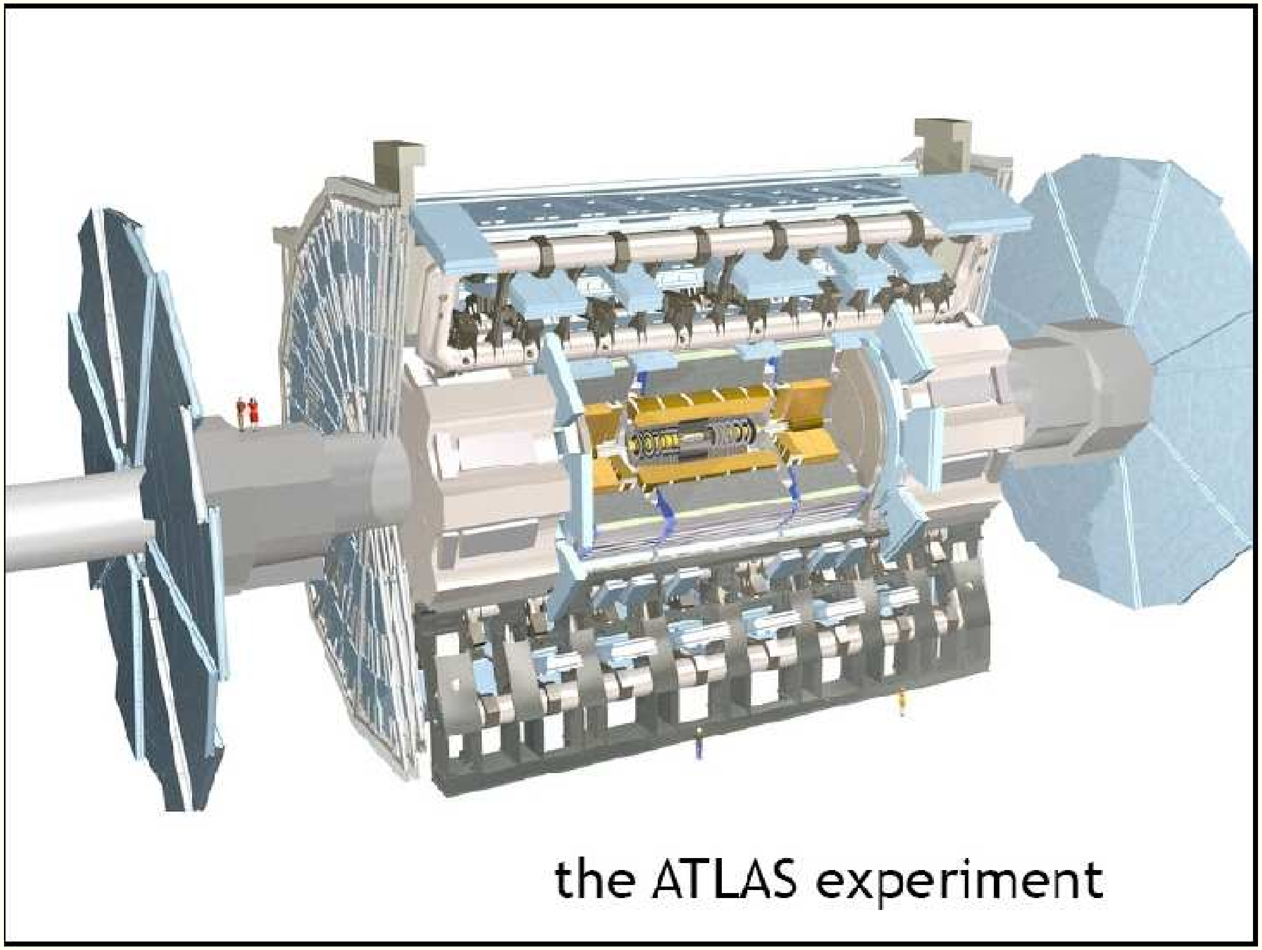
Some basics about the CERN LHC pp collider

- Center-of-mass energy $E \equiv \sqrt{s} = 7 \to 14$ TeV
- The collider is on a circular tunnel 27 km in circumference
- First run began March 30, 2010 at $\sqrt{s} = 7$ TeV
- As of July 9, luminosity is $\sim 10^{30}$cm^{-2}sec^{-1} with 7 bunches circulating; 88.4 nb^{-1} has been collected
- Goal is to reach $\sim 10^{32}$cm^{-2}sec^{-1} with 800 bunches which would allow ~ 1 fb^{-1} of integrated luminosity by end of 2011
- Protons are not fundamental particles: made of quarks q and gluons g
- The quark and gluon collisions should have enough energy to produce TeV-scale superparticles at a large enough rate that they should be detectable above SM background processes
- LHC should be able to discover SUSY or other new physics: but probably can't rule SUSY out if just a Higgs or nothing new is found

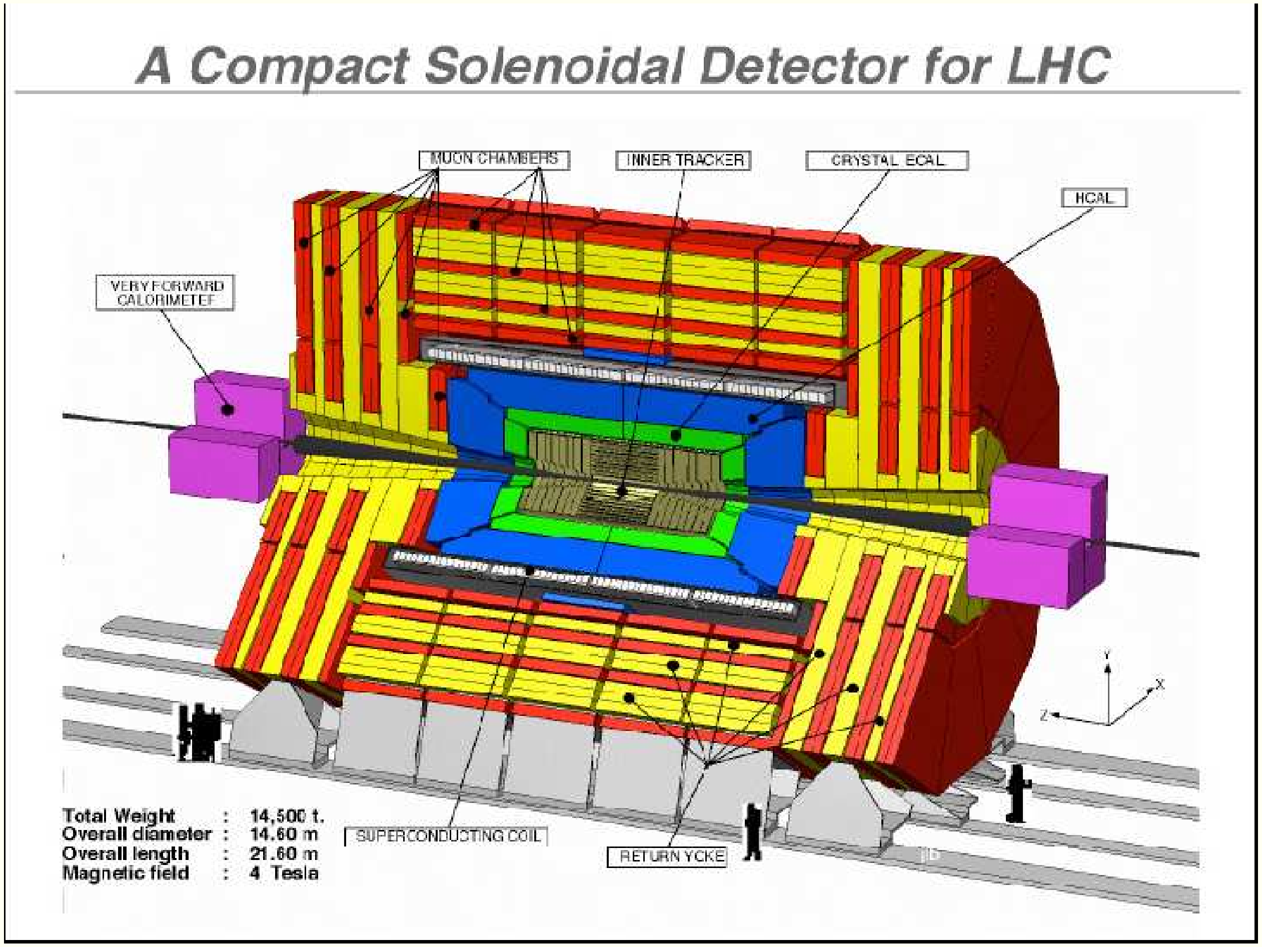
Layout of the LHC:two main detectors: Atlas and CMS



The Atlas detector



The CMS (Compact Muon Solenoid) detector



Parton model of hadronic reactions

For a hadronic reaction,

$$A + B \to c + d + X,$$

where c and d are superpartners and X represents assorted hadronic debris, we have an associated subprocess reaction

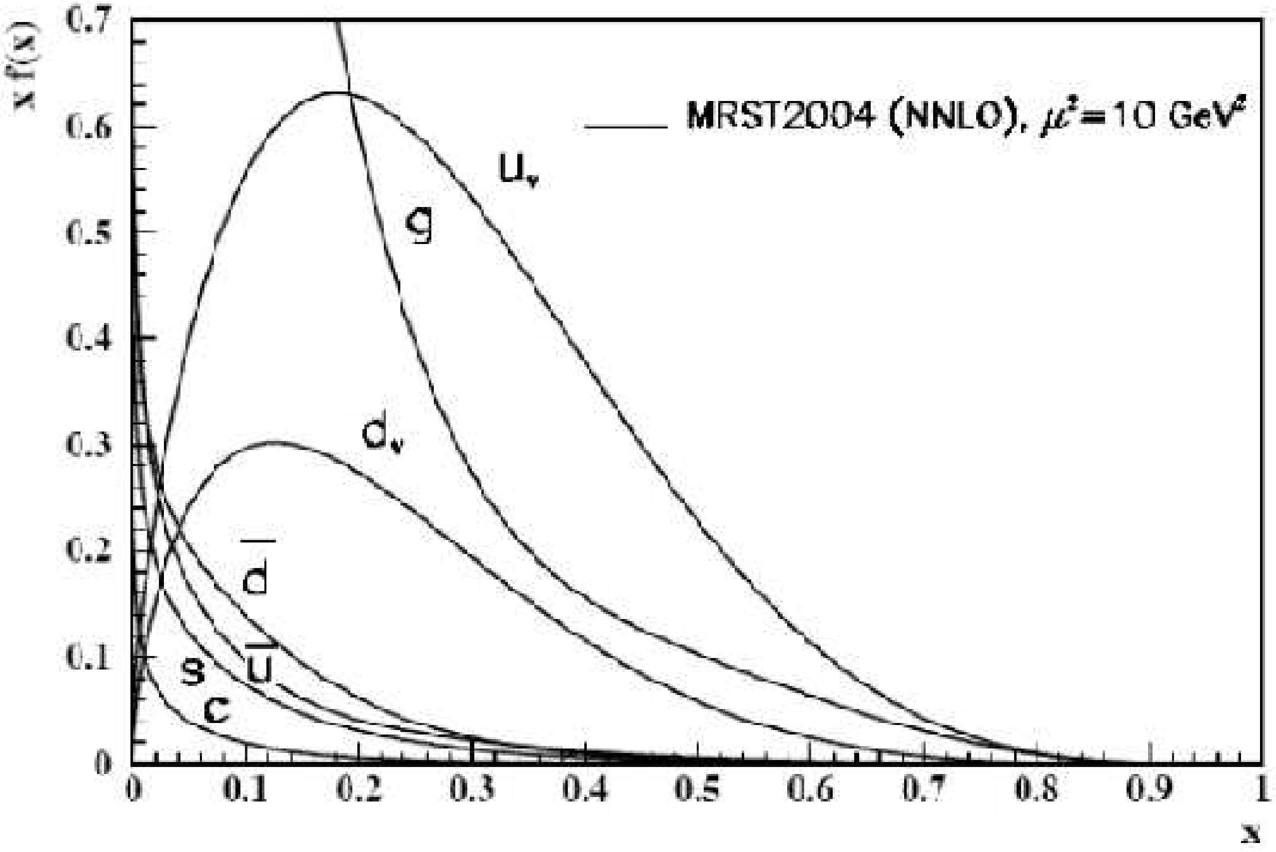
$$a + b \to c + d,$$

whose cross section can be computed using the Lagrangian for the MSSM. To obtain the final cross section, we must convolute the appropriate subprocess production cross section $d\hat{\sigma}$ with the parton distribution functions:

$$d\sigma(AB \to cdX) = \sum_{a,b} \int_0^1 dx_a \int_0^1 dx_b f_{a/A}(x_a, Q^2)\ f_{b/B}(x_b, Q^2)\ d\hat{\sigma}(ab \to cd).$$

where the sum extends over all initial partons a, b whose collisions produce the final state $c + d$.

Parton Distribution Functions (PDFs)



Calculating subprocess cross sections/decay rates in QFT

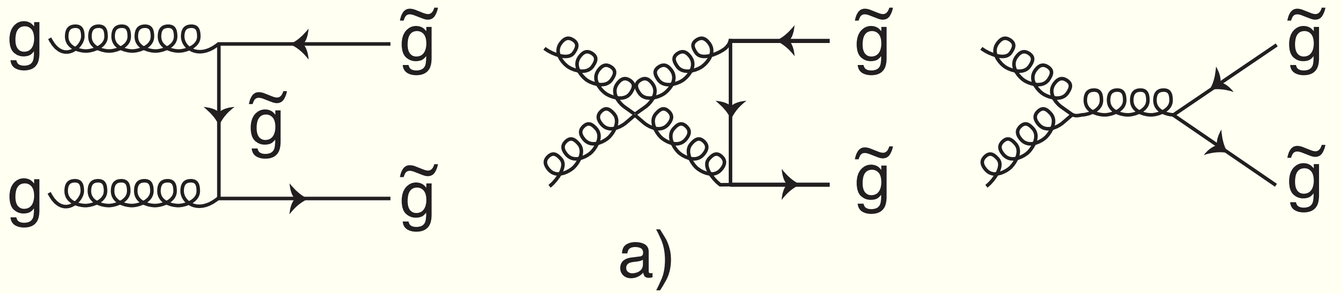
- The fundamental calculable object in QM is the *amplitude* $\mathcal{M}$ for a process to occur
- A pictorial representation of $\mathcal{M}$ is given by a *Feynman diagram*
- Feynman rules for many theories can be found in standard texts: *e.g.* Peskin& Schroeder, *Introduction to Quantum Field Theory*
- In the MSSM, an additional complication occurs due to presence of *Majorana* spinors
- Methods for handling these given *e.g.* in *Weak Scale Supersymmetry* (HB, X. Tata), or book by M. Drees, Godbole& Roy
- total amplitude $\mathcal{M}$ is sum of all different ways a process can occur
- $\mathcal{M}$ is a complex number; $|\mathcal{M}|^2$ gives probability
- must normalize and sum (integrate) over all momentum configurations to gain cross section, usually in *femtobarns*:

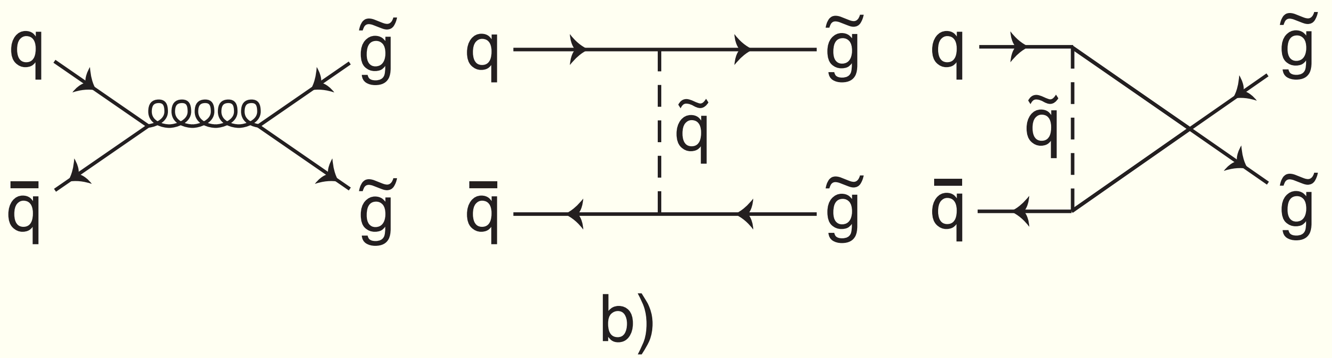
Calculating subprocess cross sections/decay rates in QFT

$$d\hat{\sigma} = \frac{1}{2\hat{s}}\frac{1}{(2\pi)^2}\int \frac{d^3p_c}{2E_c}\frac{d^3p_d}{2E_d}\delta^4(p_a+p_b-p_c-p_d)\cdot F_{\rm color}F_{\rm spin}\sum|\mathcal{M}|^2,$$

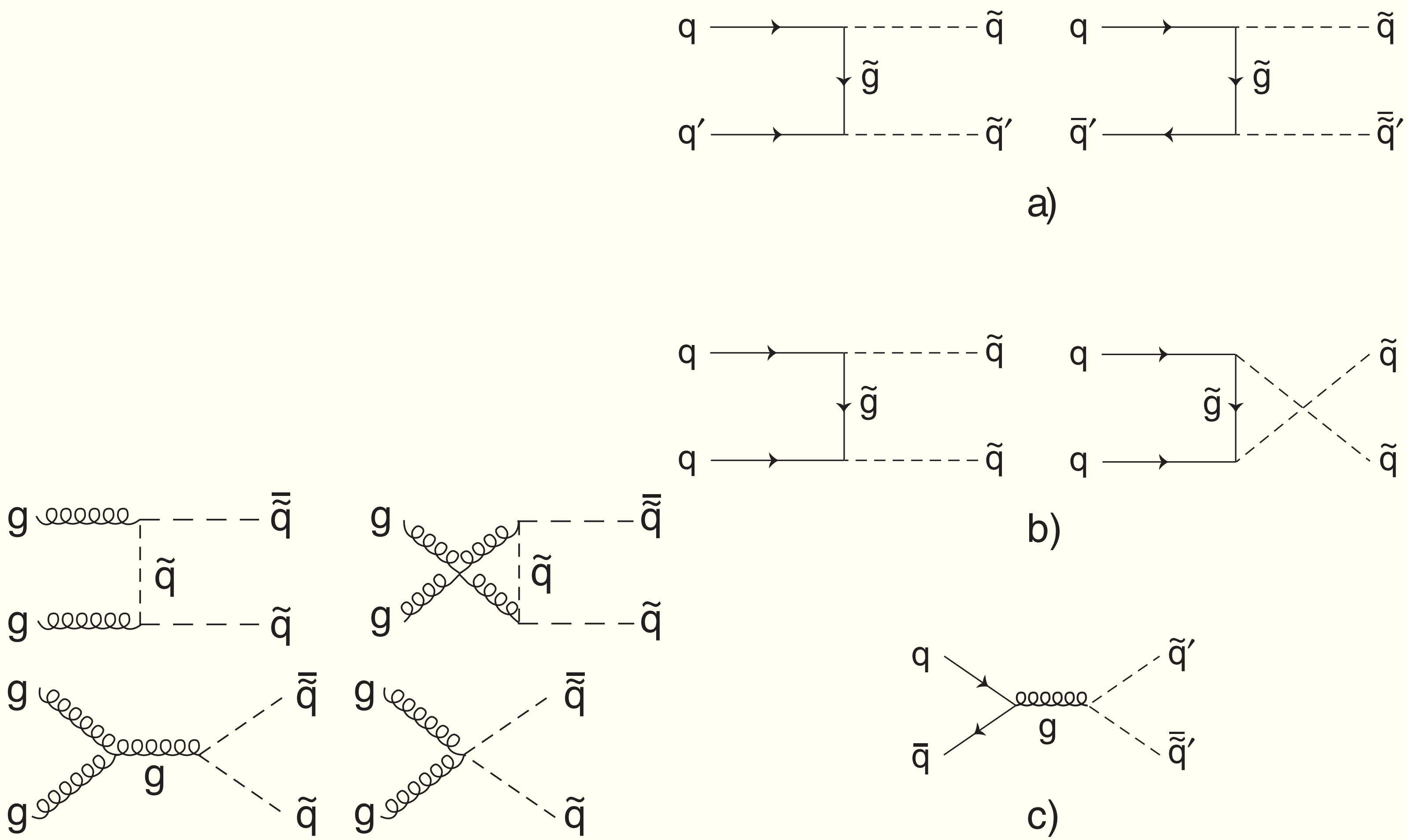
- Must sum (integrate) over all final state momentum configurations
- May be done analytically for simple processes $e.g.\ 2 \rightarrow 2$
- Usually done using Monte Carlo method for $n \geq 3$
- Monte Carlo well suited for adding on particle decays so one has really $2 \rightarrow n$ processes where n can be very large
- Convolution of subprocess cross section with PDFs must be done numerically, since PDFs distributed as *subroutines*

Gluino pair production

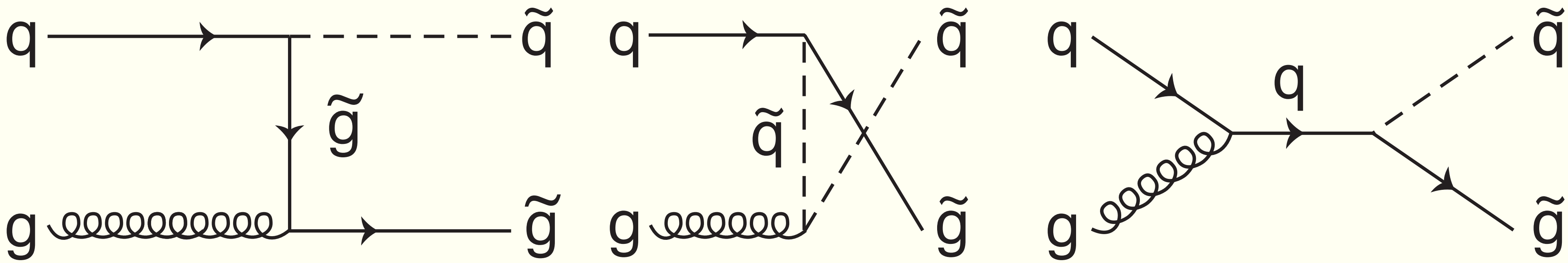




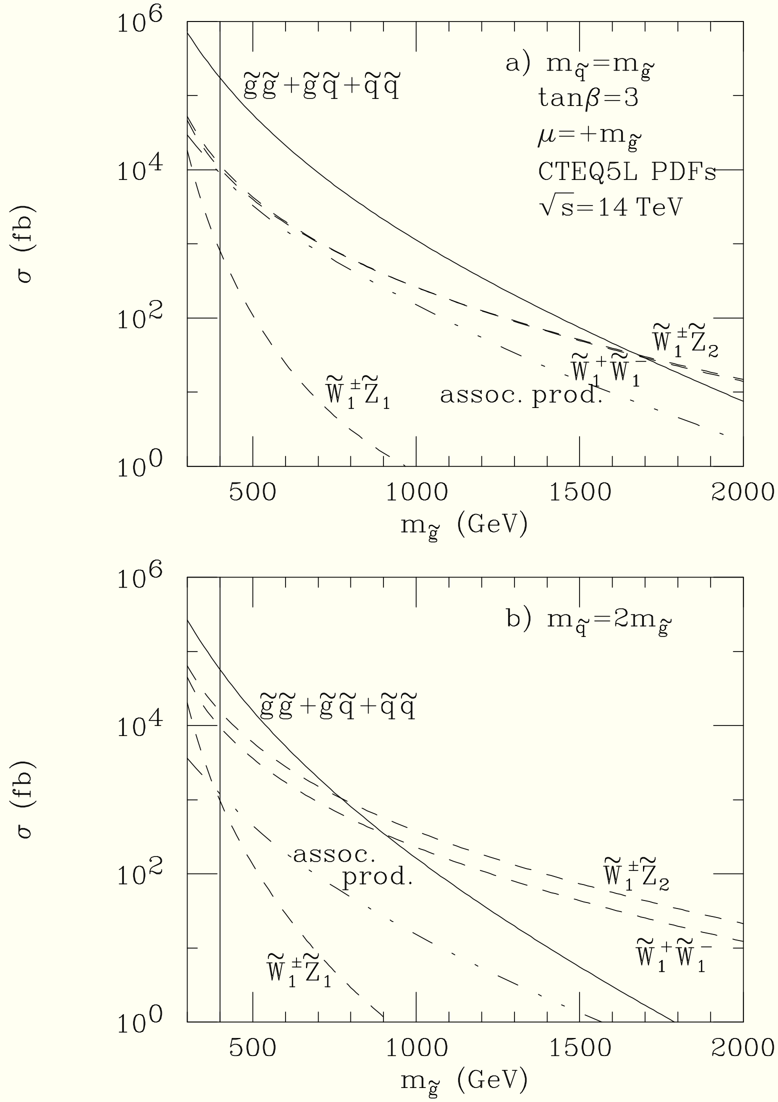
Squark pair production



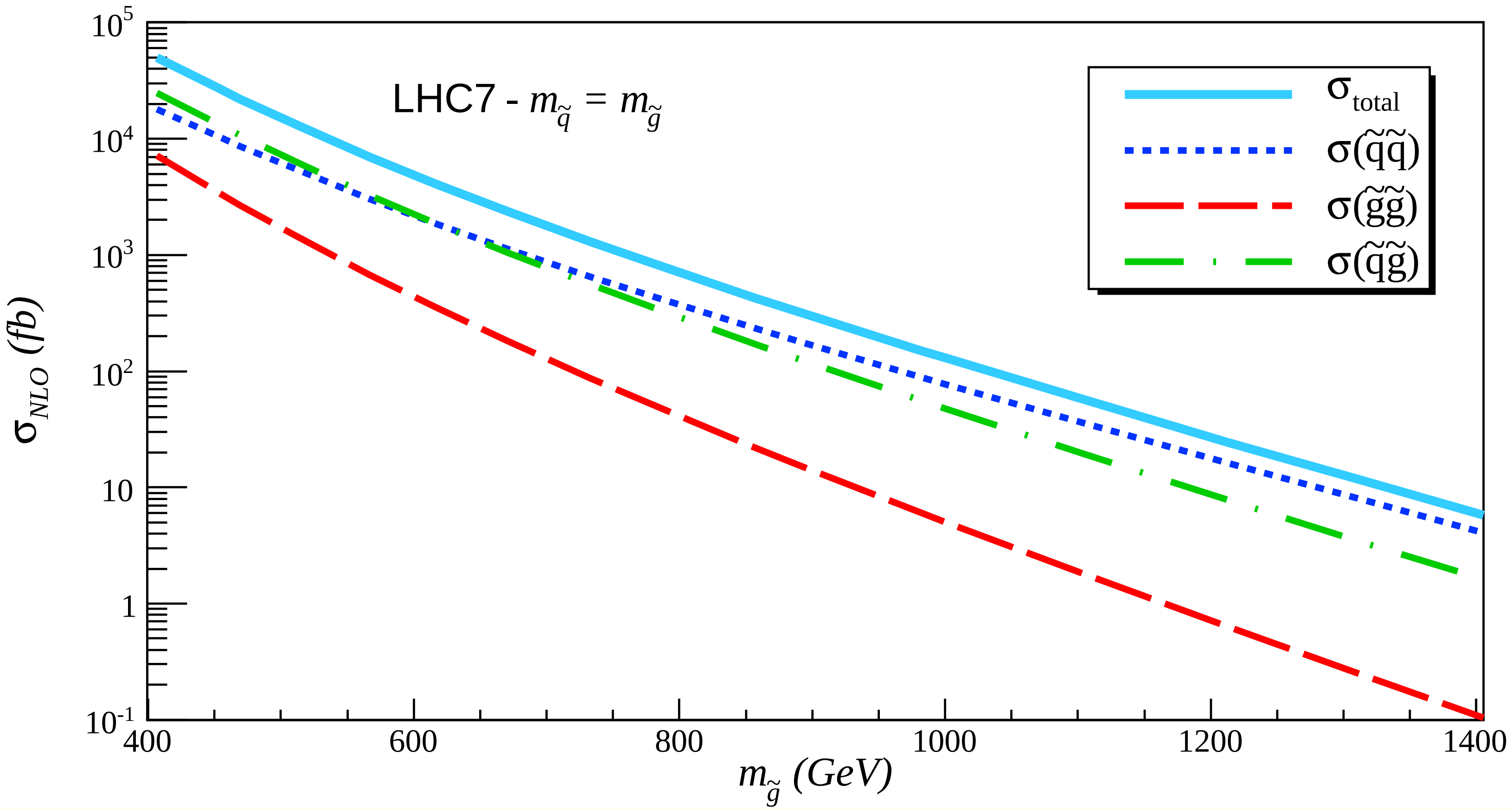
Gluino-squark associated production



Production at LHC

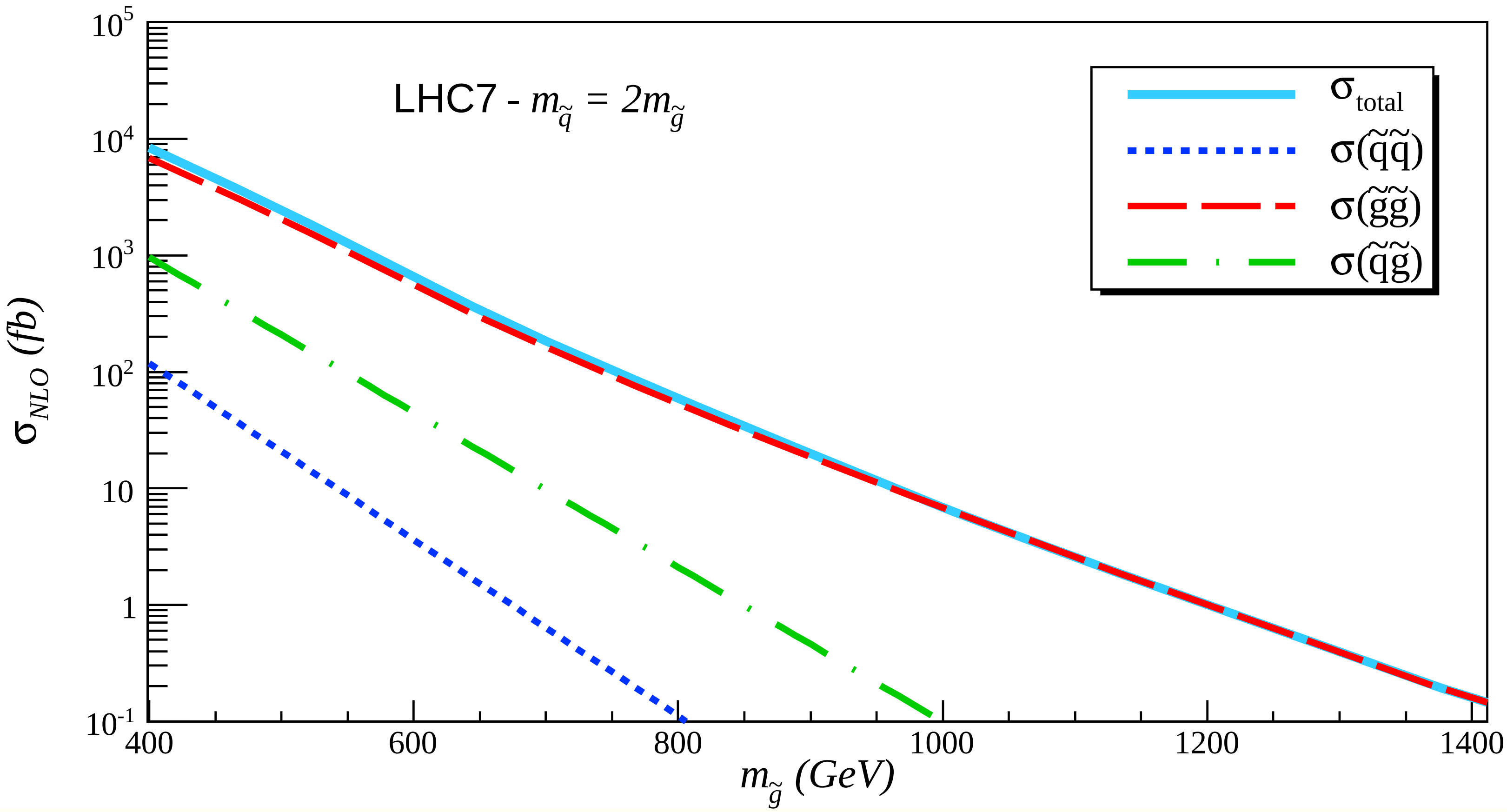


Sparticle production at LHC7 for $m_{\tilde{q}} \sim m_{\tilde{g}}$

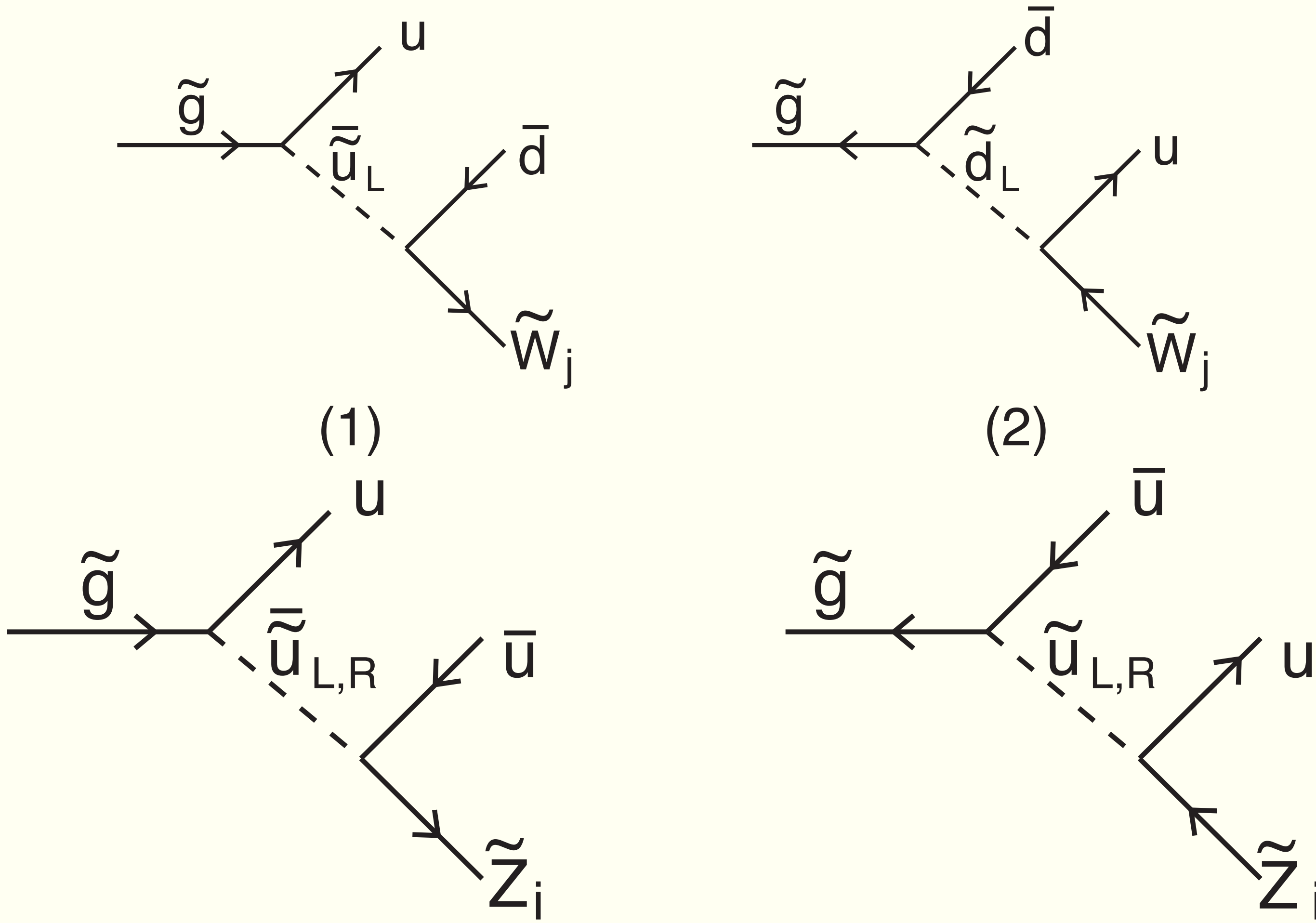


- 9×10^{-5} fb^{-1} $\times 5 \times 10^{4}$ fb ~ 4 events!

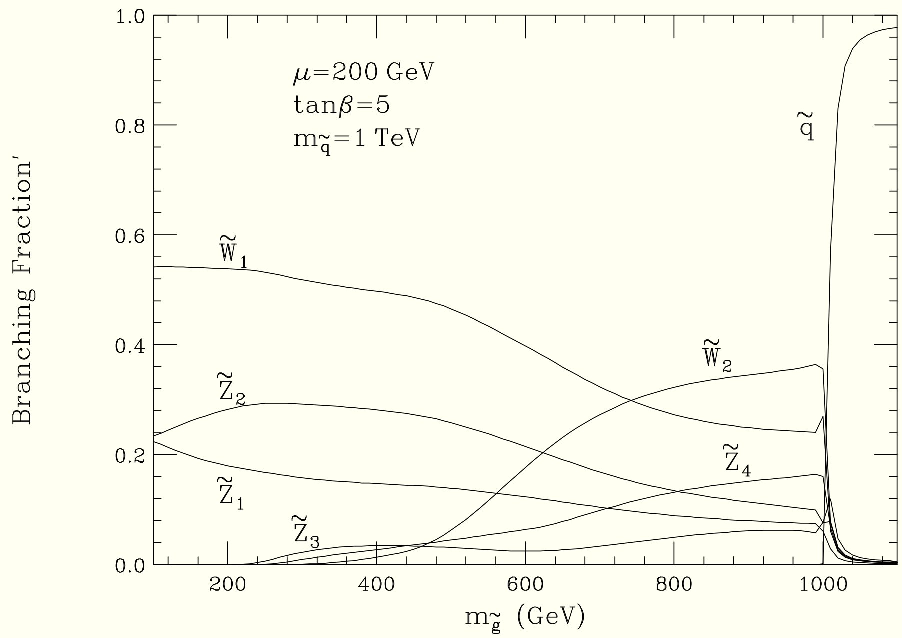
Sparticle Production at LHC7 for $m_{\tilde{q}} = 2m_{\tilde{g}}$

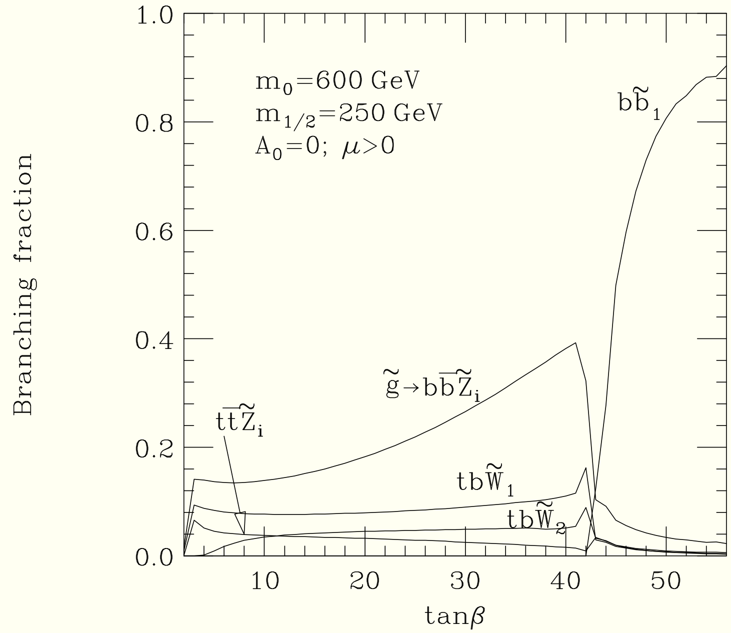


Gluino decays: $\tilde{g} \rightarrow q\tilde{q}$ or 3-body



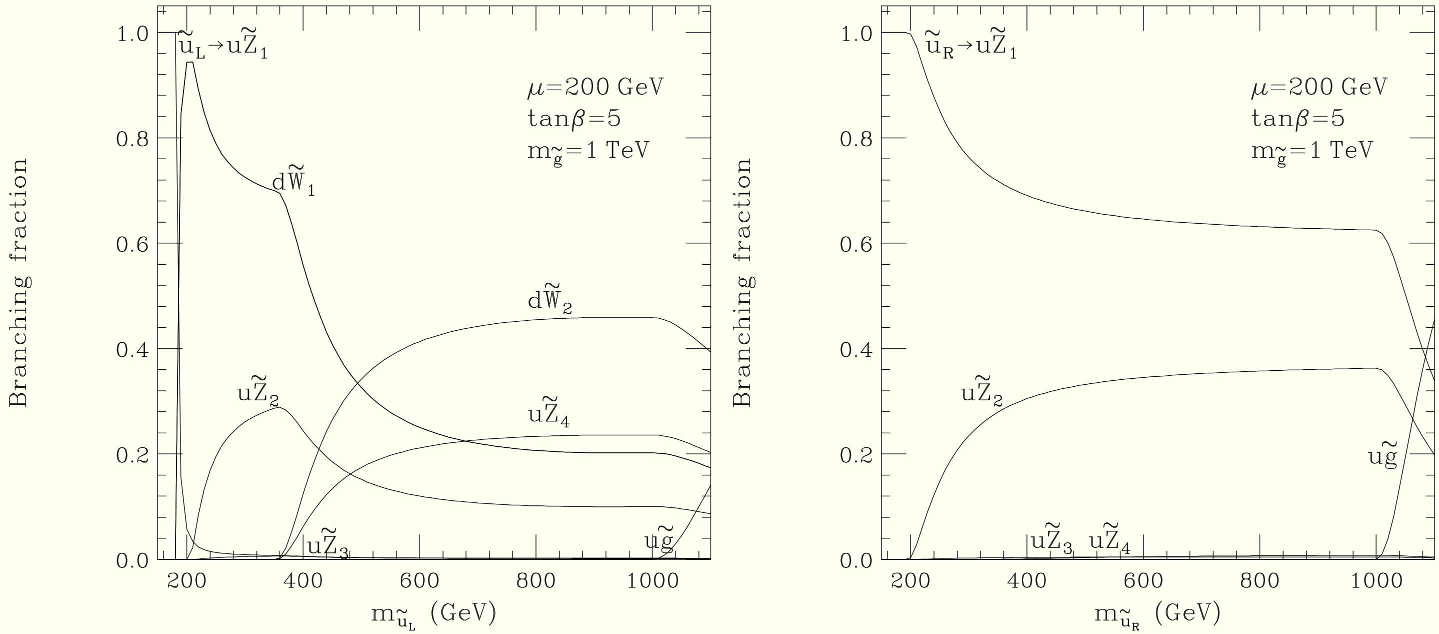
Gluino decays: branching fractions





Squark decays

$$\tilde{u}_L \rightarrow u\widetilde{Z}_i,\ d\widetilde{W}_j^+,\ u\tilde{g},$$
$$\tilde{d}_L \rightarrow d\widetilde{Z}_i,\ u\widetilde{W}_j^-,\ d\tilde{g},$$
$$\tilde{u}_R \rightarrow u\widetilde{Z}_i,\ u\tilde{g},$$
$$\tilde{d}_R \rightarrow d\widetilde{Z}_i,\ d\tilde{g}.$$

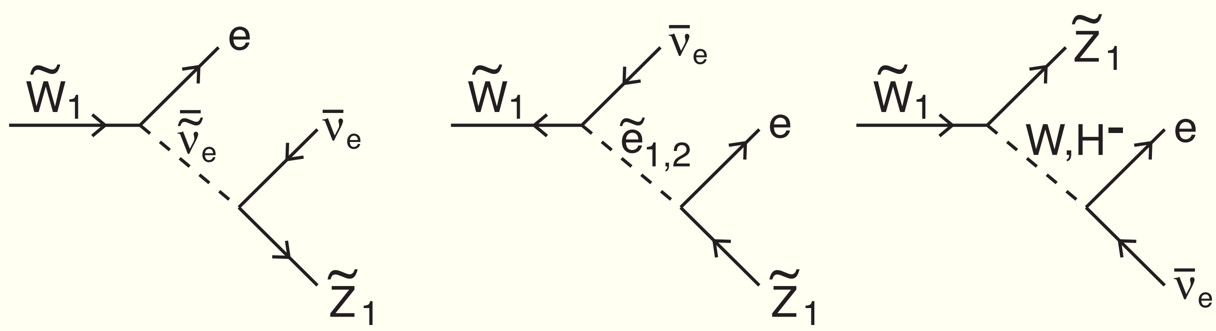


Chargino decays

$$\begin{aligned}
\widetilde{W}_j &\to W\widetilde{Z}_i,\ H^-\widetilde{Z}_i,\\
&\to \tilde{u}_L\bar{d},\ \bar{\tilde{d}}_L u,\ \tilde{c}_L\bar{s},\ \bar{\tilde{s}}_L c,\ \tilde{t}_{1,2}\bar{b},\ \tilde{b}_{1,2}t,\\
&\to \tilde{\nu}_e\bar{e},\ \bar{\tilde{e}}_L\nu_e,\ \tilde{\nu}_\mu\bar{\mu},\ \bar{\tilde{\mu}}_L\nu_\mu,\ \tilde{\nu}_\tau\bar{\tau},\bar{\tilde{\tau}}_{1,2}\nu_\tau,\ \text{and}\\
\widetilde{W}_2 &\to Z\widetilde{W}_1,\ h\widetilde{W}_1,\ H\widetilde{W}_1\ \text{and}\ A\widetilde{W}_1.
\end{aligned}$$

Charginos may decay to a lighter neutralino via

$$\widetilde{W}_j \to \widetilde{Z}_i + f\bar{f}' \ , \tag{1}$$

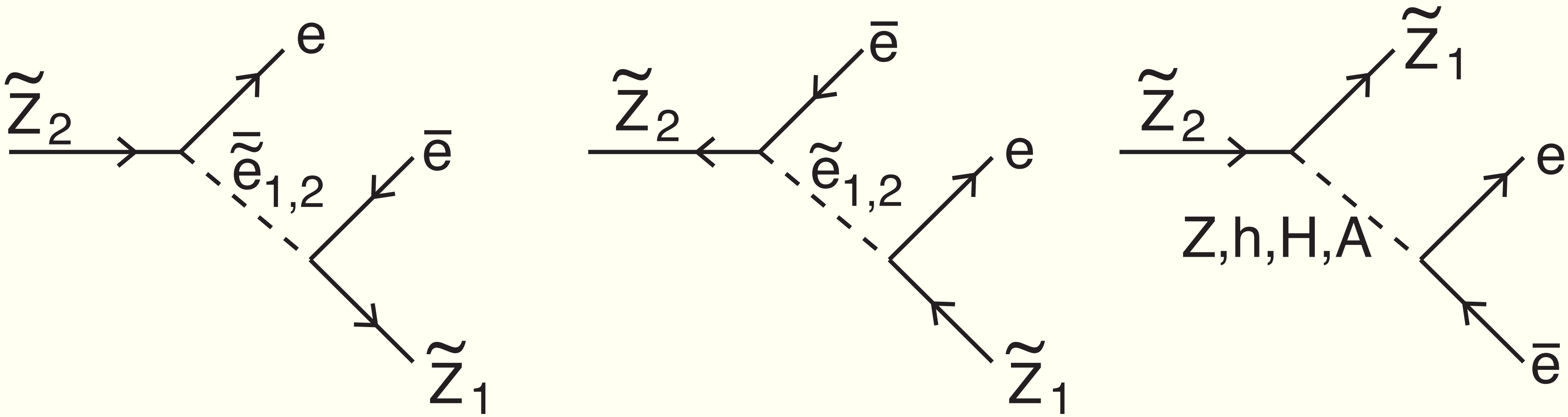


Neutralino decays

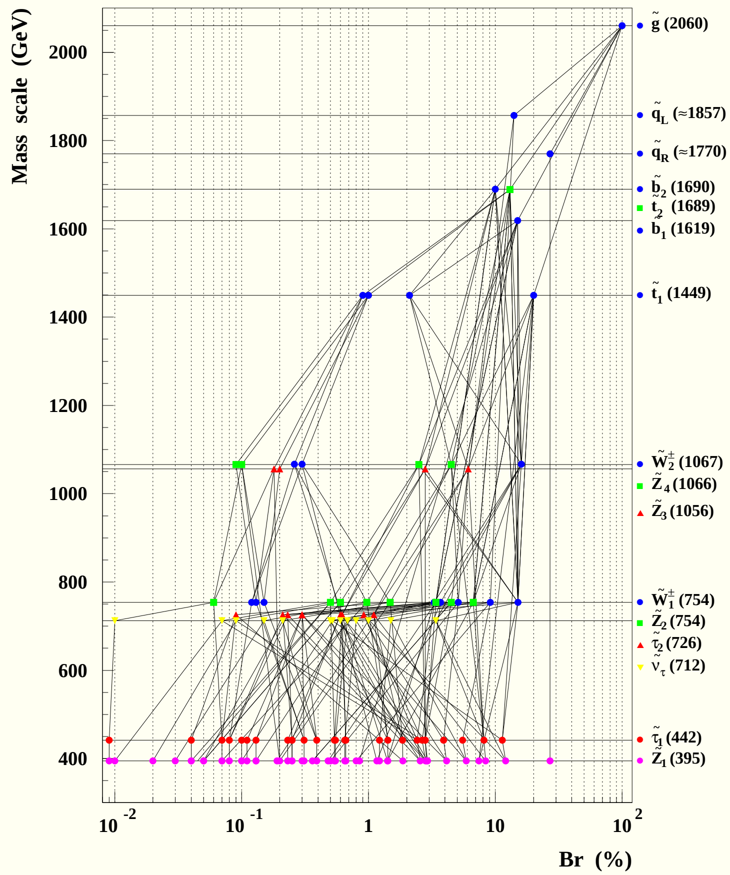
$$\widetilde{Z}_i \rightarrow W\widetilde{W}_j,\ H^-\widetilde{W}_j,\ Z\widetilde{Z}_{i'},\ h\widetilde{Z}_{i'},\ H\widetilde{Z}_{i'},\ A\widetilde{Z}_{i'}$$
$$\rightarrow \tilde{q}_{L,R}\bar{q},\ \bar{\tilde{q}}_{L,R}q,\ \tilde{\ell}_{L,R}\bar{\ell},\ \bar{\tilde{\ell}}_{L,R}\ell,\ \tilde{\nu}_\ell\bar{\nu}_\ell,\ \bar{\tilde{\nu}}_\ell\nu_\ell.$$

If 2-body modes are closed,then the neutralino can decay via

$$\widetilde{Z}_i \rightarrow \widetilde{Z}_{i'} + f\bar{f} \qquad (2)$$



Sparticle cascade decays

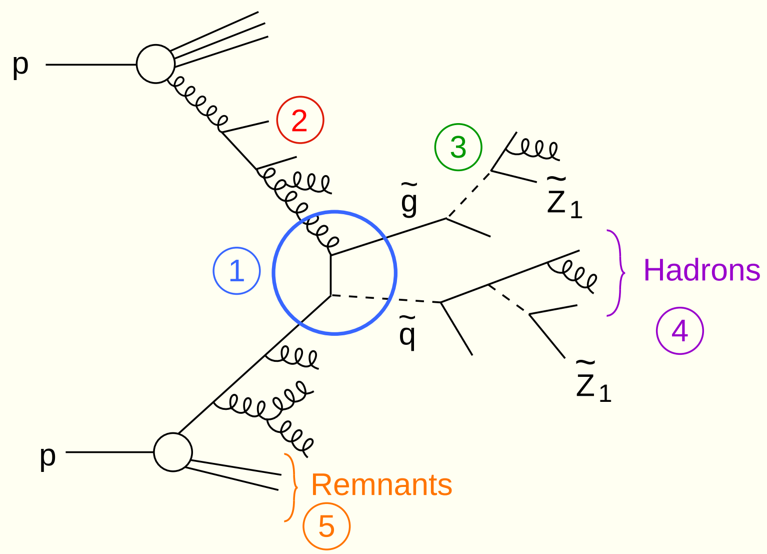


$\tilde Z_1$ qq	(27.0 %)	$\tilde Z_1$ τνWWWbb	(4.1 %)
$\tilde Z_1$ τνWbb	(12.1 %)	$\tilde Z_1$ ττbb	(2.9 %)
$\tilde Z_1$ ττWWbb	(8.4 %)	$\tilde Z_1$ ττqq	(2.9 %)
$\tilde Z_1$ WWbb	(7.4 %)	$\tilde Z_1$ τνZWbb	(2.8 %)
$\tilde Z_1$ τνqq	(5.9 %)	$\tilde Z_1$ τνhWbb	(2.6 %)

A realistic picture of what SUSY matter looks like at LHC

- ⋆ Counting different flavor states (which are potentially measurable), there are well over 1000 subprocess reactions expected at LHC from the MSSM
- ⋆ on average, each sparticle has 5-20 decay modes
- ⋆ rough estimate of distinct SUSY $2 \to n$ processes:
  - $\sim 1000 \times 10 \times 10 \sim 10^5$
  - this is actually a gross underestimate since each daughter of a produced sparticle has multiple decay modes, and so on...
- ⋆ the way forward: Monte Carlo program
  - calculate all prod'n cross sections: generate according to relative weights
  - calculate all branching fractions, and generate decays according to them
  - interface with parton shower, hadronization, underlying event
  - computer generated events should look something like what we would expect from the MSSM at the LHC

Event generation for sparticles



Event generation in LL - QCD

1) Hard scattering / convolution with PDFs

2) Intial / final state showers

3) Cascade decays

4) Hadronization

5) Beam remnants

Event generations for SUSY

⋆ Isajet (HB, Paige, Protopopsecu, Tata)

- IH, FW-PS, n-cut Pomeron UE

⋆ Pythia (Sjöstrand, Lönnblad, Mrenna)

- SH, FW-PS, multiple scatter UE, SUSY at low $\tan\beta$ only

⋆ Herwig (Marchesini, Webber, Seymour, Richardson,...)

- CH, AO-PS, Phen. model UE, Isawig, Spin corr.!

⋆ SUSYGEN (Ghodbane, Katsanevas, Morawitz, Perez)

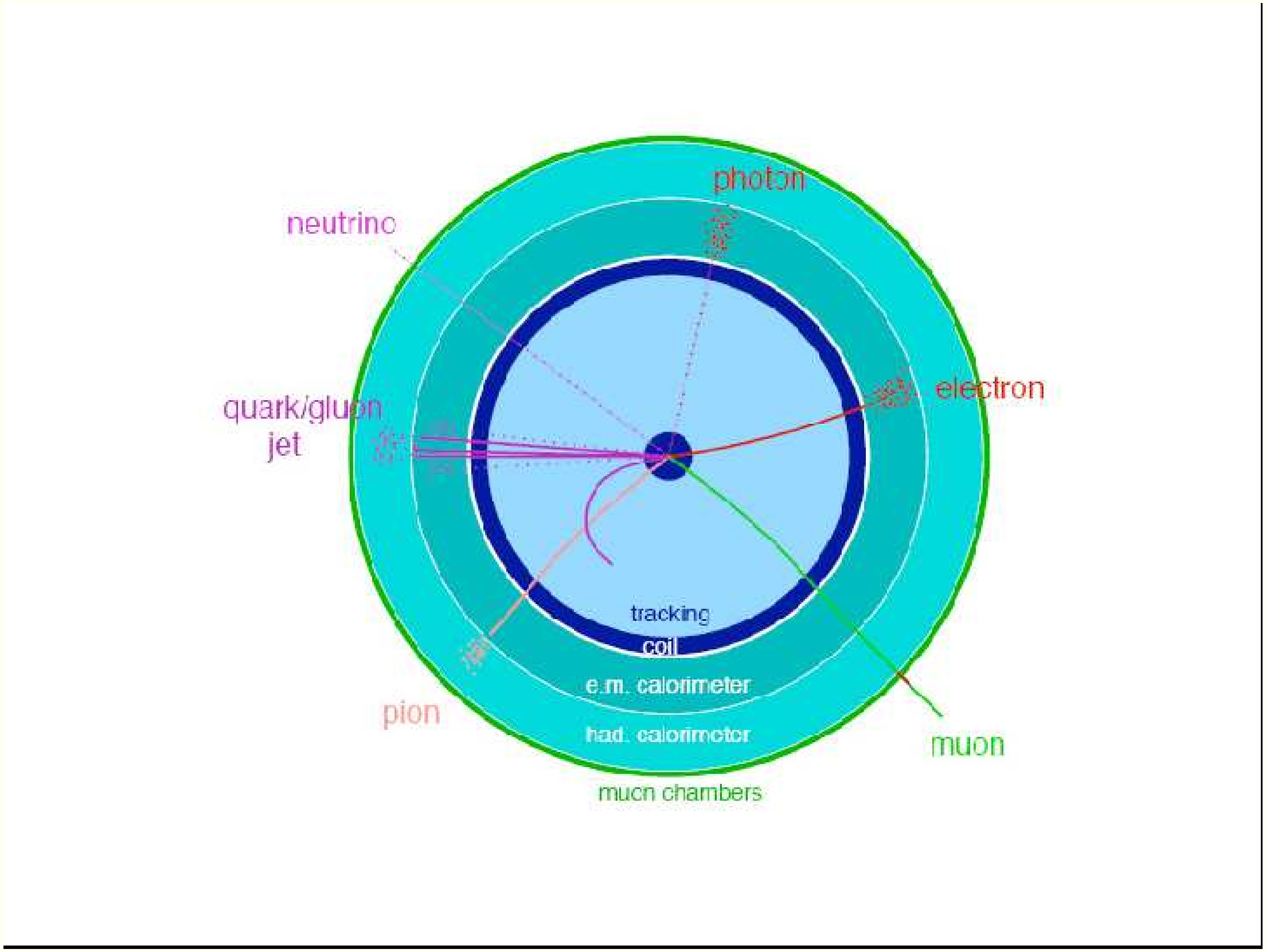
- mainly for e^+e^-; interfaces to Pytha

⋆ SHERPA (Gleisberg, Hoche, krauss, Schalicke, Schumann, Winter)

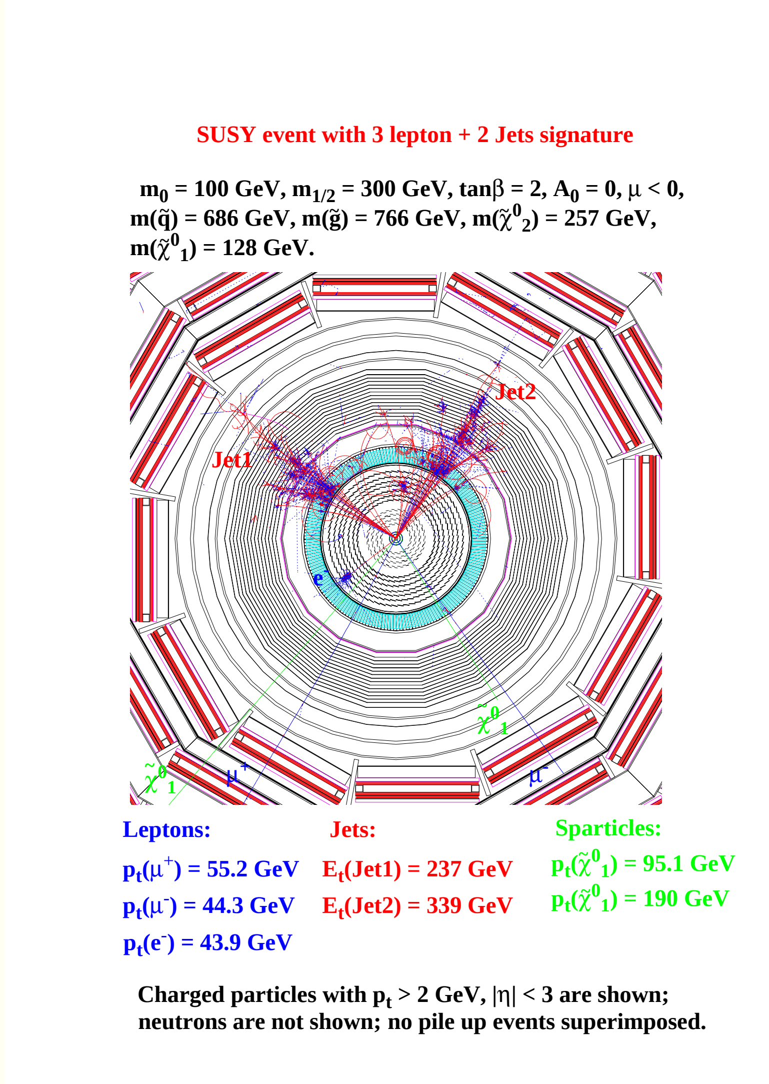
- $C++$ code for various $2 \to n$ processes

⋆ CompHEP, CalcHEP, Madgraph: for automatic Feynman diagram evaluation: interface via LHA

Briefly: particle interactions with detector



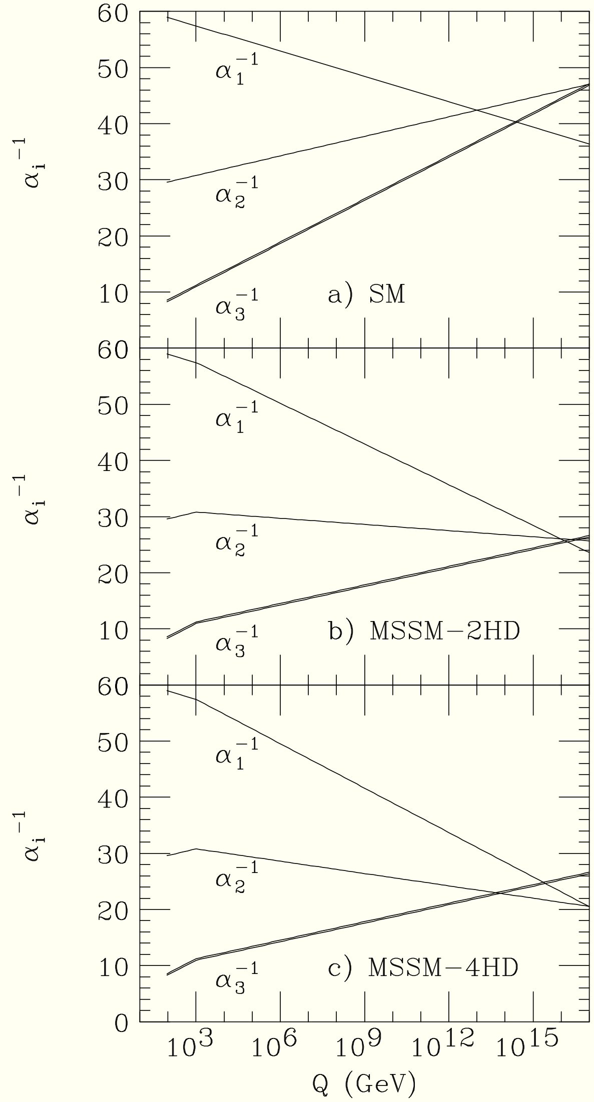
SUSY scattering event: Isajet simulation



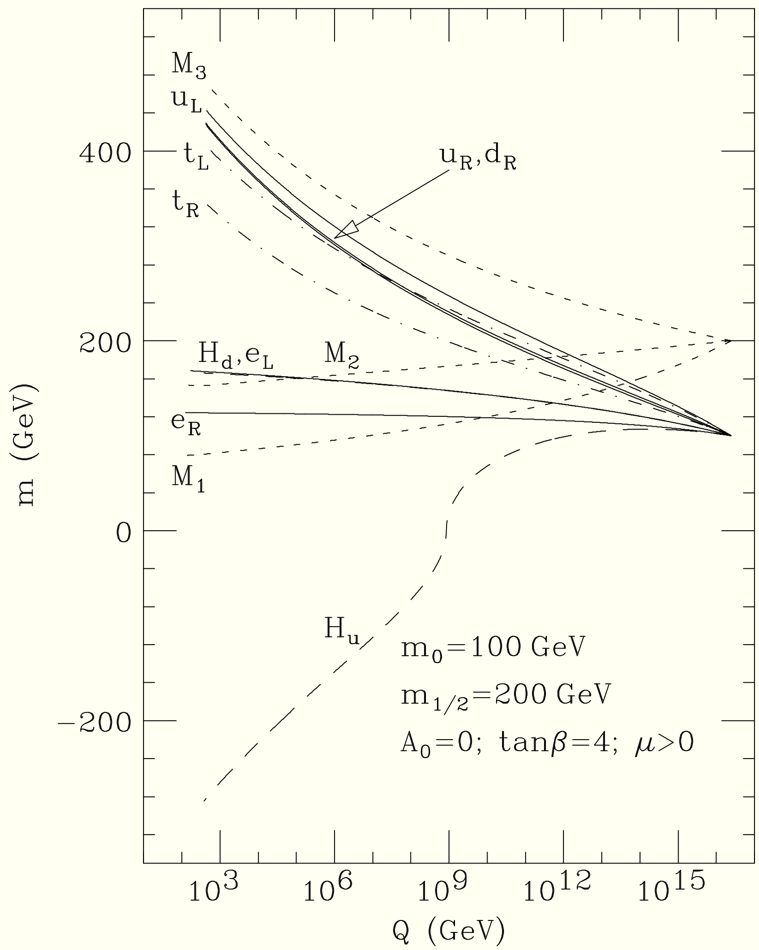
Search for SUSY at LHC: model dependent

- ⋆ GMSB
- ⋆ AMSB
  - MM-AMSB (mirage mediation)
  - hypercharged-AMSB (HCAMSB)
  - deflected AMSB
  - gaugino AMSB (inoAMSB)
- ⋆ gravity-mediated models
  - mSUGRA or CMSSM
  - NUHM1, NUHM2
  - non-universal gaugino masses: MWDM, BWCA, LM3DM, HM2DM, ...
  - normal scalar mass hierarchy ($m_0(1,2) > m_0(3)$)
  - compressed SUSY
- ⋆ Split SUSY, pMSSM, NMSSM, $\cdots$

Gauge coupling evolution



Right or wrong, most analyses work in mSUGRA model



- $m_0,\ m_{1/2},\ A_0,\ \tan\beta, sign(\mu)$

Search for SUSY at CERN LHC

- ⋆ $\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$, $\tilde{q}\tilde{q}$ production dominant for $m \lesssim 1$ TeV
- ⋆ lengthy cascade decays are likely
  - $\not{E}_T+$ jets
  - $1\ell+\not{E}_T+$ jets
  - $OS\ 2\ell+\not{E}_T+$ jets
  - $SS2\ell+\not{E}_T+$ jets
  - $3\ell+\not{E}_T+$ jets
  - $4\ell+\not{E}_T+$ jets
- ⋆ BG: $W+jets$, $Z+jets$, $t\bar{t}$, $b\bar{b}$, WW, $4t$, $\cdots$
- ⋆ Grid of cuts gives optimized S/B

Grid of cuts for optimized S/B

- $\not{E}_T > 100 - 1000$ GeV (steps of 100 GeV)
- $n_j \geq 2$, 3, 4, 5, 6 (where $p_T(jet) > 50$ GeV and $|\eta(jet)| < 3$, $R < 0.4$)
- $n(b-jets) \geq$0,1,2,3
- $E_T(j1) > 50 - 1000$ GeV (steps of 50,100 GeV)
- $E_T(j2) > 50 - 500$ GeV (steps of 30,100 GeV)
- $n(\ell) = 0, 1, 2, 3$, OS, SS and inclusive ($\ell = e$ or μ)
- $10 \text{ GeV} < m(\ell^+\ell^-) < 75$ GeV or > 105 GeV for OS/SF dileptons
- $S_T > 0.2$

⋆ $S > max(5\sqrt{B}, 5, 0.2B)$ for optimal set of cuts

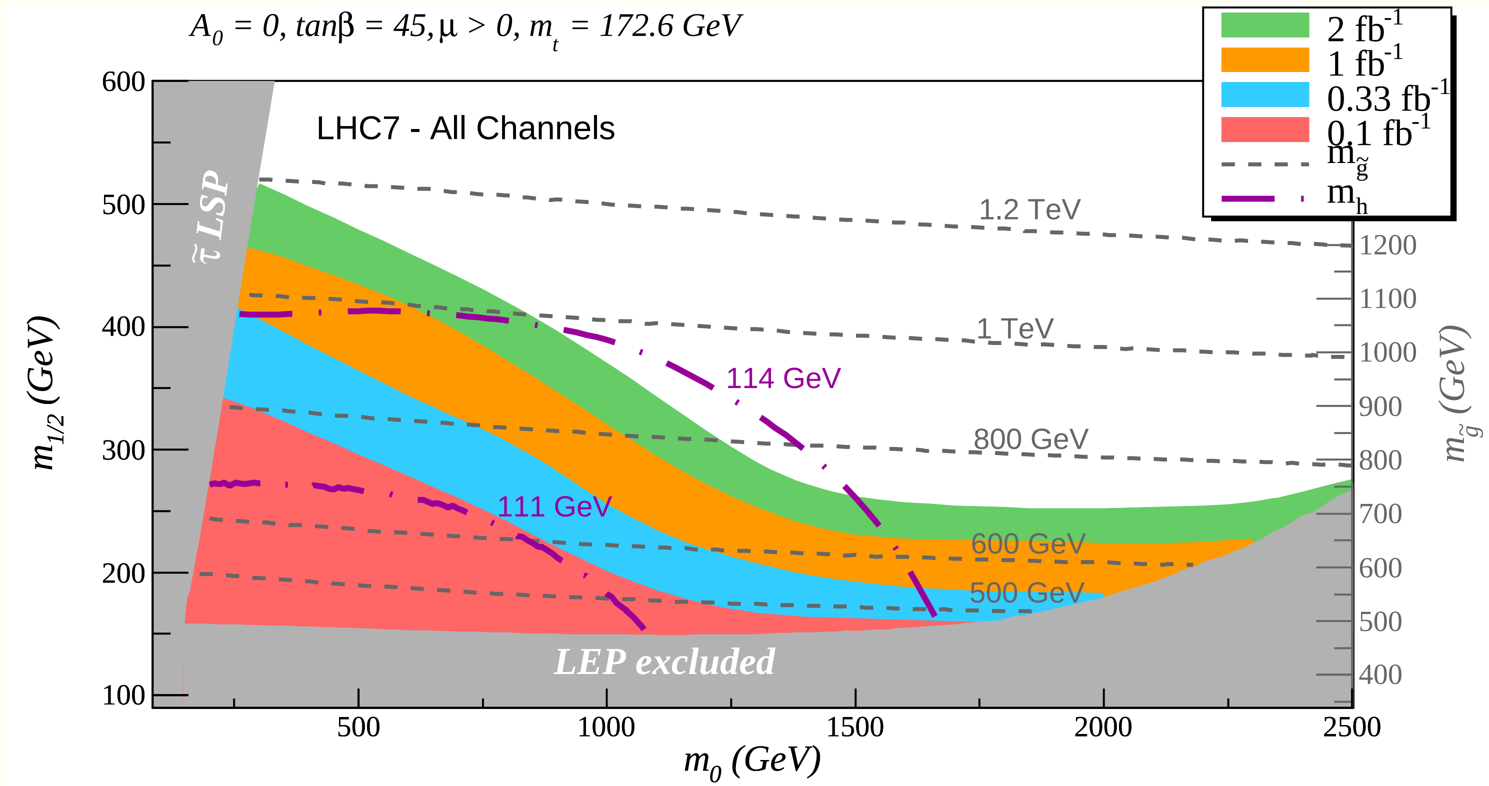
Standard Model backgrounds

SM process	Generator	Cross section
QCD: 2, 3 and 4 jets (40 GeV$< E_T(j1) < 100$ GeV)	AlpGen	2.6×10^9 fb
QCD: 2, 3 and 4 jets (100 GeV$< E_T(j1) < 200$ GeV)	AlpGen	3.9×10^8 fb
QCD: 2, 3 and 4 jets (200 GeV$< E_T(j1) < 500$ GeV)	AlpGen	1.6×10^7 fb
QCD: 2, 3 and 4 jets (500 GeV$< E_T(j1) < 3000$ GeV)	AlpGen	9.4×10^4 fb
$t\bar{t}$: $t\bar{t}$ + 0, 1 and 2 jets	AlpGen	1.6×10^5 fb
$b\bar{b}$: $b\bar{b}$ + 0, 1 and 2 jets	AlpGen	8.8×10^7 fb
Z + jets: $Z/\gamma(\rightarrow l\bar{l}, \nu\bar{\nu})$ + 0, 1, 2 and 3 jets	AlpGen	8.6×10^6 fb
W + jets: $W^{\pm}(\rightarrow l\nu)$ + 0, 1, 2 and 3 jets	AlpGen	1.8×10^7 fb
$Z + t\bar{t}$: $Z/\gamma(\rightarrow l\bar{l}, \nu\bar{\nu}) + t\bar{t}$ + 0, 1 and 2 jets	AlpGen	53 fb
$Z + b\bar{b}$: $Z/\gamma(\rightarrow l\bar{l}, \nu\bar{\nu}) + b\bar{b}$ + 0, 1 and 2 jets	AlpGen	2.6×10^3 fb
$W + b\bar{b}$: $W^{\pm}(\rightarrow all) + b\bar{b}$ + 0, 1 and 2 jets	AlpGen	6.4×10^3 fb
$W + t\bar{t}$: $W^{\pm}(\rightarrow all) + t\bar{t}$ + 0, 1 and 2 jets	AlpGen	1.8×10^2 fb

$W+tb$: $W^{\pm}(\to all)+\bar{t}b(t\bar{b})$	AlpGen	6.8×10^{2} fb
$t\bar{t}t\bar{t}$	MadGraph	0.6 fb
$t\bar{t}b\bar{b}$	MadGraph	1.0×10^{2} fb
$b\bar{b}b\bar{b}$	MadGraph	1.1×10^{4} fb
WW: $W^{\pm}(\to l\nu)+W^{\pm}(\to l\nu)$	AlpGen	3.0×10^{3} fb
WZ: $W^{\pm}(\to l\nu)+Z(\to all)$	AlpGen	3.4×10^{3} fb
ZZ: $Z(\to all)+Z(\to all)$	AlpGen	4.0×10^{3} fb

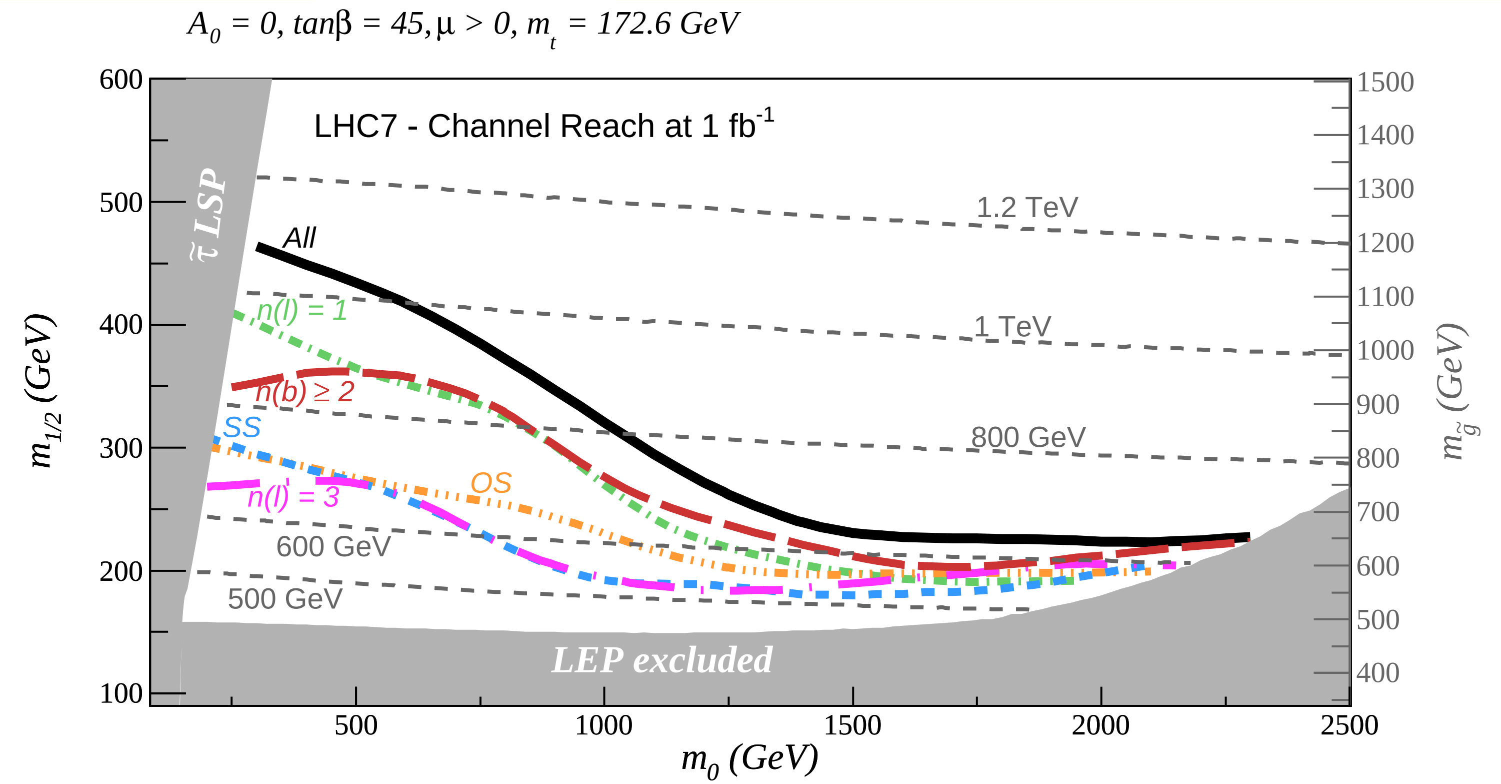
Table 1: Background processes included in this LHC7 study, along with their total cross sections and number of generated events. All light (and b) partons in the final state are required to have $E_T > 40$ GeV. For QCD, we generate the hardest final parton jet in distinct bins to get a better statistical representation of hard events. For Wtb production, additional multi-jet production is only via the parton shower because the AlpGen calculation including all parton emission matrix elements is not yet available. For this process, we apply the cut $|m(Wb)-m_t|\geq 5$ GeV to avoid double counting events from real $t\bar{t}$ production.

Sparticle reach of LHC for $\sqrt{s} = 7$ TeV

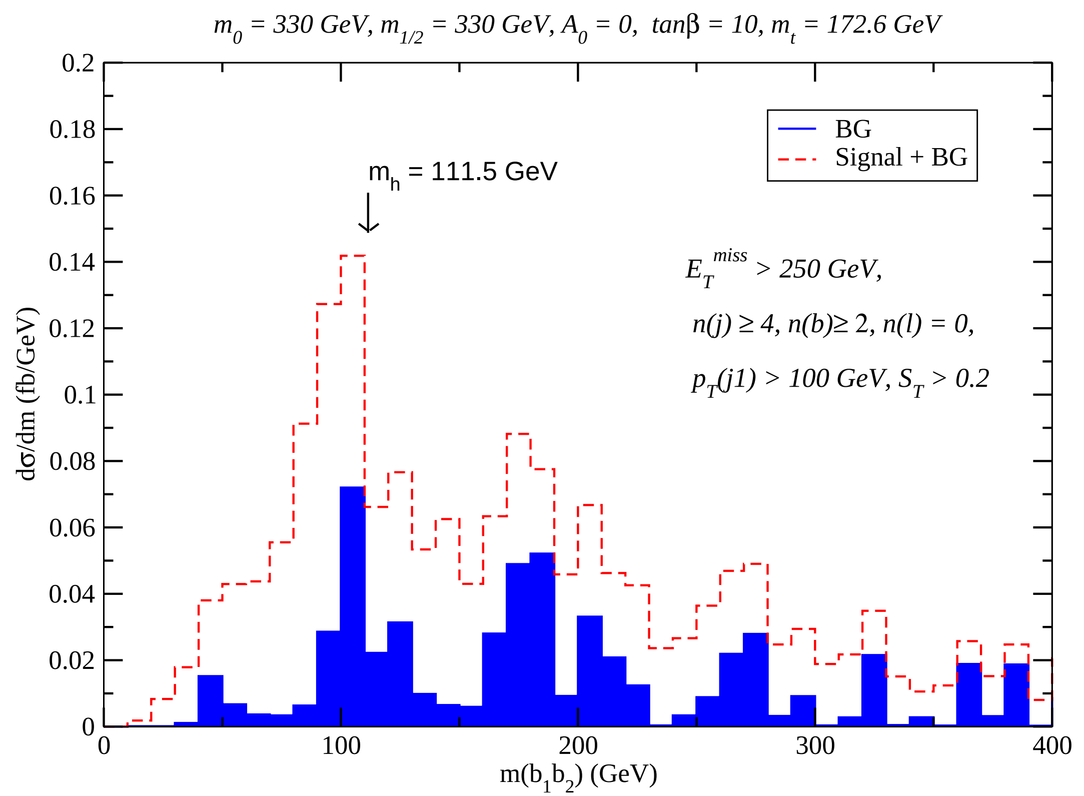


HB, Barger, Lessa, Tata: JHEP 1006: 102 (2010)

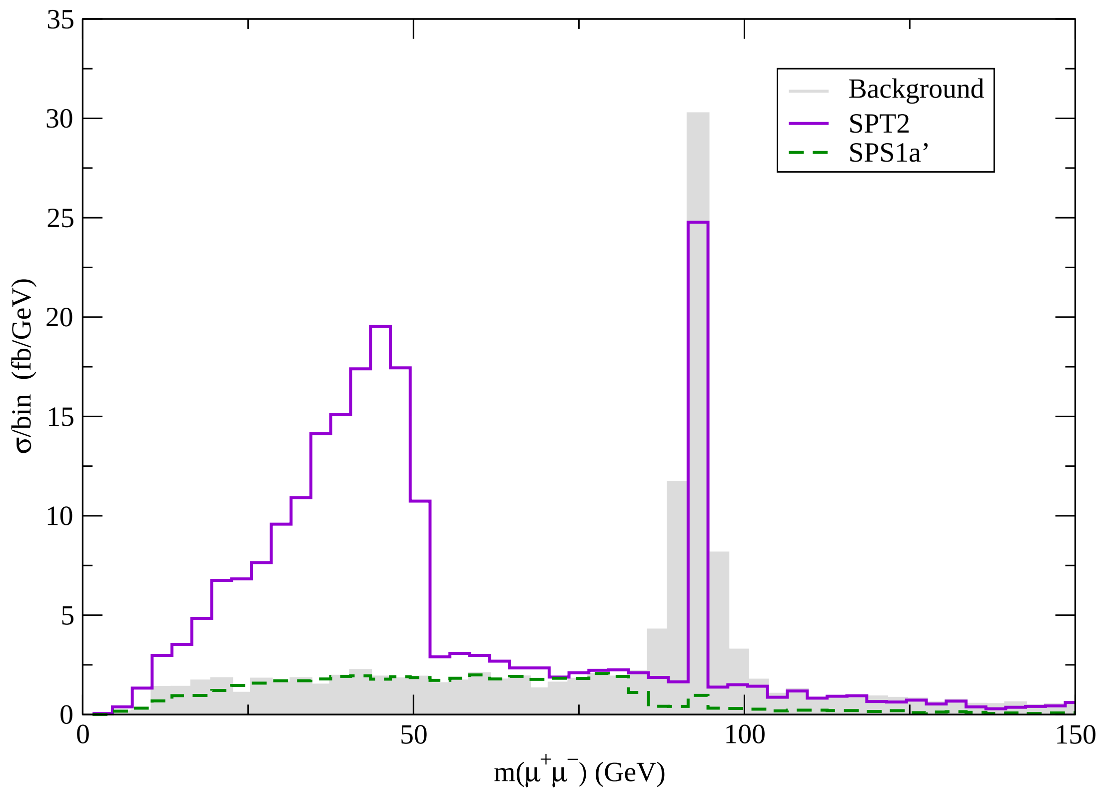
Sparticle reach with individual modes: 1 fb^{-1}



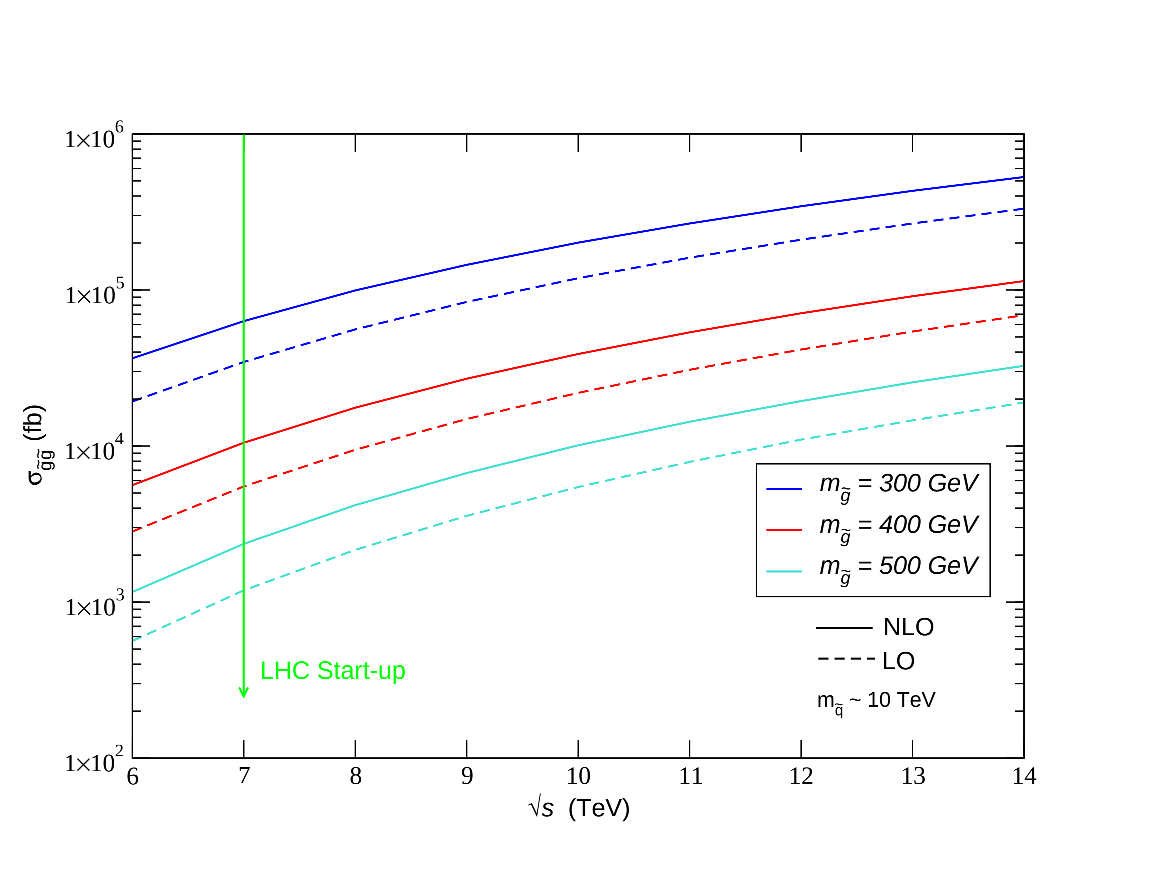
What about Higgs? Might see first in SUSY events



Smoking gun for $m_{\tilde{g}} \lesssim 630$ GeV: $m(\ell^+\ell^-)$ edge



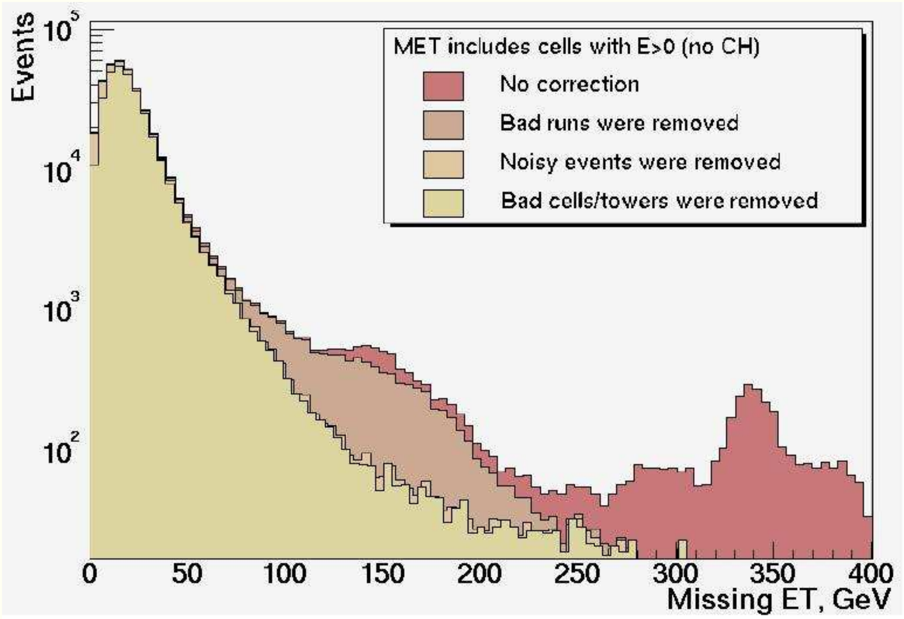
Issues in early search for SUSY: beam energy



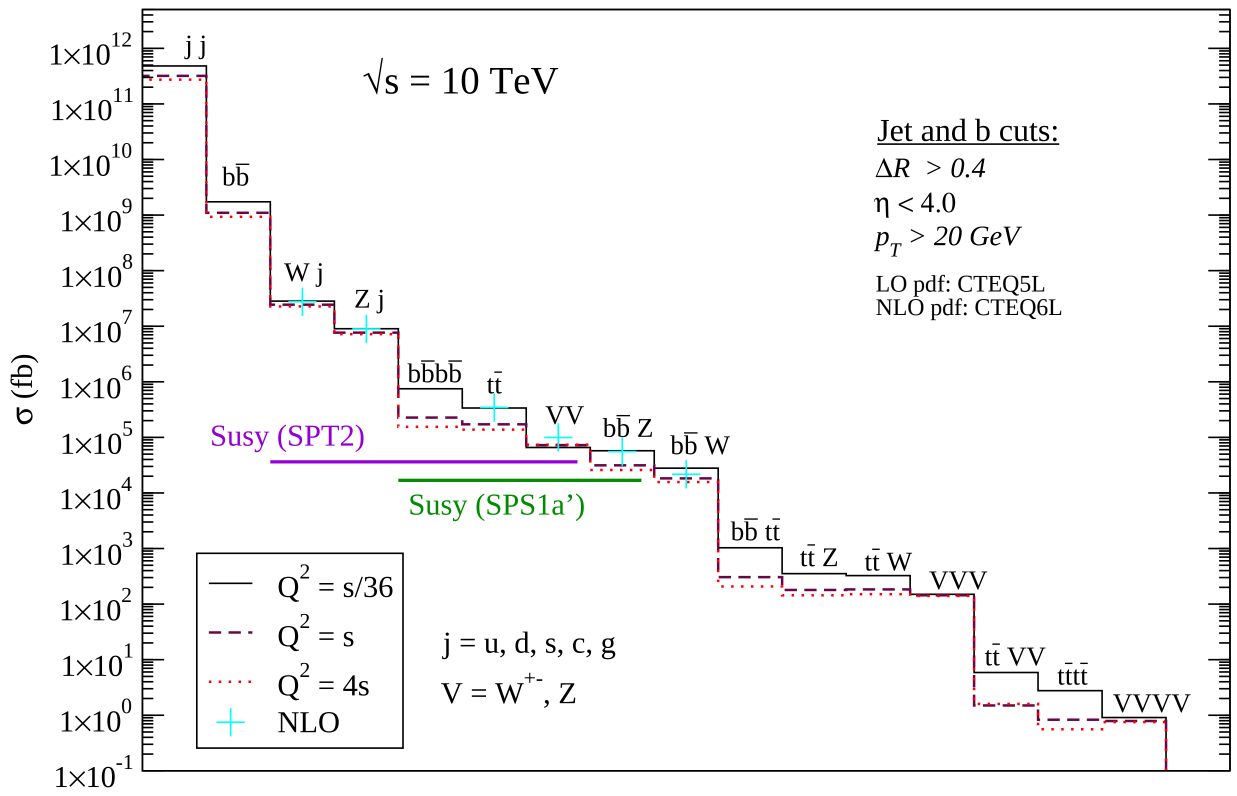
Early SUSY discovery at LHC with just 0.1 fb^{-1}?

- To make $\not{E}_T$ cut, complete knowledge of detector needed
  - dead regions
  - "hot" cells
  - cosmic rays
  - calorimeter mis-measurement
  - beam-gas events
- Can we make early discovery of SUSY at LHC *without* $\not{E}_T$?
- Expect SUSY events to be rich in jets, b-jets, isolated ℓs, τ-jets,....
- Use multiplicity of isolated muons rather than $\not{E}_T$
- HB, Prosper, Summy, PR**D77**, 055017 (2008); HB, Lessa, Summy, PL**B674**, 49 (2009)
- HB, Barger, Lessa, Tata, JHEP**0909**, 063 (2009)

D0 saga with missing E_T

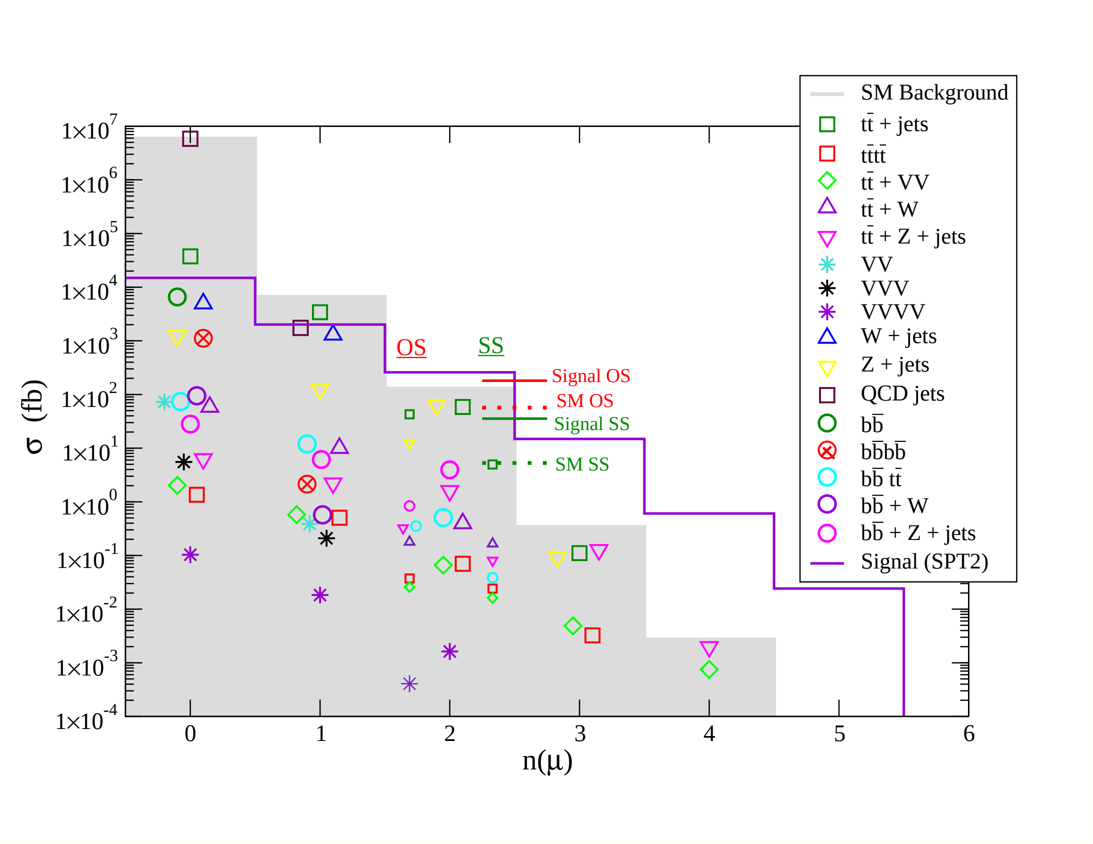


Possible SM sources of multi-muon events: $\sqrt{s} = 10$ TeV

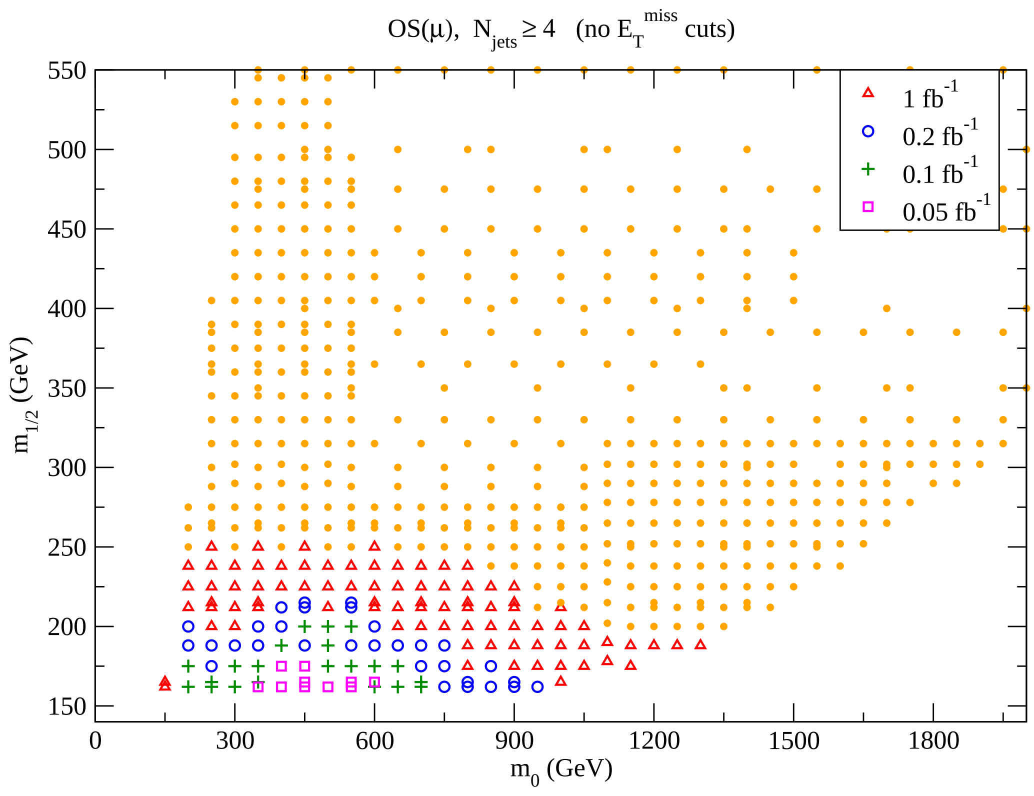


Simple cuts: ≥ 4 jets plus isolated muons: no $\not\!\!E_T$-cut

- SPT2 point: $(m_0, m_{1/2}, A_0, \tan\beta, sgn(\mu)) = (450\ \mathrm{GeV}, 170\ \mathrm{GeV}, 0, 45, +1)$
- note: dis-allowed by $\widetilde{Z}_1$ CDM but allowed for mixed $a/\tilde{a}$ CDM

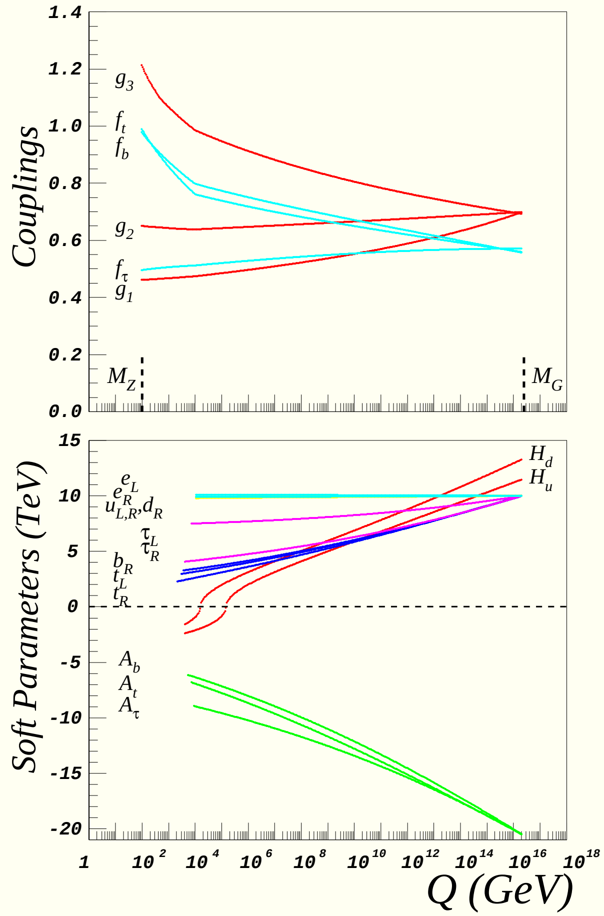


Require $n(jets) \geq 4$ and $\mu^+\mu^-$ pair: no $\not{E}_T$



Prediction for LHC: SUSY with $t-b-\tau$ Yukawa unification

- $m_{16},\ m_{10},\ M_D^2,\ m_{1/2},\ A_0,\ \tan\beta,\ sign(\mu)$
- need $m_{16} \sim 10$ TeV and $m_{1/2}$ very small
- need $m_{10} \simeq \sqrt{2} m_{16}$; $A_0 \simeq -2m_{16}$
- inverted scalar mass hierarchy: Bagger et al.
- split Higgs: $m_{H_u}^2 < m_{H_d}^2$
- Auto, HB, Balazs, Belyaev, Ferrandis, Tata
- HB, Kraml, Sekmen, Summy
  - $m_{\tilde{q},\tilde{\ell}}(1,2) \sim 10$ TeV
  - $m_{\tilde{t}_1},\ m_A,\ \mu \sim 1-2$ TeV
  - $m_{\tilde{g}} \sim 300-500$ GeV
- see also Blazek, Dermisek, Raby
- Altmannshofer, Guadagnoli, Raby, Straub



Consequences of $t-b-\tau$ Yukawa unified SUSY

- for $m_{16} \sim m_{3/2} > 5$ TeV allow $T_R \sim 10^6 - 10^8$ GeV (solve grav itino problem and allow non-thermal or DRT leptogenesis)
- huge $\Omega_{\widetilde{Z}_1} h^2 \sim 10^3 \Rightarrow$ dark matter is mixed axion/axino instead of neutralino
- $m_{\tilde{g}} \sim 400$ GeV $\Rightarrow \sigma(pp \to \tilde{g}\tilde{g}X) \sim 10^5$ fb at $\sqrt{s} = 14$ TeV LHC
- $\tilde{g} \to b\bar{b}\widetilde{Z}_2$ dominant; also, $\tilde{g} \to tb\widetilde{W}_1$
- expect beautiful mass edge in $m(\ell^+\ell^-)$
- testable at LHC with $\sim 0.1 - 1$ fb^{-1}
- reconstruct $m_{\tilde{g}}$ via $m(bb\ell^+\ell^-)$
- possible axion signal at ADMX?
- WIMP direct/indirct searches yield null result

Conclusions

★ LHC reach for SUSY very substantial for $\sqrt{s} = 7$ TeV and $\sim 0.1 - 1$ fb^{-1}!

	0.1 fb^{-1}	0.33 fb^{-1}	1 fb^{-1}	2 fb^{-1}
$\sqrt{s} = 7$ TeV	0.8 TeV	0.9 TeV	1.1 TeV	1.2 TeV
$\sqrt{s} = 10$ TeV	1.0 TeV	1.1 TeV	1.4 TeV	1.5 TeV
$\sqrt{s} = 14$ TeV	1.3 TeV	1.6 TeV	1.8 TeV	2.0 TeV

Table 2: The optimized SUSY reach of the LHC within the mSUGRA model expressed in terms of the gluino mass for integrated luminosity values of 0.1, 0.33, 1 and 2 fb^{-1} at $\sqrt{s} = 7$ TeV, 10 TeV and 14 TeV, assuming $m_{\tilde{q}} \sim m_{\tilde{g}}$.

- $SO(10)$ SUSY GUT with $t - b - \tau$ unification
- $m_{\tilde{g}} \sim 350 - 500$ GeV: huge rate for $\tilde{g}\tilde{g}$ production
- DM composed of axions/axinos: good prospects for axions at ADMX

Paige, Hinchliffe *et al.* case studies:

- examined many model case studies in mSUGRA, GMSB, high $\tan\beta$...
- classic study: pt.5 of PRD**55**, 5520 (1997) and PRD**62**, 015009 (2000)
- $m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ sign(\mu) = (100, 300, 0, 2, 1)$ in GeV
- dominant $\tilde{g}\tilde{g}$ production with $\tilde{g} \to q\tilde{q}_L \to qq\widetilde{Z}_2 \to q_1q_2\ell_1\tilde{\ell} \to q_1q_2\ell_1\ell_2\widetilde{Z}_1$ (string of 2-body decays)
- can reconstruct 4 mass edges; allows one to fit four masses: $m_{\tilde{q}_L},\ m_{\widetilde{Z}_2},\ m_{\tilde{\ell}},\ m_{\widetilde{Z}_1}$ to $3-12\%$
- can also find Higgs h in the SUSY cascade decay events
- if enough sparticle masses measured, can fit to MSSM/SUGRA parameters