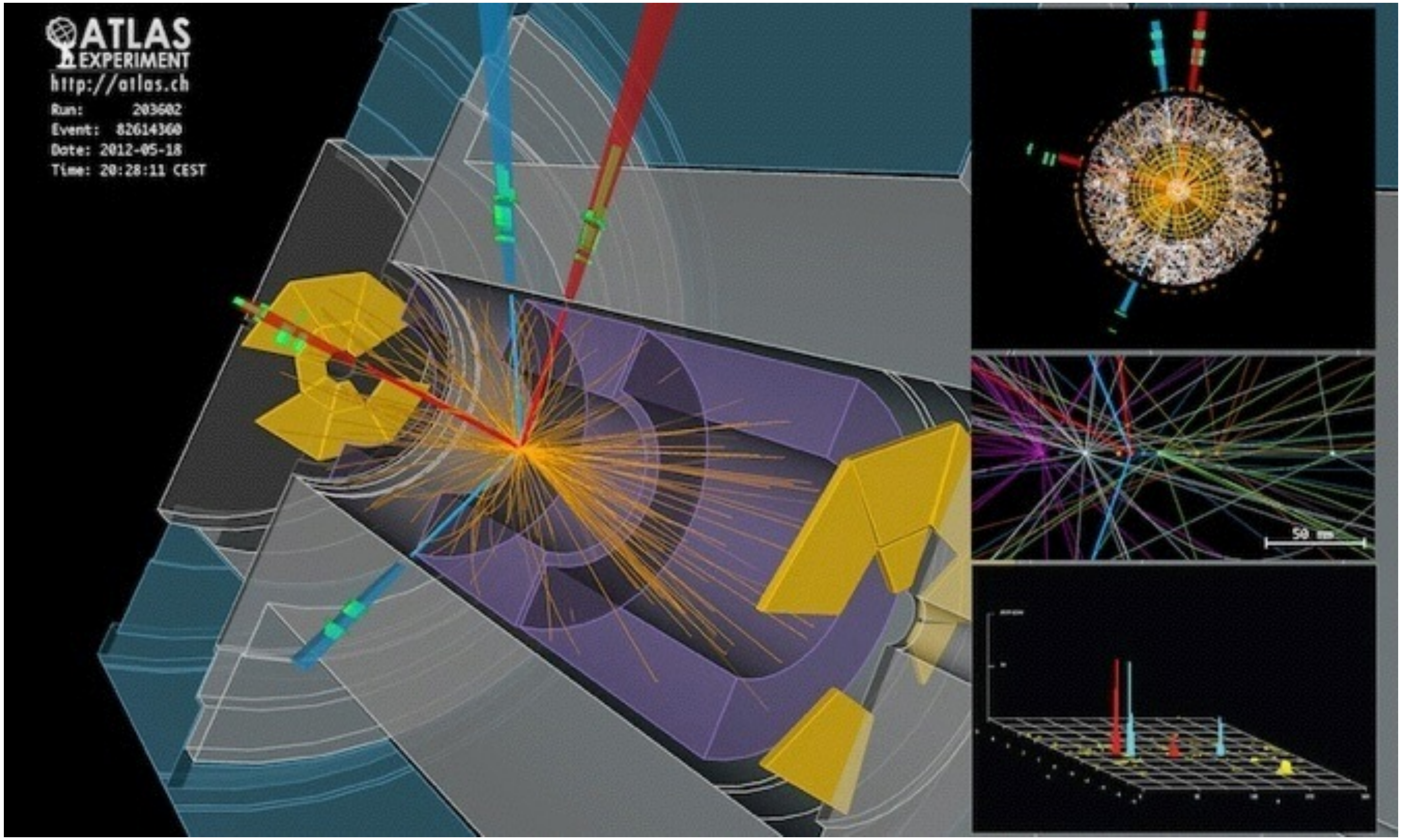
Teilchenphysik mit höchstenergetischen Beschleunigern (Higgs & Co)



12. Beyond the Standard Model - Supersymmetry

27.01.2014

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Prof. Dr. Siegfried Bethke
Dr. Frank Simon

Important: Registration for Exams

If you want to take an exam in this course remember to register!

The time & date for the exam is flexible
(the one given in TUMOnline is a dummy date) - Send me an email to fix one!

Interesting Opportunity for the Summer: CERN Summer Student Program

http://home.web.cern.ch/students-educators/updates/2013/10/apply-now-cerns-summer-student-programme

The Standard Model - Recap

- fundamental fermions: 3 families of quarks and leptons
- fundamental interactions: mediated by gauge bosons:
  - $W^{\pm}$, Z, γ : electroweak interactions (SU(2) x U(1))
  - Gluones: strong interaction (SU(3))
- Higgs mechanism to achieve electroweak symmetry breaking

... very good description of (almost) all observations to date: An impressive triumph of the Standard Model!

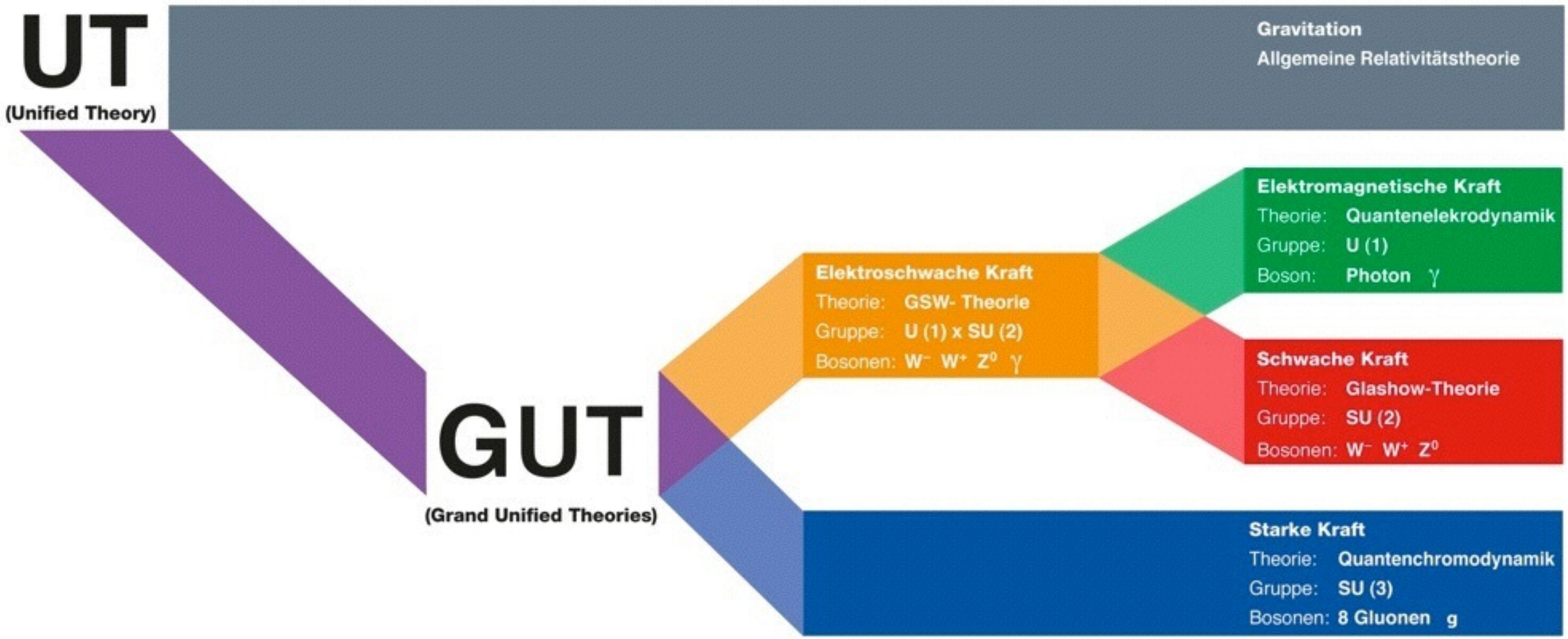
The Standard Model - Questions and Problems

- Reminder (outlined in the first lecture):

- Many free parameters - ~ 18 masses, couplings and mixing angles
- No unification of strong and electroweak interaction
  - GUT, E ~ 10^{16} GeV
- Why do quarks have exactly a charge of 1/3 e? Connection leptons - quarks
  - GUT, E ~ 10^{16} GeV
- Gravitation is not included (Quantum-theory of gravitation?)
  - TOE, E ~ 10^{19} GeV
- Hierarchy problem: Mass scale of SM vs Planck scale, cancelling of radiative corrections
  - SUSY, E ~ 10^3 GeV
- Dark Matter, CP violation, …
  - New particles & interactions

The Big Picture:
Grand Unified Theories - GUT

Physics beyond the Standard Model



- GUT in its simplest form (has to be a symmetry that encloses U(1), SU(2), SU(3)): SU(5) (Georgi, Glashow 1974)

GUT: Properties

- Multipletts of quarks and leptons
- New, heavy gauge bosons *X*, *Y*, which can transform quarks into leptons and vice versa: Electric charge 1/3, 4/3, carry color

- One of the features:
  - Electric charge is one of the generators of SU(5) - Gruppe - consequences:
    - Quantization of charge required
    - $\sum Q_i = 0$ for every multiplet: Families of quarks and leptons, for example [e, ν_e, 3 (u, d)]: The 3 colors automatically result in 1/3 - Ladungen für Quarks: Explanation of the neutrality of atoms!

- Other consequences:
  - Small, non-zero neutrino masses
  - Magnetic monopoles with a mass of ~ 10^{17} GeV

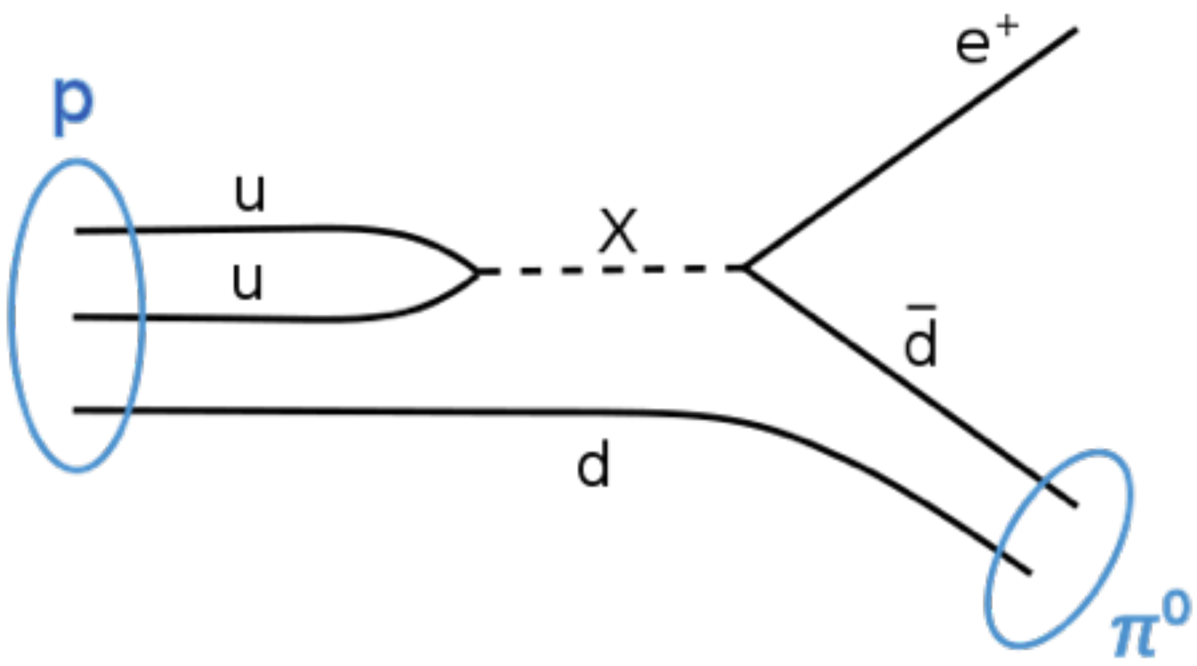
GUT: Proton Decay

- A consequence: proton decay via $p \rightarrow \pi^0 e^+$

  - Expected lifetime:

$$\tau_p \sim \frac{M_X^4}{\alpha_{GUT}^2 M_p^5} \sim 10^{30\pm1} \text{ yr}$$

for $M_X \sim 10^{15}$ GeV



Experimental result: $\tau_p > 5 \times 10^{32}$ yr (SuperKamiokande, 50 kT H_2O)

➩ Standard - SU(5) GUT already excluded!

➩ Several other possibilities exist which allow for larger proton lifetimes

GUT: Unification of Coupling Constants

- In GUTs the three interactions of the SM are different low-energy forms of one single interaction which is relevant above the GUT scale

Expectation: Unification of the running U(1), SU(2) and SU(3) coupling constants:

$\alpha_1(M_X) = \alpha_2(M_X) = \alpha_3(M_X)$ with: $\alpha_1 = 8\,\alpha_{em}/3 = 8(e^2/4\pi)/3$;

$\alpha_2 = g^2/4\pi$; $(g = e / \sin\theta_w)$

$\alpha_3 = \alpha_s$

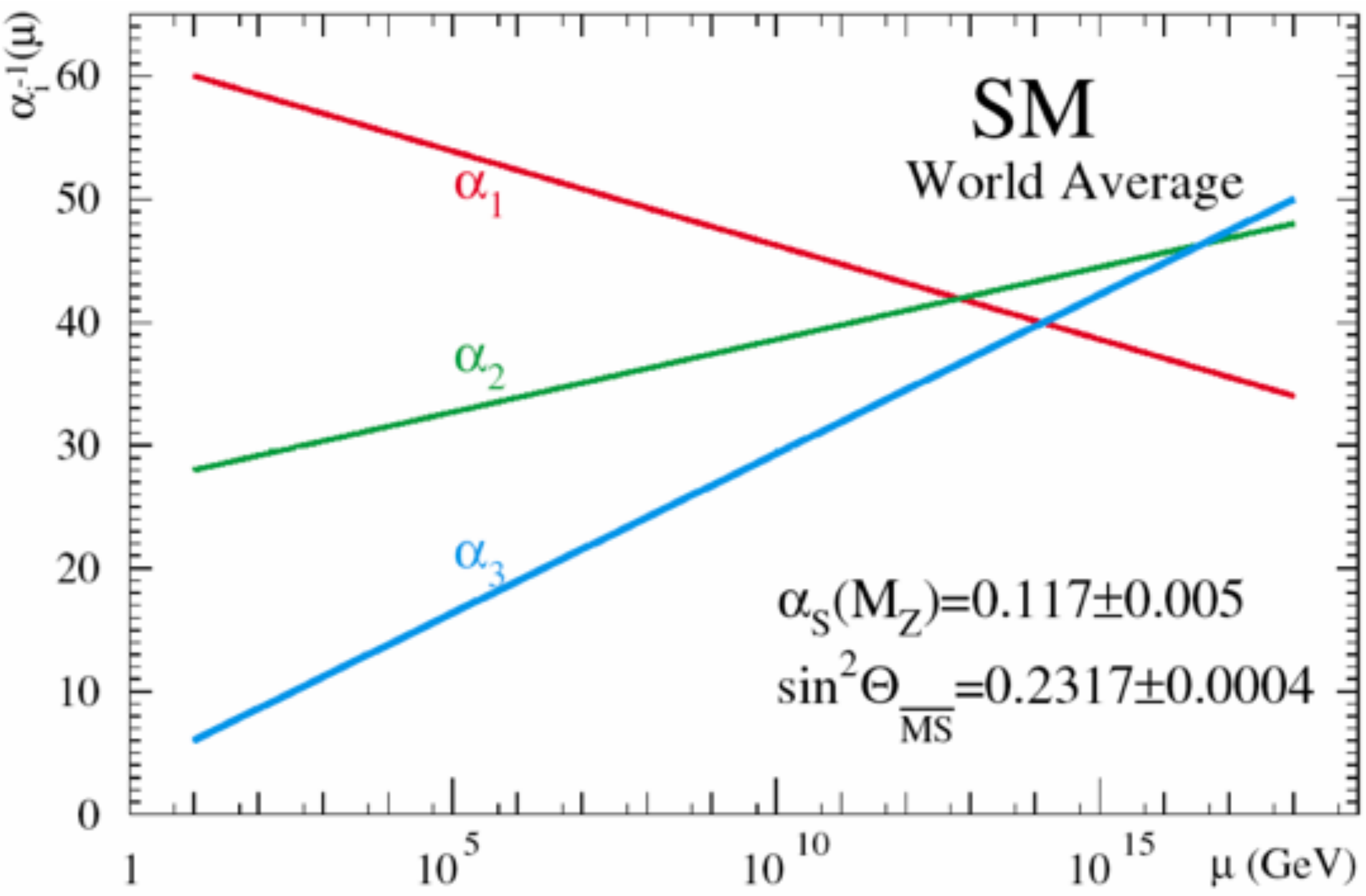
energy dependence: $$\alpha\left(q^2\right) = \frac{\alpha(\mu^2)}{1-\beta_0\alpha(\mu^2)\ln(q^2/\mu^2)} \;;\; \text{mit} \;\; -\beta_0 = \frac{11N_c - 4N_f}{12\pi}$$

$N_c = 0, 2, 3$ für U(1), SU(2), SU(3),

$N_f = 3$ (Number of fermion generations)

GUT: Unification of Coupling Constants

- Extrapolation of measured values:



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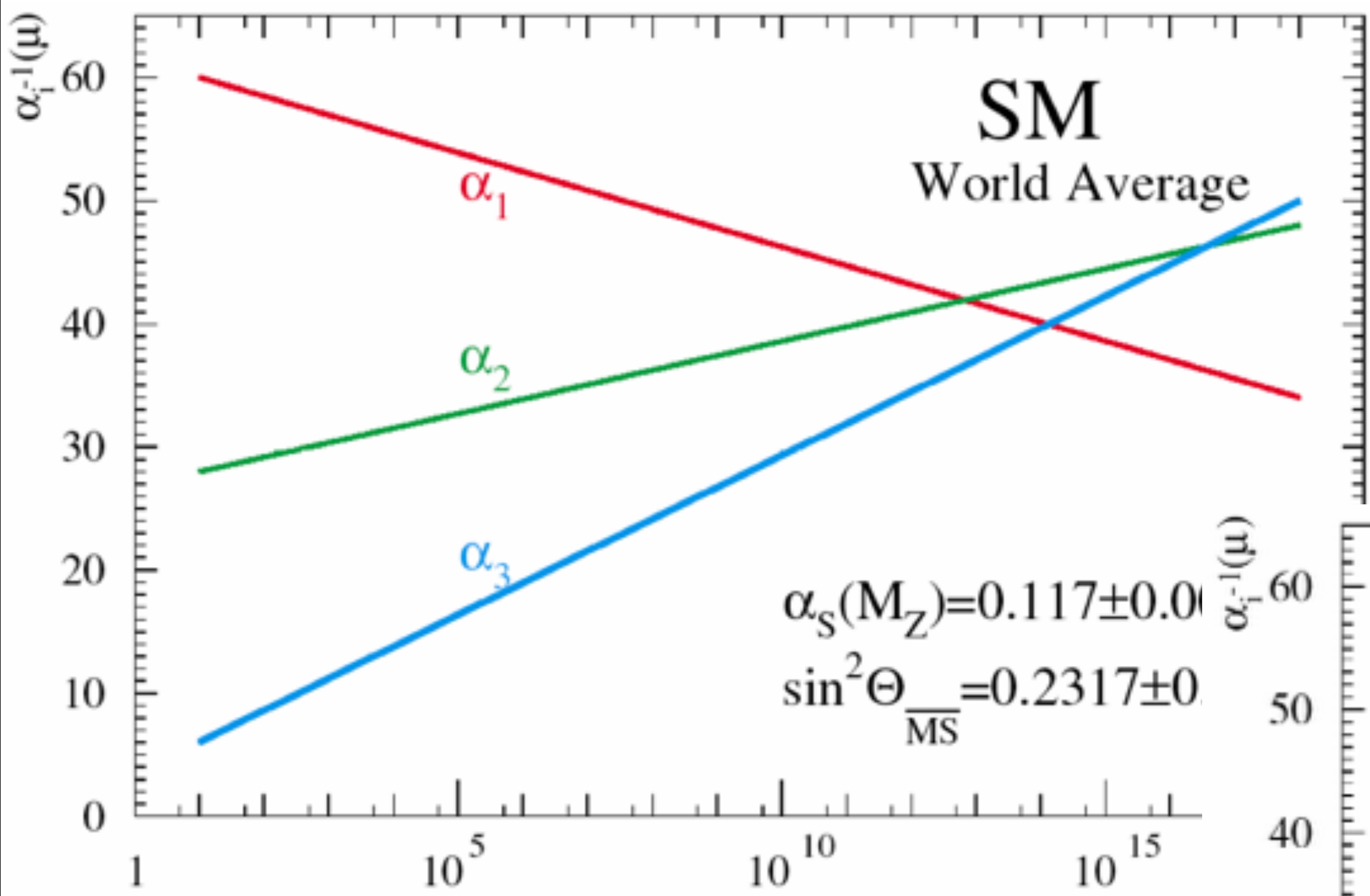
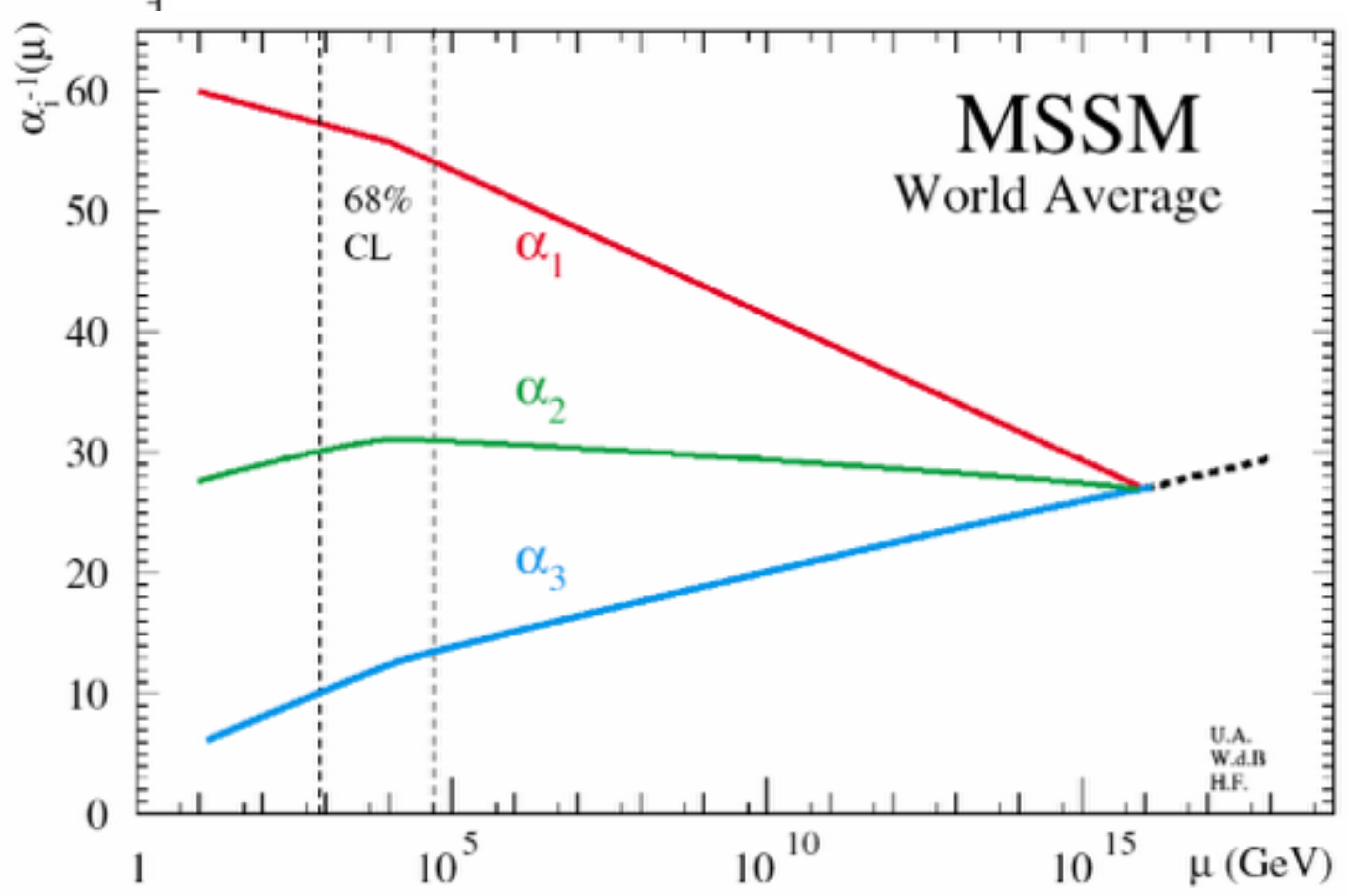


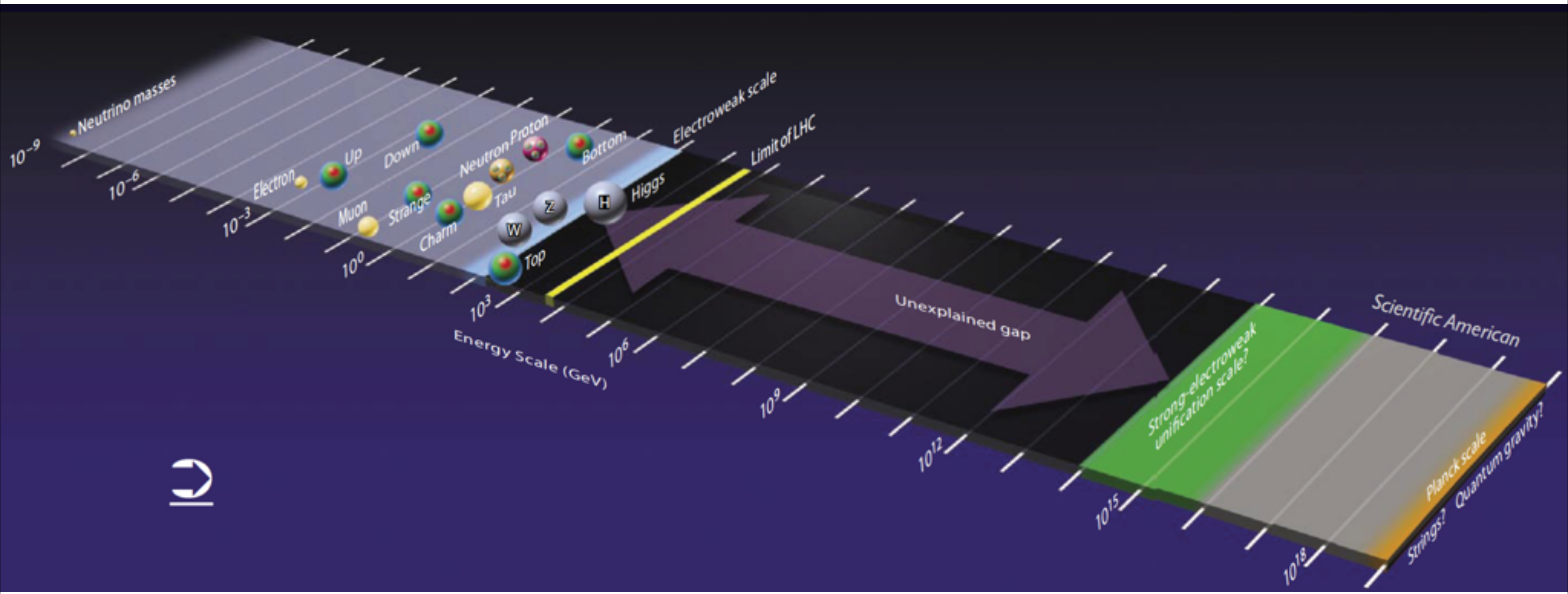
- Extrapolation when introducing new particles on the TeV scale (Supersymmetrie):



The most popular Extension of the SM
Supersymmetry - SUSY

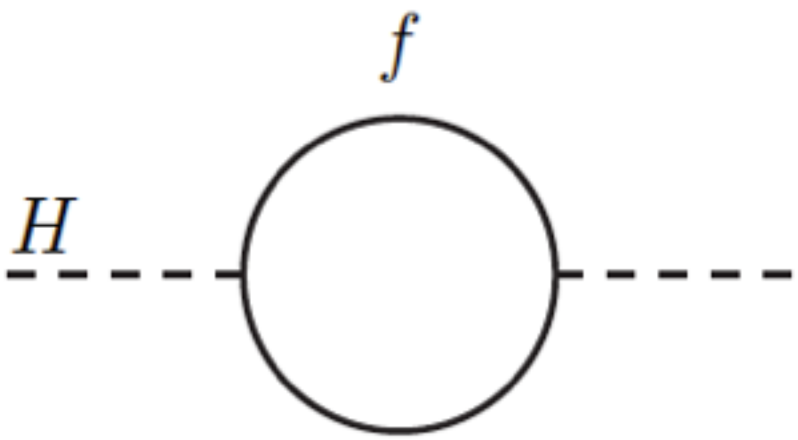
The Hierarchy Problem

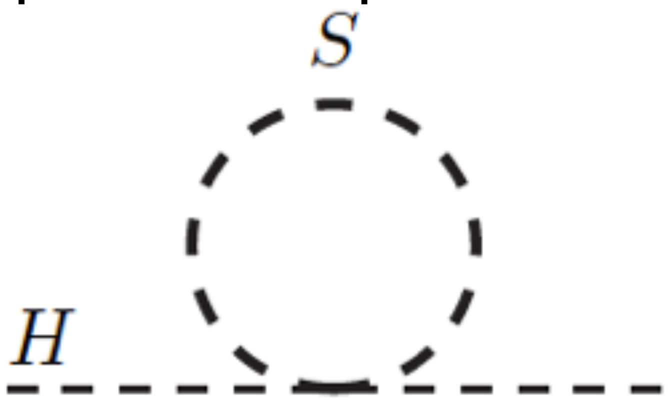
- The problem: Two mass scales: The Planck scale (~10^{19} GeV) and the electroweak scale (~10^{2} GeV) - separated by 17 orders of magnitude!
  - The consequence: Gravitation is much weaker than all other interactions
  - In the Standard Model: Higgs-Mass of 125 GeV: How is this stabilized?



Quantum Corrections to the Higgs Mass

Quantum corrections to the Higgs mass via particle loops





Contribution of fermion loops

$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{\mathrm{UV}}^2 + \ldots .$$

contribution of boson loops

$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}\left[\Lambda_{\mathrm{UV}}^2 - 2m_S^2 \ln(\Lambda_{\mathrm{UV}}/m_S) + \ldots\right]$$

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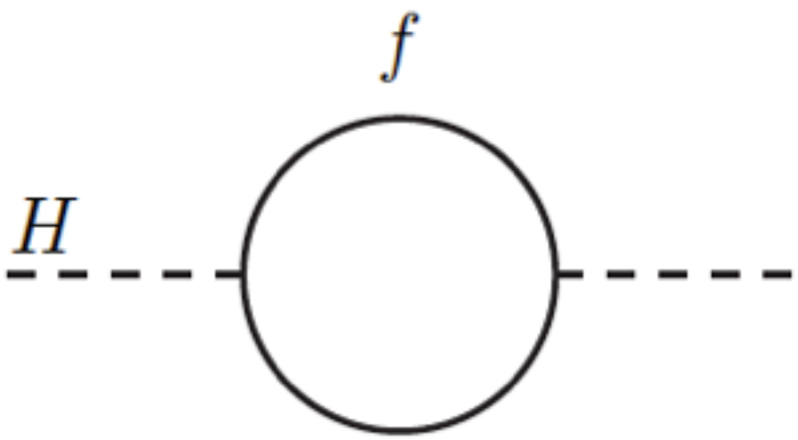

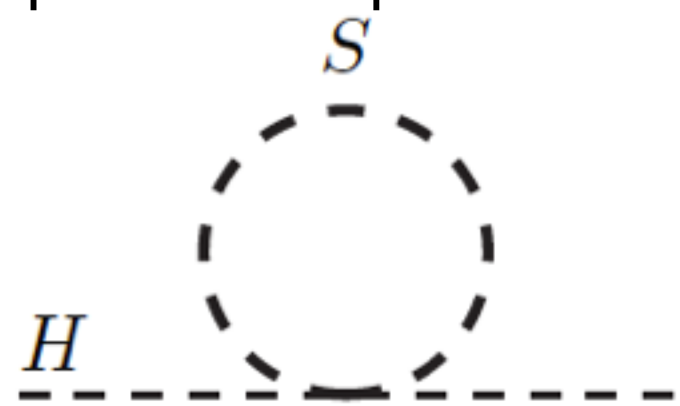

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Corrections depend on the scale until which they have to be taken into account - The natural UV scale: M_P, results in enormous corrections due to the Λ^2 behavior

In the SM: Largest contribution from the top quark: Strongest coupling to the Higgs field, $\lambda_f \sim 1$

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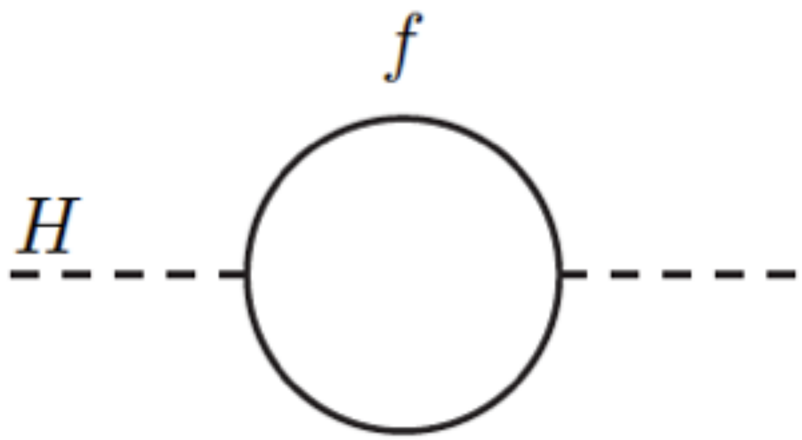

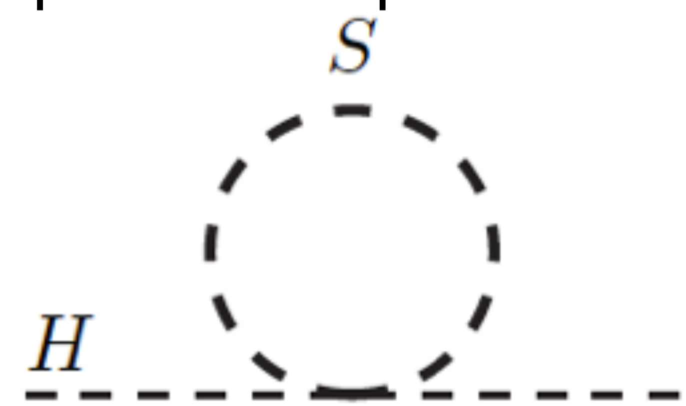

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In the SM: Largest contribution from the top quark: Strongest coupling to the Higgs field, $\lambda_f \sim 1$

Also so far unknown, heavy particles contribute, the heaviest particle which couples to the Higgs field dominates!

➯ Requires unnatural fine tuning to save a small Higgs mass

A Solution: A New Symmetry

- The strategy for a solution is suggested by the correction terms:

$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{\mathrm{UV}}^2 + \ldots. \qquad \Delta m_H^2 = \frac{\lambda_S}{16\pi^2}\left[\Lambda_{\mathrm{UV}}^2 - 2m_S^2 \ln(\Lambda_{\mathrm{UV}}/m_S) + \ldots\right]$$

  Contributions of fermions and bosons have opposite sign!

- Cancelation of these contributions is automatic, if there is a symmetry between bosons and fermions, a so-called ***Supersymmetry***
- A SUSY - gauge transformation transforms bosons into fermions and vice versa:

$$Q|\mathrm{Boson}\rangle = |\mathrm{Fermion}\rangle, \qquad Q|\mathrm{Fermion}\rangle = |\mathrm{Boson}\rangle$$

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- Consequences of Supersymmetry:
  - Each fermion in the SM has a bosonic “superpartner” with 1/2 different spin, analoguous for every boson
  - The partners are arranged in so-called “super-multipletts”
  - For an exact symmetry, the masses of particles and their superpartners are identical

Side Remark: Origin of Supersymmetry

- Was originally not developed to solve the hierarchy problem, but was studied as a theoretically interesting new symmetry

Nuclear Physics B70 (1974) 39–50. North-Holland Publishing Company

~ 2000 citations!

SUPERGAUGE TRANSFORMATIONS IN FOUR DIMENSIONS

J. WESS
Karlsruhe University

B. ZUMINO
CERN, Geneva

Received 5 October 1973

Julius Wess,
MPP and LMU,
† 2007

The Supersymmetric Fields

chiral super-multiplets

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)	$\overline{u}$	$\tilde{u}^*_R$	$u^\dagger_R$	$(\overline{\mathbf{3}}, \mathbf{1}, -\frac{2}{3})$
	$\overline{d}$	$\tilde{d}^*_R$	$d^\dagger_R$	$(\overline{\mathbf{3}}, \mathbf{1}, \frac{1}{3})$
sleptons, leptons	L	$(\tilde{\nu} \ \ \tilde{e}_L)$	$(\nu \ \ e_L)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$
(×3 families)	$\overline{e}$	$\tilde{e}^*_R$	$e^\dagger_R$	$(\mathbf{1}, \mathbf{1}, 1)$
Higgs, higgsinos	H_u	$(H_u^+ \ \ H_u^0)$	$(\tilde{H}_u^+ \ \ \tilde{H}_u^0)$	$(\mathbf{1}, \mathbf{2}, +\frac{1}{2})$
	H_d	$(H_d^0 \ \ H_d^-)$	$(\tilde{H}_d^0 \ \ \tilde{H}_d^-)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$

gauge super-multiplets

Names	spin 1/2	spin 1	$SU(3)_C, SU(2)_L, U(1)_Y$
gluino, gluon	$\tilde{g}$	g	$(\mathbf{8}, \mathbf{1}, 0)$
winos, W bosons	$\tilde{W}^\pm \ \ \tilde{W}^0$	$W^\pm \ \ W^0$	$(\mathbf{1}, \mathbf{3}, 0)$
bino, B boson	$\tilde{B}^0$	B^0	$(\mathbf{1}, \mathbf{1}, 0)$

- Important: Left- and right-handed fermions have separate superpartners
- 2 scalar Higgs doublets: 5 physical Higgs particles

R Parity

- Supersymmetry introduces a new quantum number that allows to distinguish normal particles and their superpartners:
  The so-called R parity

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

  with baryon number B, lepton number L und spin s
  - The SM particles and the Higgs multiplets have $P_R = 1$
  - The sfermions, Higgsinos and gauginos have $P_R = -1$

- Consequence: If R parity is conserved supersymmetric particles can only be produced in pairs, and there has to be a stable supersymmetric particle (the lightest supersymmetric particles, LSP)

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In general we assume R parity conservation in the following…

The Supersymmetric Particle Spectrum I

- In general: The fields with the same quantum numbers can mix and can form new mass eigenstates

- The Higgs sector (not supersymmetric)
  - The fields H_u and H_d describe the Yukawa coupling to the up- and down families (hypercharge!)
  - The result:
    - One light neutral Higgs h^0 (the SM Higgs), a heavy H^0, and the A^0
    - Two charged Higgs bosons H^+, H^-

  - New parameters:
    - Vaccum expectation values of the Higgs fields: $< H_u > / < H_d >= tan\beta$
    - Higgs mass term μ
    - Consistency bounds: the mass of the lightest Higgs has to be < ~ 130 GeV ✔

The Supersymmetric Particle Spectrum II

- Mixing of higgsinos $(\tilde{H}_u^+, \tilde{H}_d^-, \tilde{H}_u^0, \tilde{H}_d^0)$ and gauginos $(\tilde{B}^0, \tilde{W}^+, \tilde{W}^-, \tilde{W}^0)$ to neutralinos und charginos: $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$ $\quad \tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$

The full picture:

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$
squarks	0	−1	$\tilde{u}_L\ \tilde{u}_R\ \tilde{d}_L\ \tilde{d}_R$	(same)
			$\tilde{s}_L\ \tilde{s}_R\ \tilde{c}_L\ \tilde{c}_R$	(same)
			$\tilde{t}_L\ \tilde{t}_R\ \tilde{b}_L\ \tilde{b}_R$	$\tilde{t}_1\ \tilde{t}_2\ \tilde{b}_1\ \tilde{b}_2$
sleptons	0	−1	$\tilde{e}_L\ \tilde{e}_R\ \tilde{\nu}_e$	(same)
			$\tilde{\mu}_L\ \tilde{\mu}_R\ \tilde{\nu}_\mu$	(same)
			$\tilde{\tau}_L\ \tilde{\tau}_R\ \tilde{\nu}_\tau$	$\tilde{\tau}_1\ \tilde{\tau}_2\ \tilde{\nu}_\tau$
neutralinos	1/2	−1	$\tilde{B}^0\ \tilde{W}^0\ \tilde{H}_u^0\ \tilde{H}_d^0$	$\tilde{N}_1\ \tilde{N}_2\ \tilde{N}_3\ \tilde{N}_4$
charginos	1/2	−1	$\tilde{W}^\pm\ \tilde{H}_u^+\ \tilde{H}_d^-$	$\tilde{C}_1^\pm\ \tilde{C}_2^\pm$
gluino	1/2	−1	$\tilde{g}$	(same)
goldstino (gravitino)	1/2 (3/2)	−1	$\tilde{G}$	(same)

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			$\tilde{t}_L\ \tilde{t}_R\ \tilde{b}_L\ \tilde{b}_R$	$\tilde{t}_1\ \tilde{t}_2\ \tilde{b}_1\ \tilde{b}_2$
sleptons	0	−1	$\tilde{e}_L\ \tilde{e}_R\ \tilde{\nu}_e$	(same)
			$\tilde{\mu}_L\ \tilde{\mu}_R\ \tilde{\nu}_\mu$	(same)
			$\tilde{\tau}_L\ \tilde{\tau}_R\ \tilde{\nu}_\tau$	$\tilde{\tau}_1\ \tilde{\tau}_2\ \tilde{\nu}_\tau$
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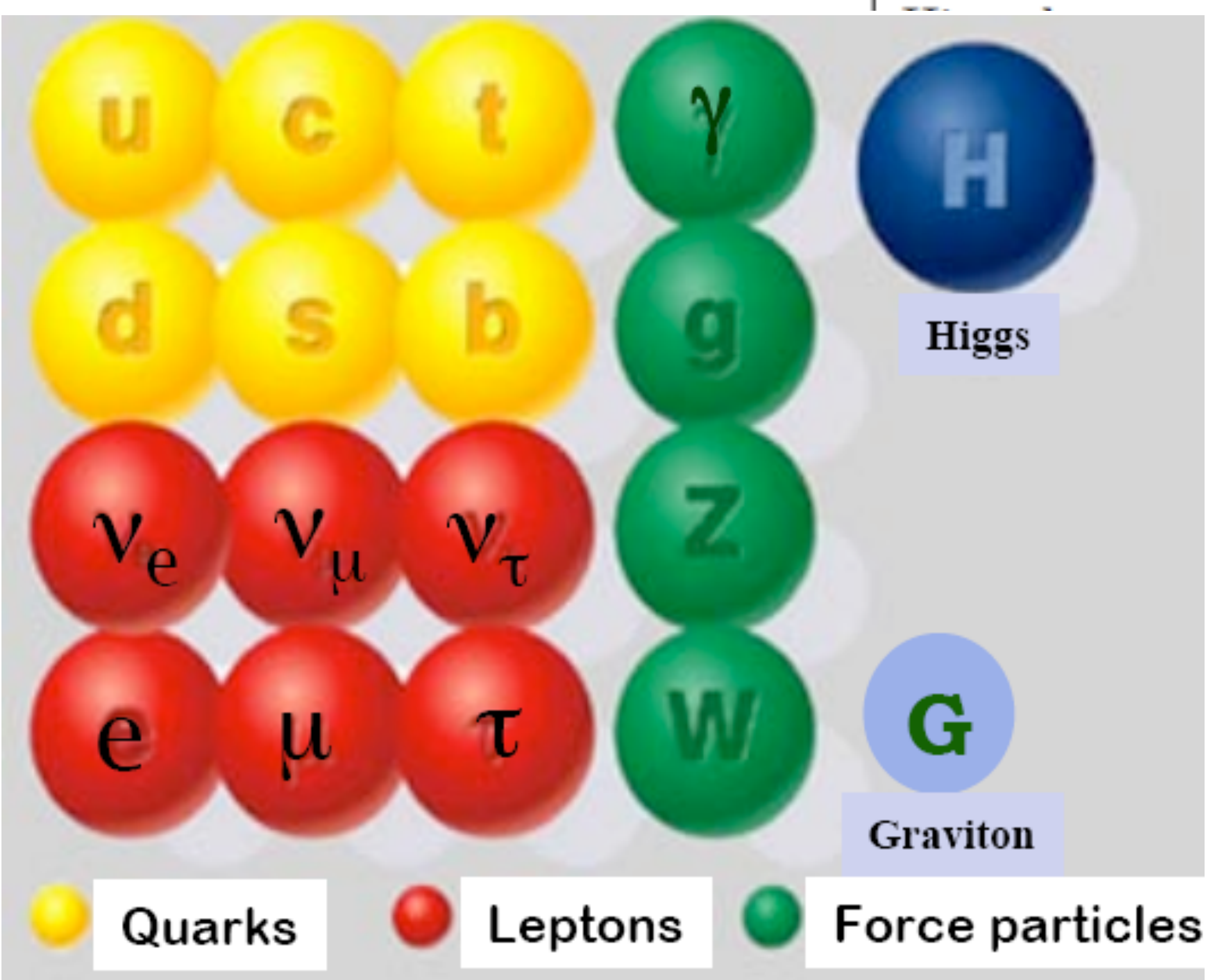
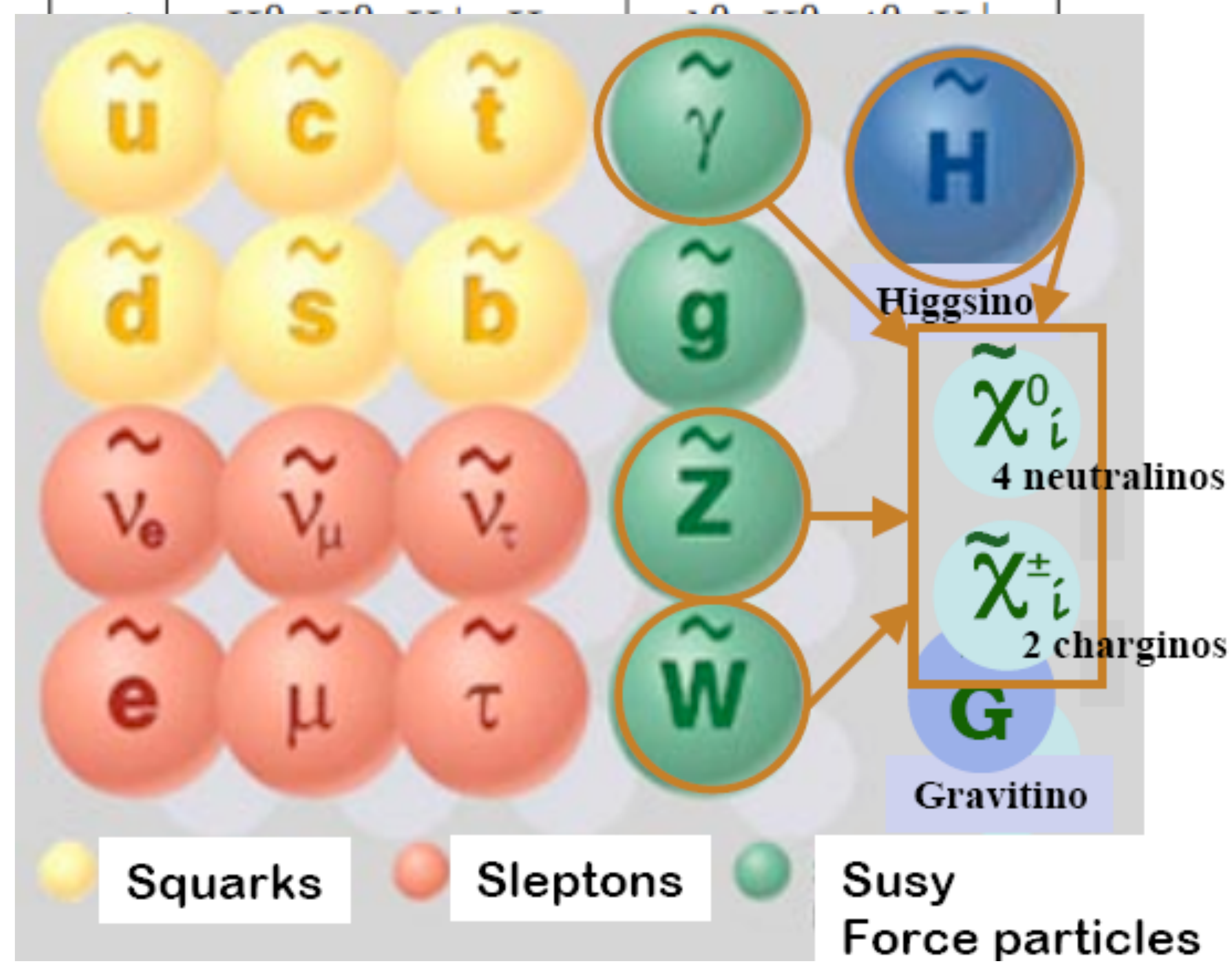




Supersymmetry Breaking I

- To date not a single SUSY particle has been observed: If SUSY exists, the superpartners have to be considerably more heavy than the SM particles
  ➯ Supersymmetry has to be broken in the ground state!
  - Important: The symmetry breaking should not destroy the beneficial effects such as cancellation of loop corrections - So-called soft SUSY breaking by the addition of a “soft” term to the Lagrange density

$$\mathcal{L} = \mathcal{L}_{\mathrm{SUSY}} + \mathcal{L}_{\mathrm{soft}}$$

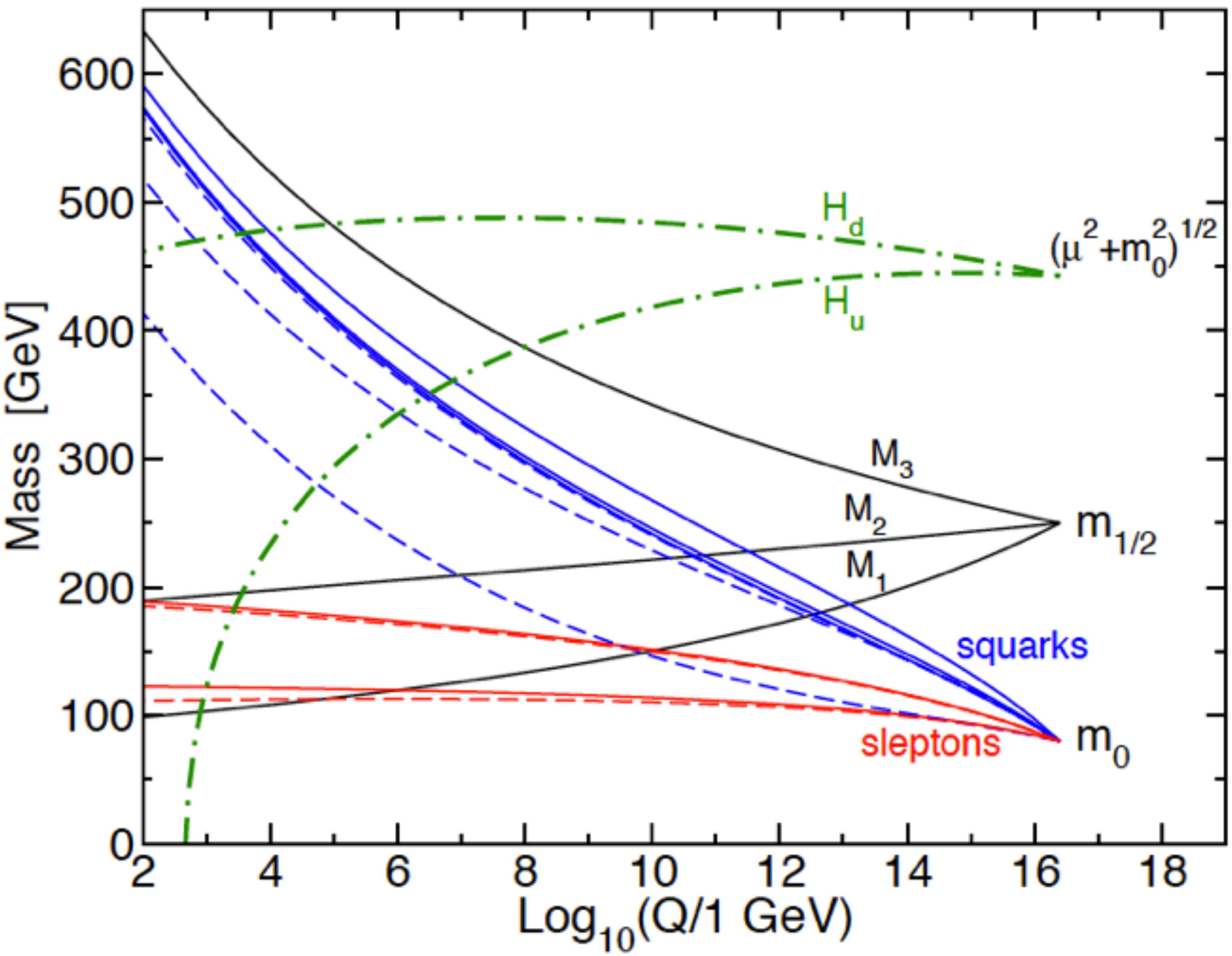
Different SUSY models (distinguished by the mechanism of SUSY breaking):

- MSSM (Minimal Supersymmetric Standard Model):
  - minimal particle content
  - SUSY breaking “done by hand”
  - ▸ 105 new free parameters to describe SUSY breaking!

Supersymmetry Breaking II - Selected Models

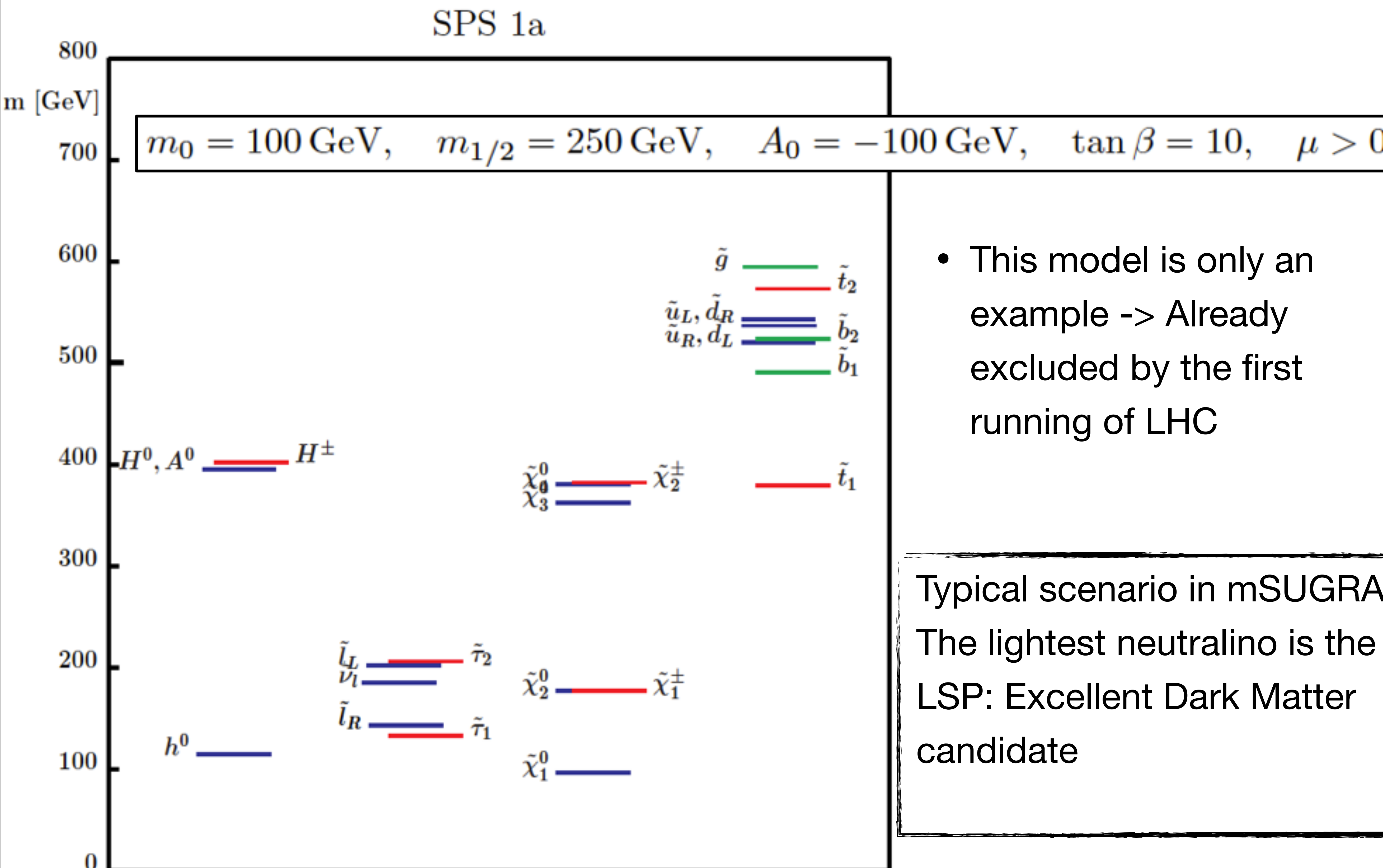
- SUGRA (SuperGravity):
  - SUSY breaking in a "hidden sector", which is connected via gravity to the MSSM sector
    - Very heavy gravitino: irrelevant for particle physics
- mSUGRA (minimal SuperGravity) - Very popular for SUSY studies
  - Simple parameter set due to the assumption, that all squarks and sleptons have the same mass $\boldsymbol{m_0}$ and all gauginos have the same mass $\boldsymbol{m_{1/2}}$ at the GUT scale. The masses at lower energies can then be calculated based on that.
  - 5 free parameters: m_0, $m_{1/2}$, m_A, $\tan\beta$, $\mathrm{sgn}(\mu)$
- GMSB (gauge mediated SUSY breaking)
  - Normal gauge interactions are responsible for soft SUSY breaking in the MSSM, Einführung neuer "Messengers", introdution of new messenger particles
  - Gravitino as lightest SUSY particle, particle physics phenomenology is given by the second lightest SUSY particle
- ...

A Typical Mass Spectrum in mSUGRA



- Evolution of particle masses as a function of scale
  - Common mass values at the GUT scale (here 2.5 x 10^{16} GeV)

A Typical Mass Spectrum in mSUGRA

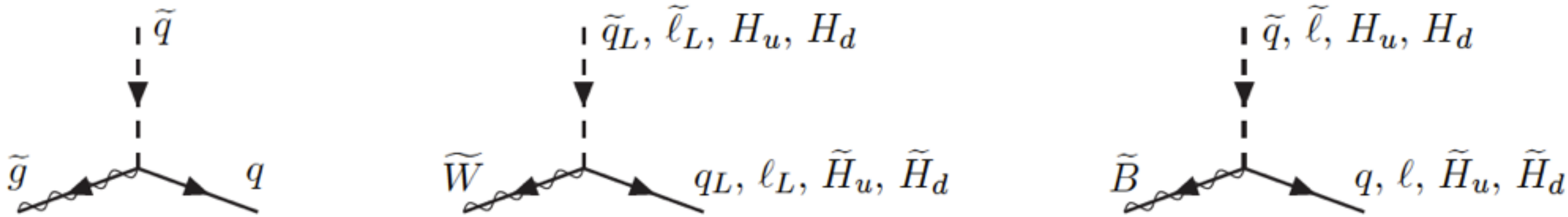


- This model is only an example -> Already excluded by the first running of LHC

Typical scenario in mSUGRA: The lightest neutralino is the LSP: Excellent Dark Matter candidate

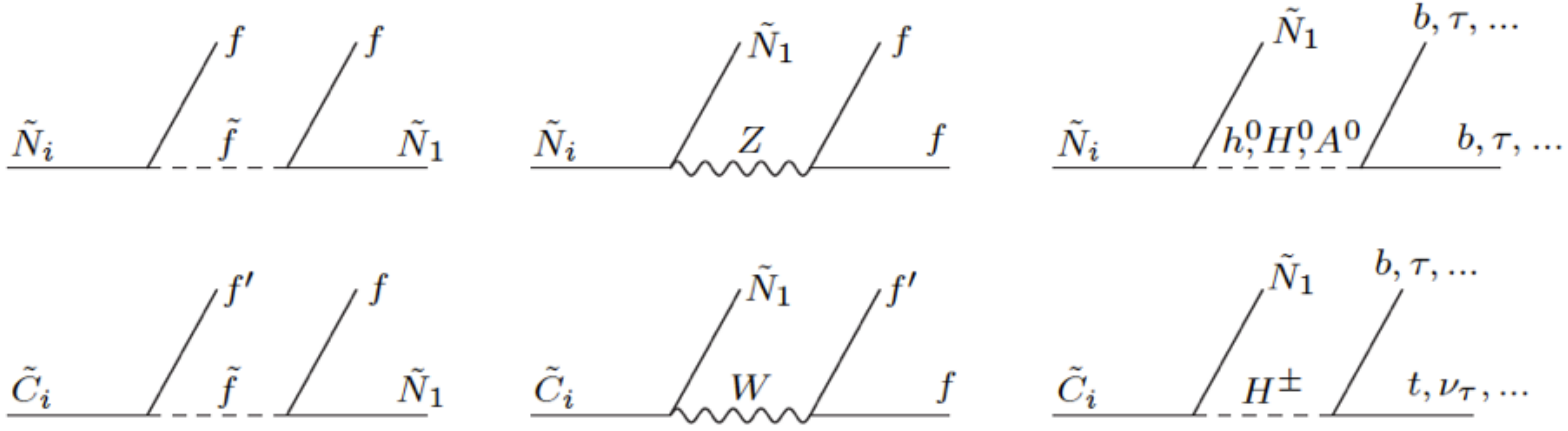
The Interaction of SUSY Particles

- SUSY - interact just as SM particles according to their quantum numbers
  - Right-sfermions (handedness here refers to the SM partners, since the sfermions have spin 0) do not carry weak isospin and therefore do not couple to W bosons
- Coupling to SUSY gauge bosons:



Decay of SUSY Particles I

- Strongly depends on the particle spectrum, here assuming typical mSUGRA
- Neutralinos / Charginos



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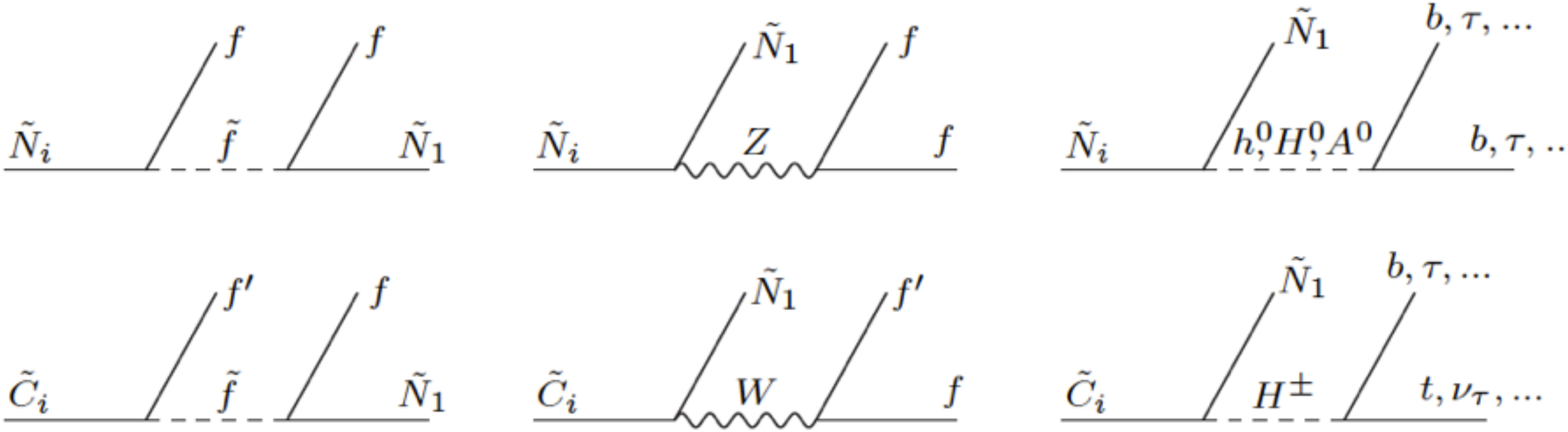

- Sleptons $\qquad \widetilde{\ell} \to \ell \widetilde{N}_i, \quad \widetilde{\ell} \to \nu \widetilde{C}_i, \quad \widetilde{\nu} \to \nu \widetilde{N}_i, \quad \widetilde{\nu} \to \ell \widetilde{C}_i$

  Possible differences of left and right-sleptons: R-sleptonen only couple to Binos, in many models this results in decays directly to the lightest Charginos - Neutralinos, L-sleptonen may prefer heavier particles with higher Wino-content (stronger coupling!)

Decay of SUSY Particles II

- Squarks
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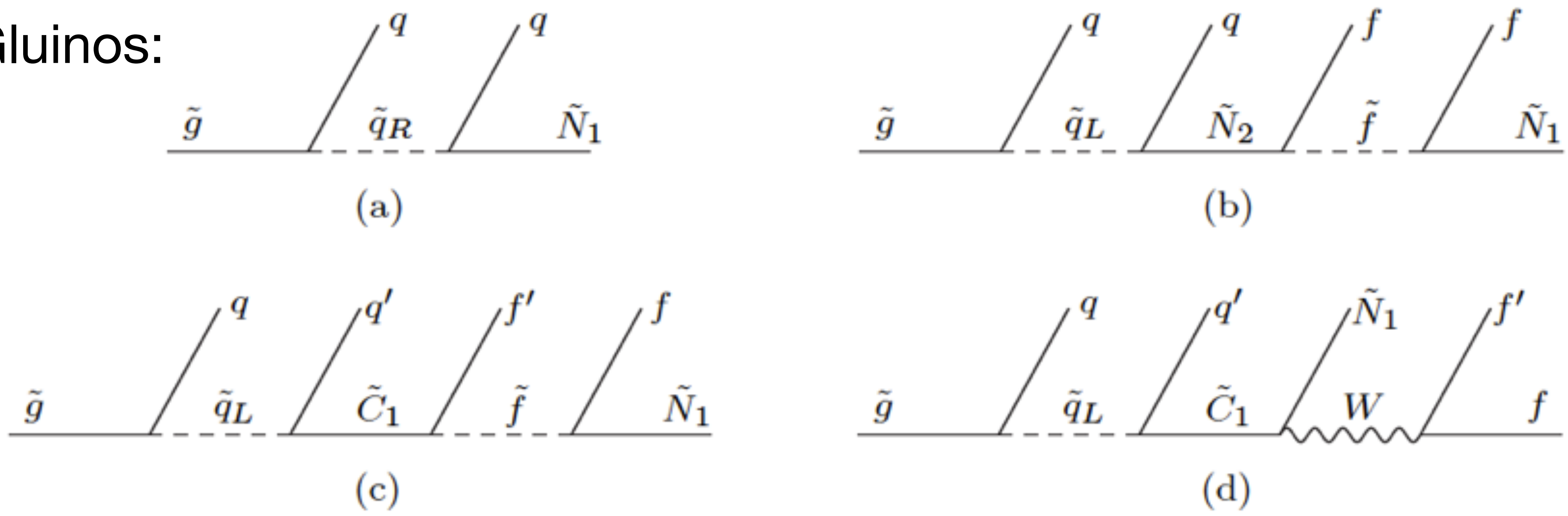

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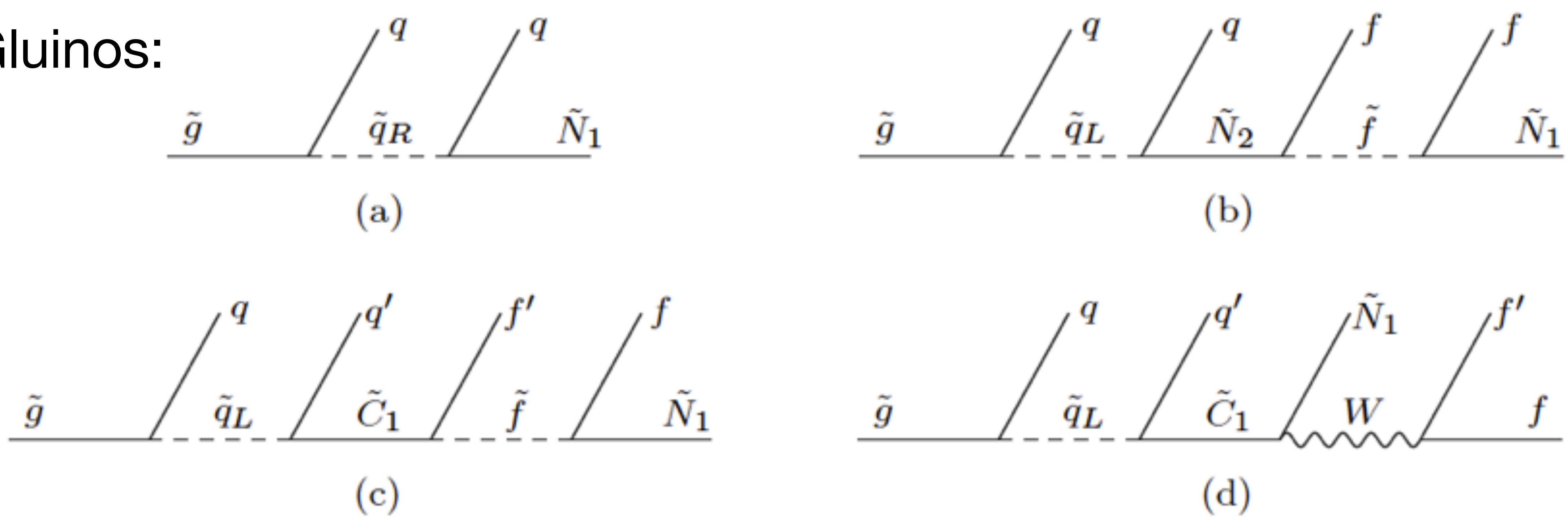
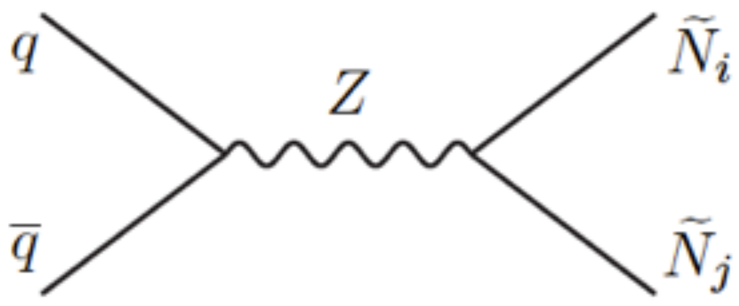


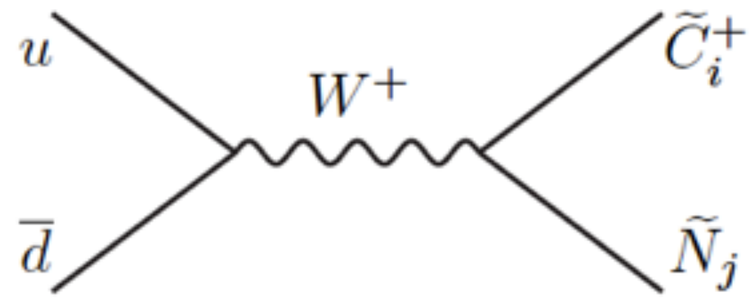
In general: If R-parity is conserved the final particle of any decay chain is the LSP!

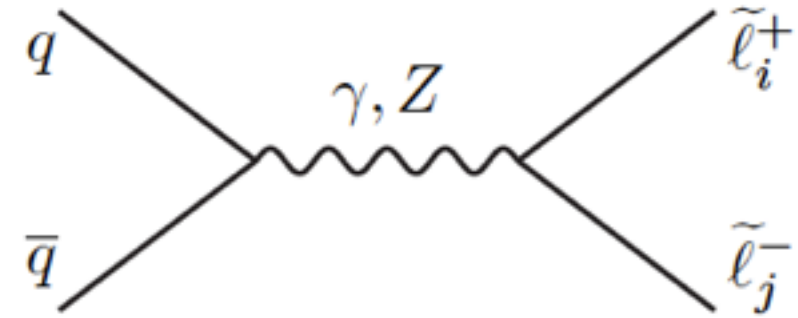
Experimental Search for SUSY

Produktion supersymmetrischer Teilchen

- Many ways to create SUSY particles at hadron colliders, for example:
- Electroweak production: neutralinos, charginos, sleptons







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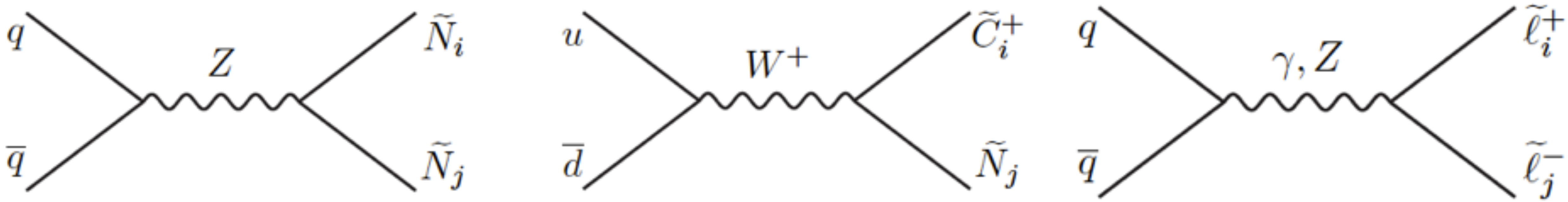
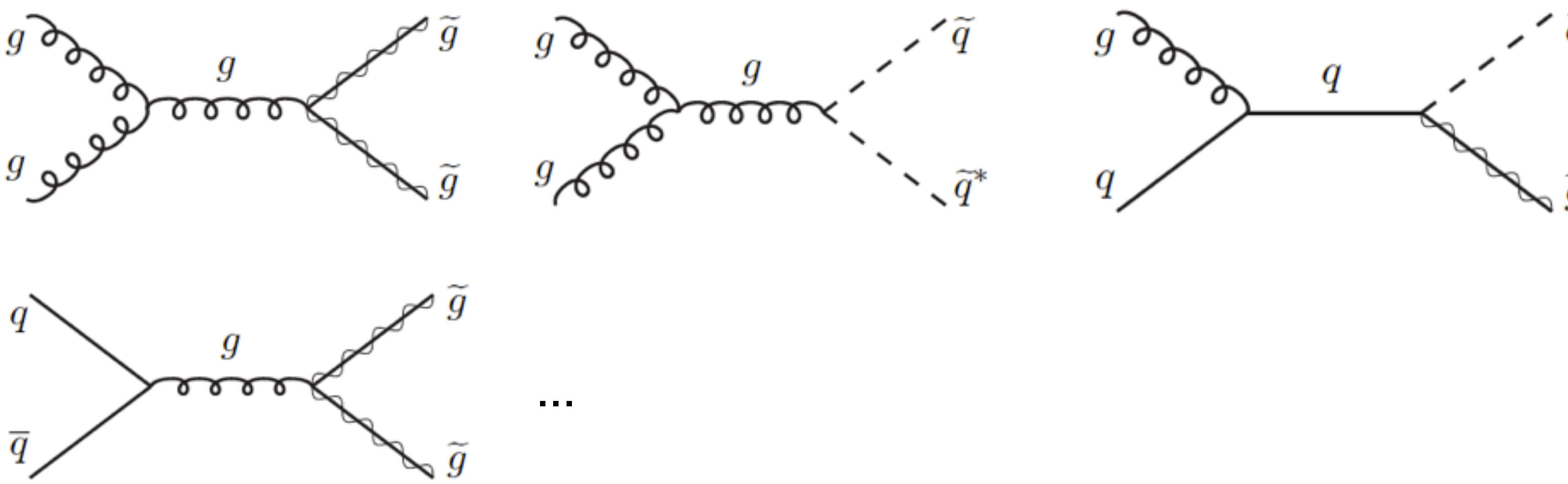


- Strong production: gluions, squarks



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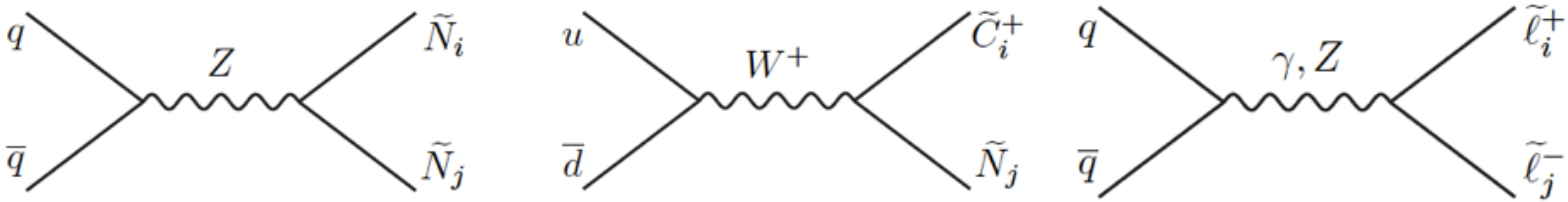

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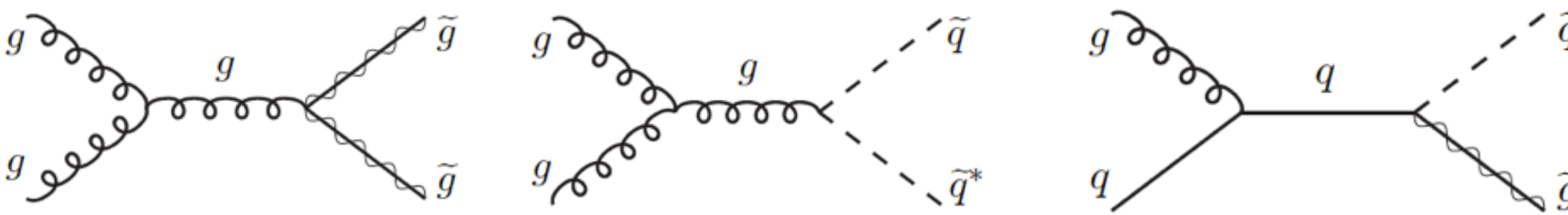

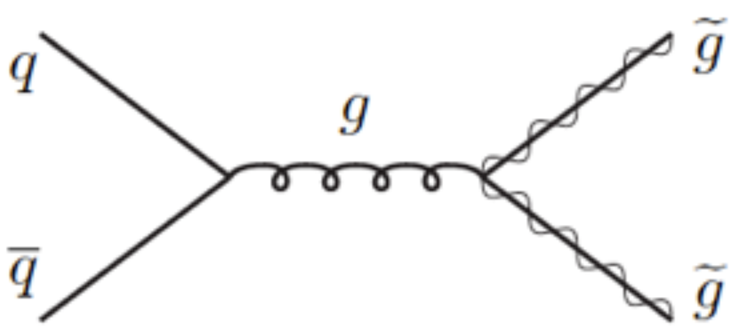

...

Which process is dominating depends on particle masses and on energy - at LHC gluon-induced processes are dominant: Access in particular to strongly interacting particles!

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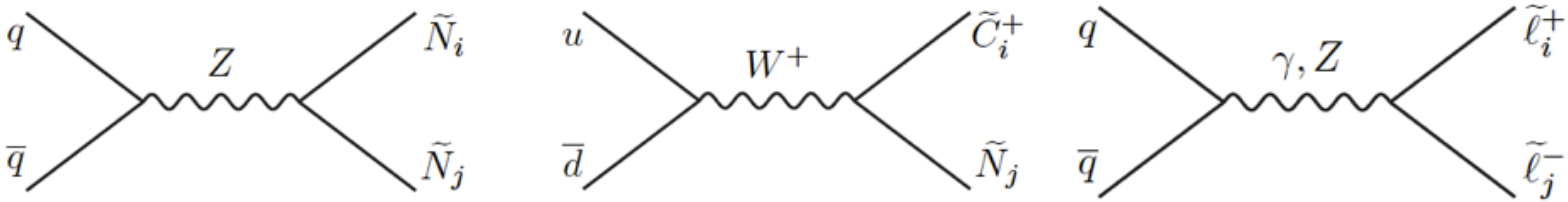

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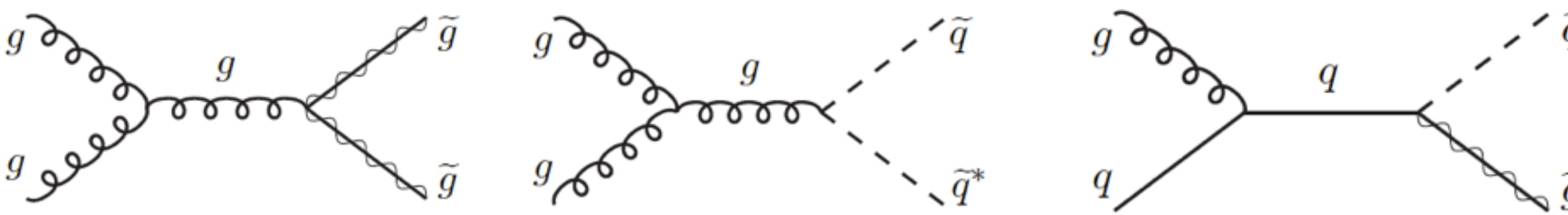
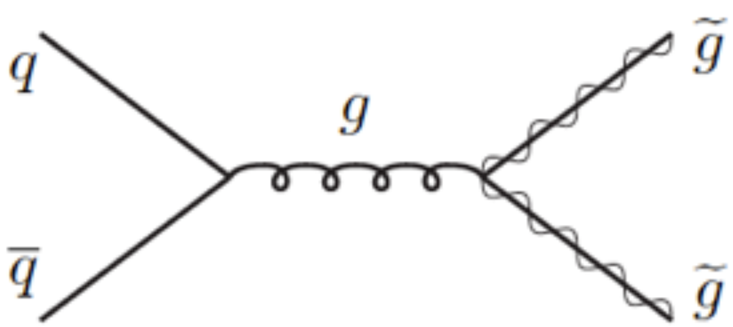


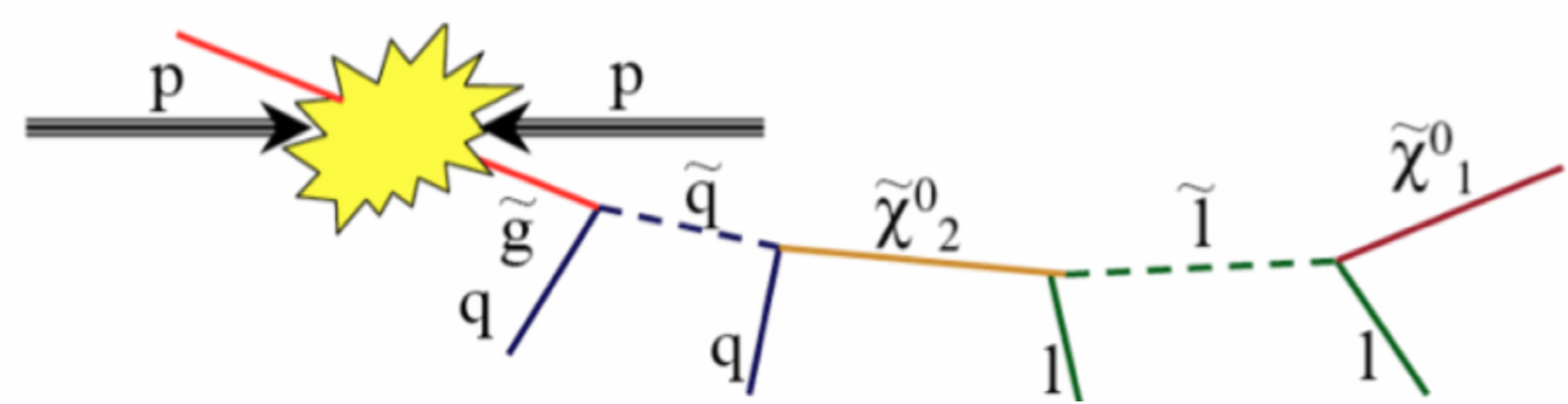


...

Which process is dominating depends on particle masses and on energy - at LHC gluon-induced processes are dominant: Access in particular to strongly interacting particles!

In general: SUSY particles always produced in pairs!

Experimental Signatures of SUSY



Experimental Signatures

- several highly energetic leptons +
- several highly energetic jets +
- missing transverse energy / momentum (LSP)

Background

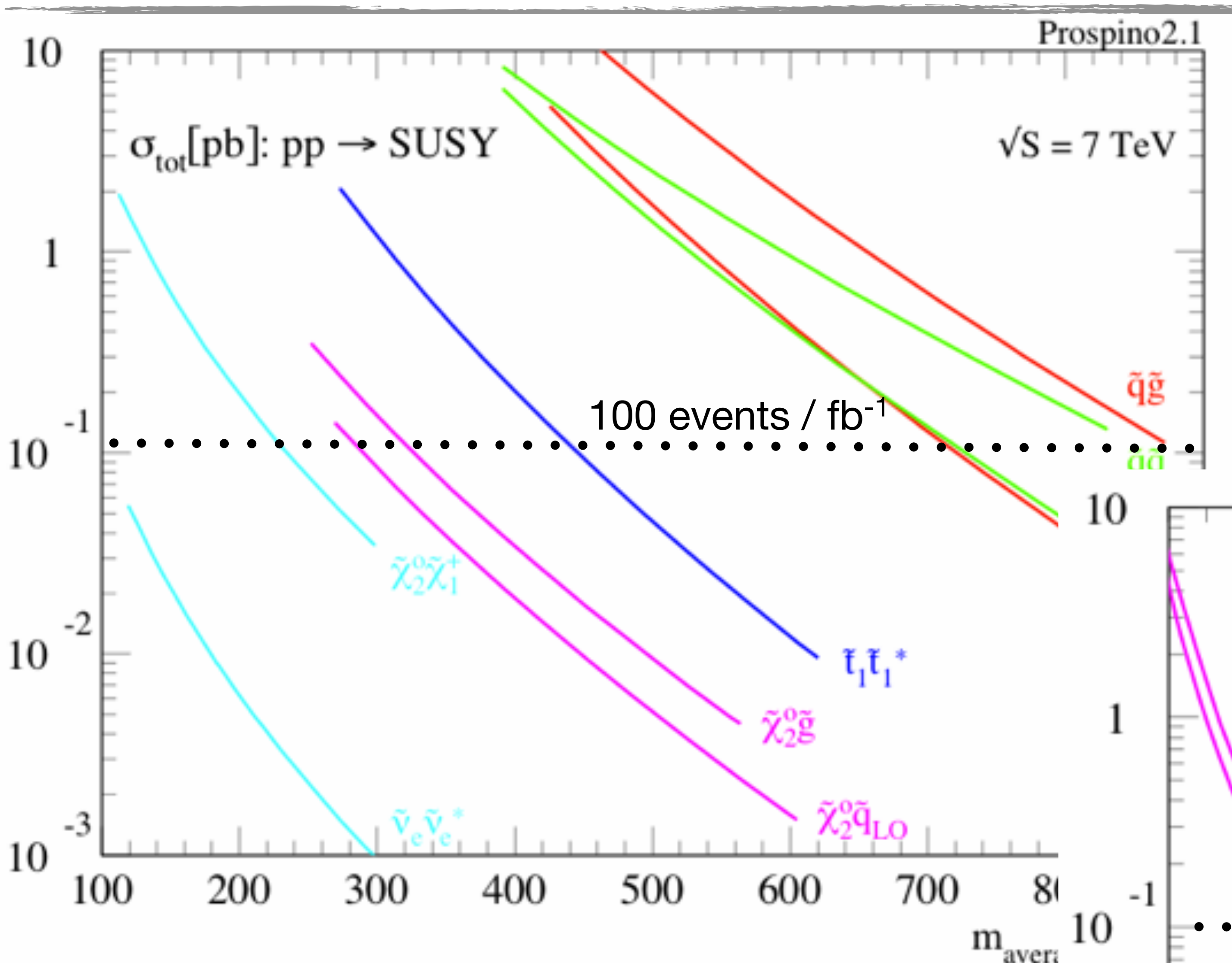
- W, Z, top, b, c decays
- QCD, top
- Neutrinos from b, c decays

If R-parity is not conserved

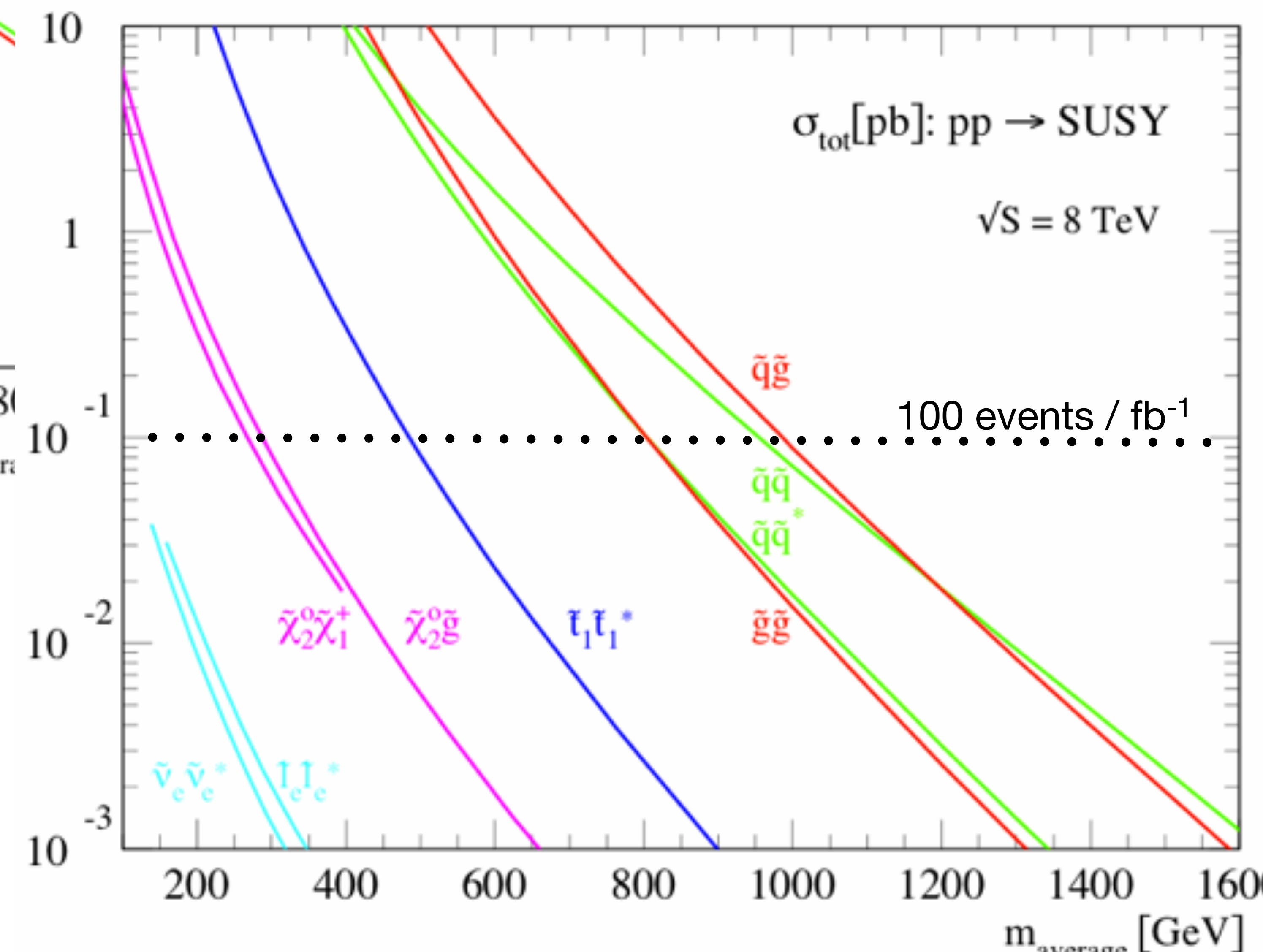
- instead of missing energy:
  - end-points in momentum distributions
  - Mass differences of states in decay chains

combinatorics!

SUSY - Expectations for the LHC



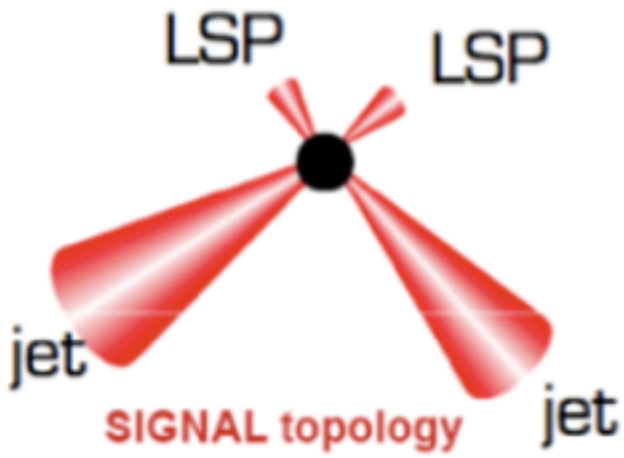
- The general feature of the production cross sections:
  - Strongly interacting particles win
  - Cross sections fall with increasing mass



- Higher energy pays of:
  > 100 events / fb^{-1} for squarks & gluions:
  ~ 800 GeV @ 7 TeV,
  ~1 TeV @ 8 TeV
- Charginos ~ 250 GeV -> 300 GeV

Searching for SUSY

- A variety of search techniques are used - too diverse to cover in detail. One example: Searches in hadronic final states:

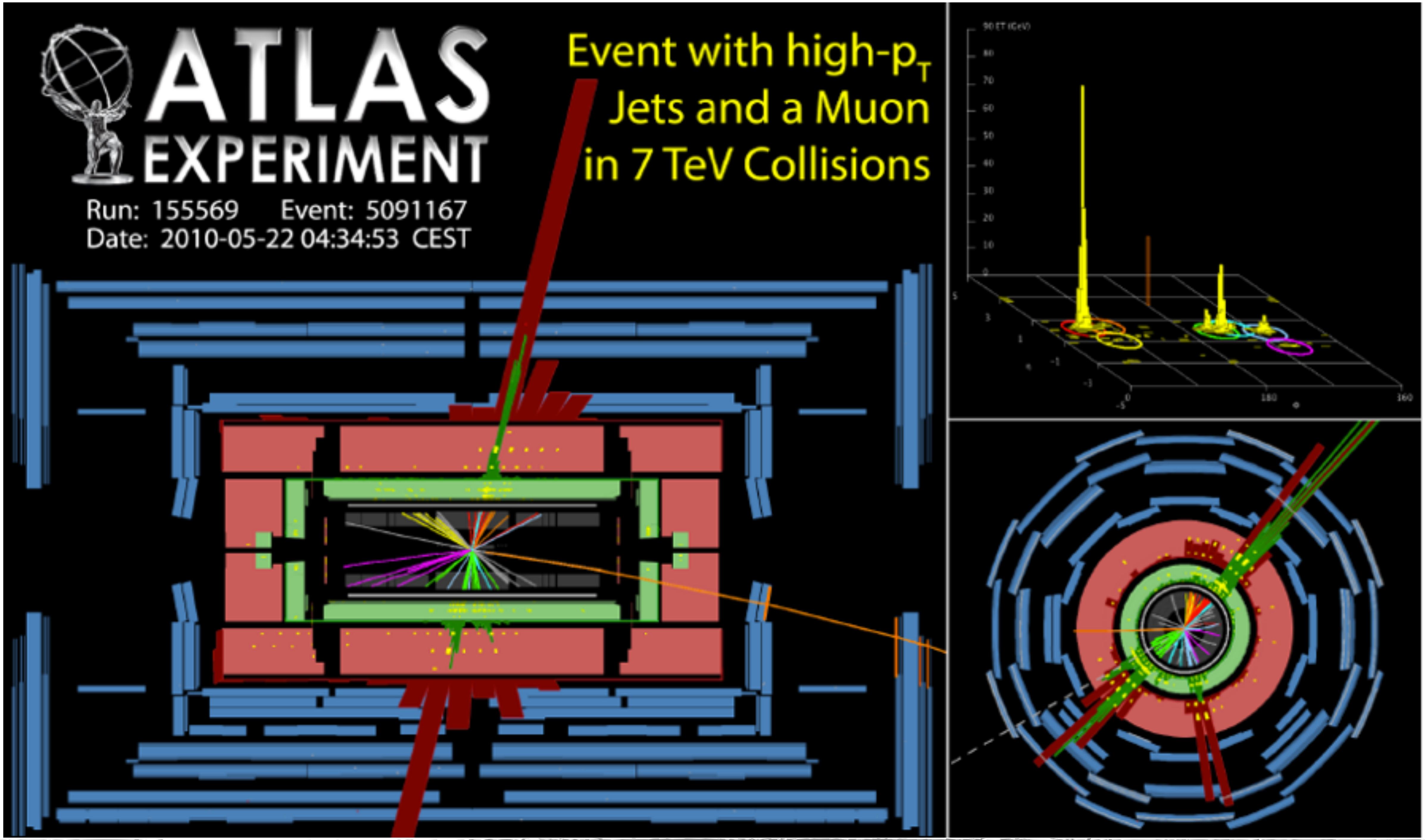


Look for missing transverse energy to discriminate signal from background

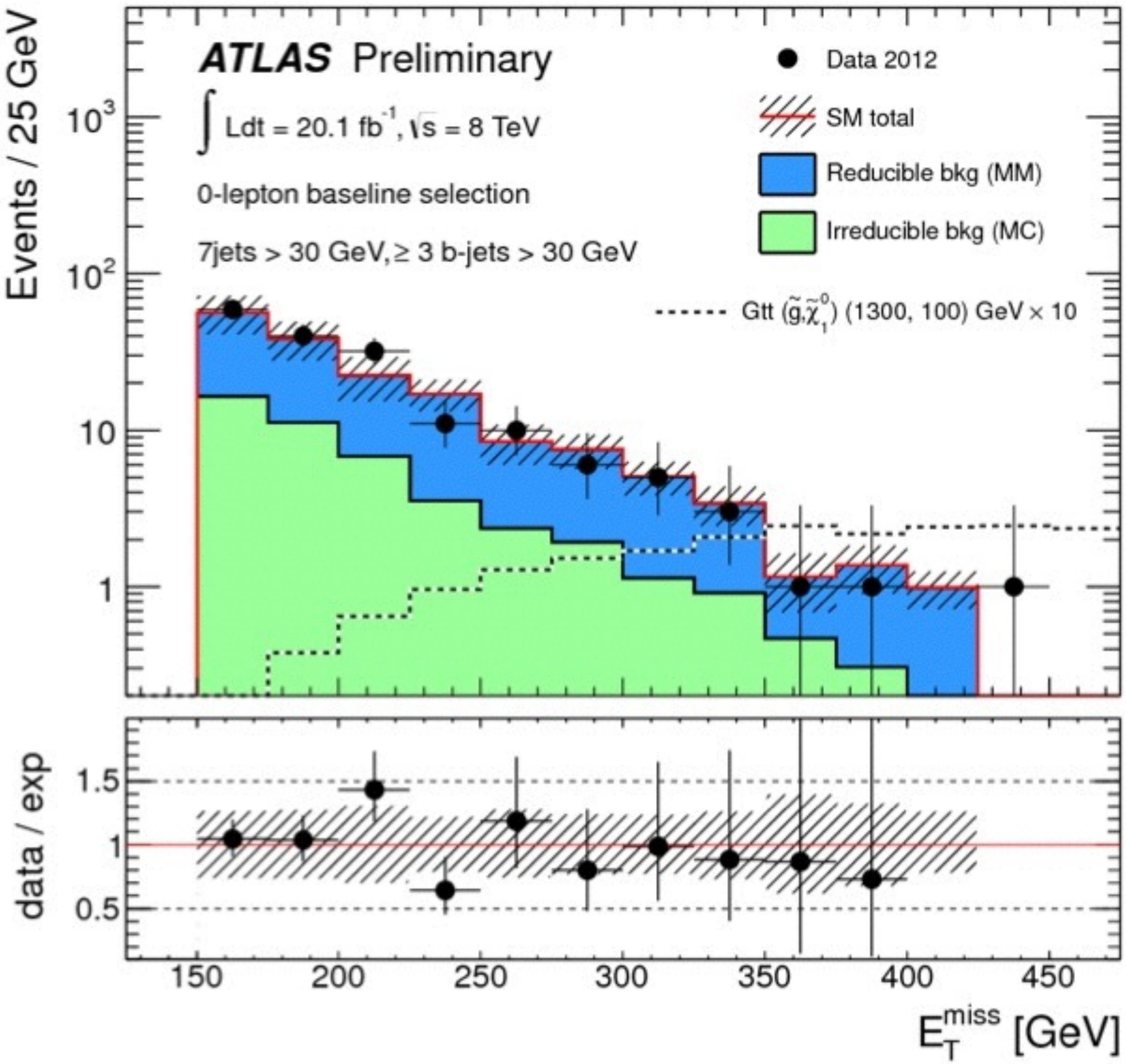
Typically high-mass particles - Lots of transverse energy in the event
Good variable (also signal / background separation): effective mass
$m_{eff} = \sum|p_{t,jets}| + |E_{t,miss}|$ - a measure for the “total mass” of the event

SUSY Searches: Missing Energy, Leptons

- As for other studies as well: Leptons are good to trigger on (but restrict the underlying physics to specific particles…)!

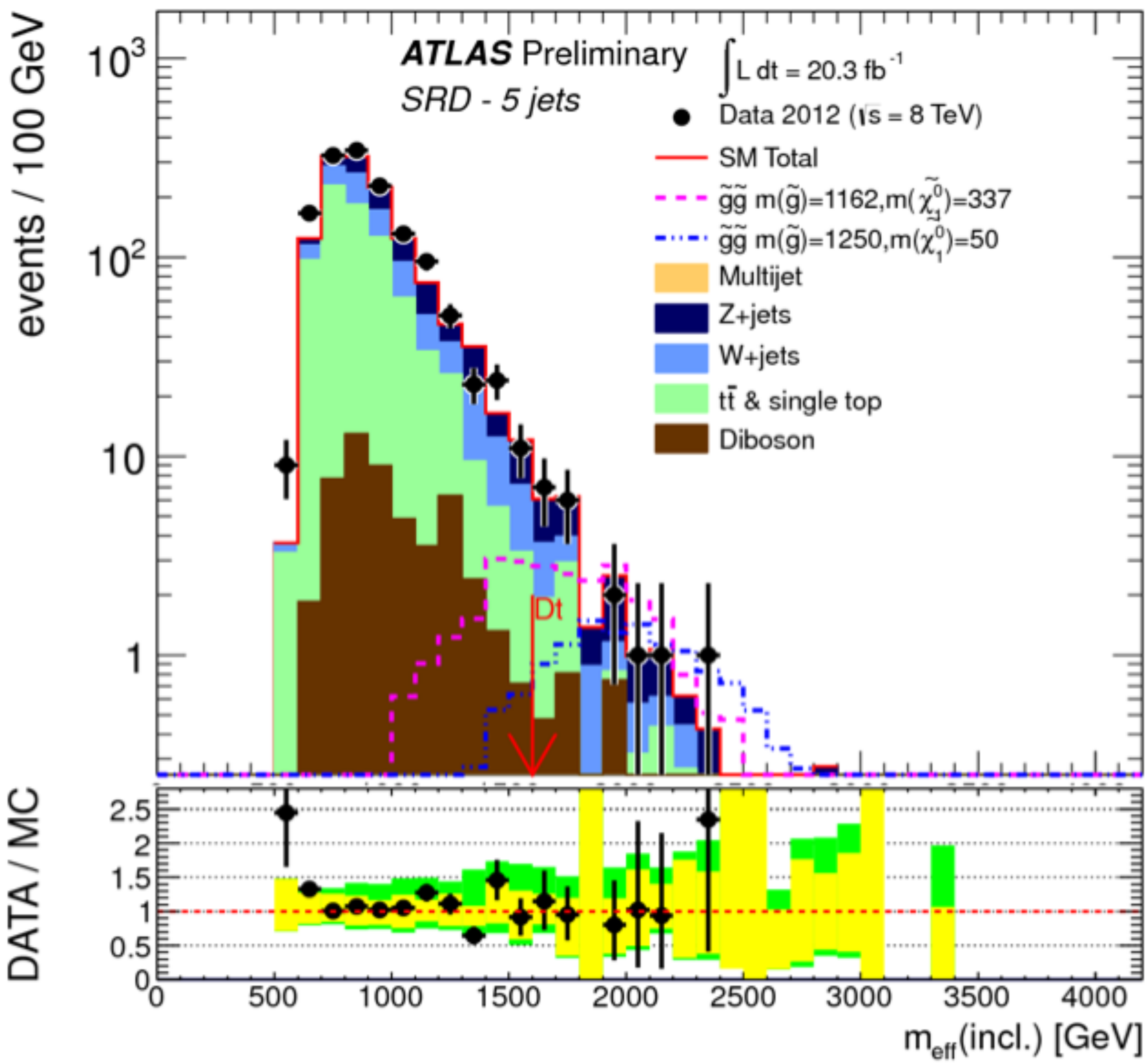


Example Distributions



- Missing transverse energy for events with many jets, including b-jets (sensitive to 3rd-generation squarks)

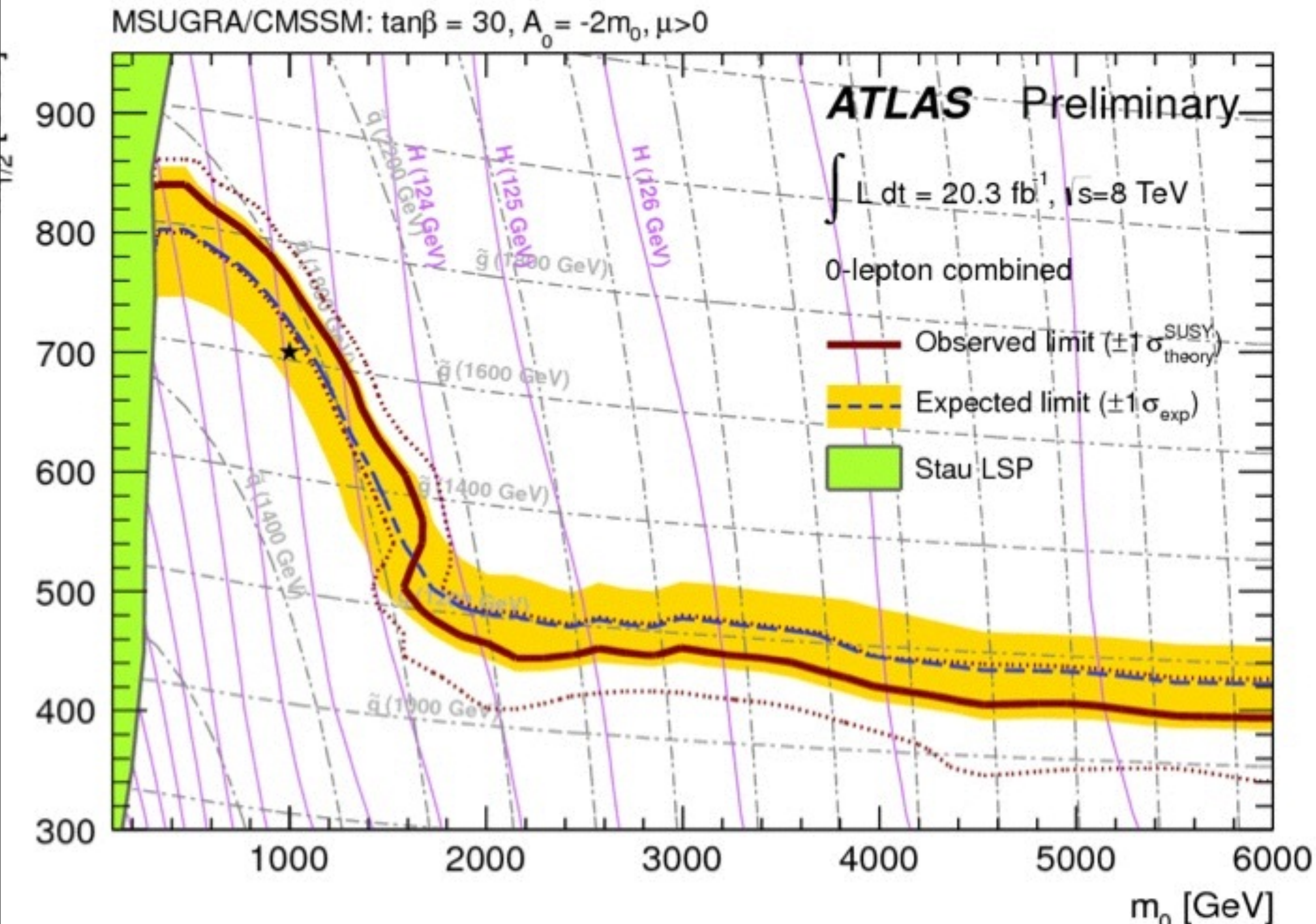
Example Distributions



- Effective mass for multi-jet events without leptons (here 5 jets), sensitive to first and second generation squarks and gluinos

Interpretation of Results

- Not an easy job: There is always a model-dependence!
  - Initial strategy: Interpret in the cMSSM - provide exclusion limits in a plane of two of the five parameters



Example taken from measurements shown on previous slide

Very hard to draw universally valid conclusions - Obvious that mass limits in the cMSSM are already quite high

Interpretation of Results

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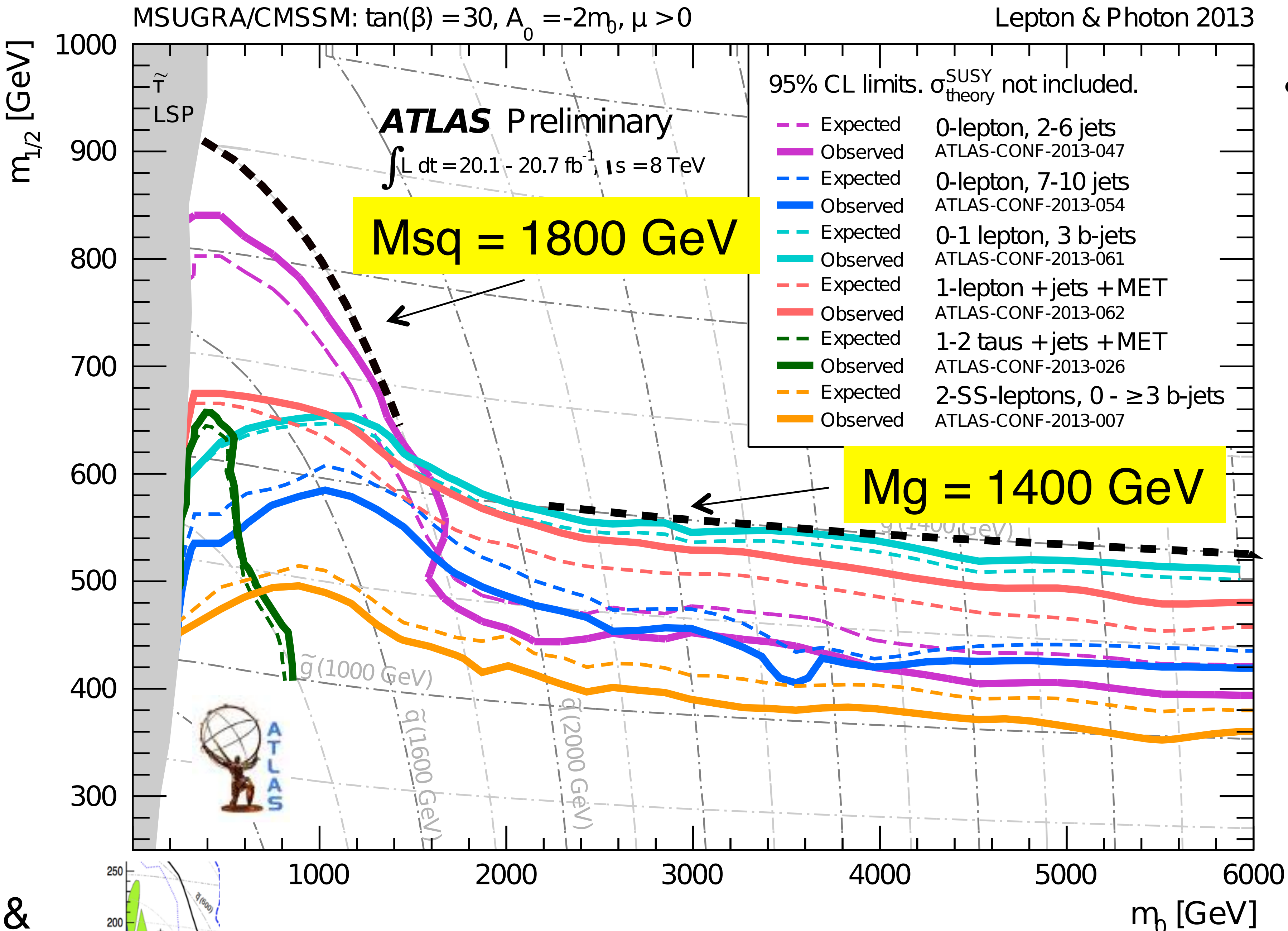

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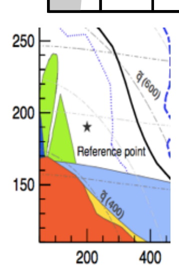
LEP & Tevatron

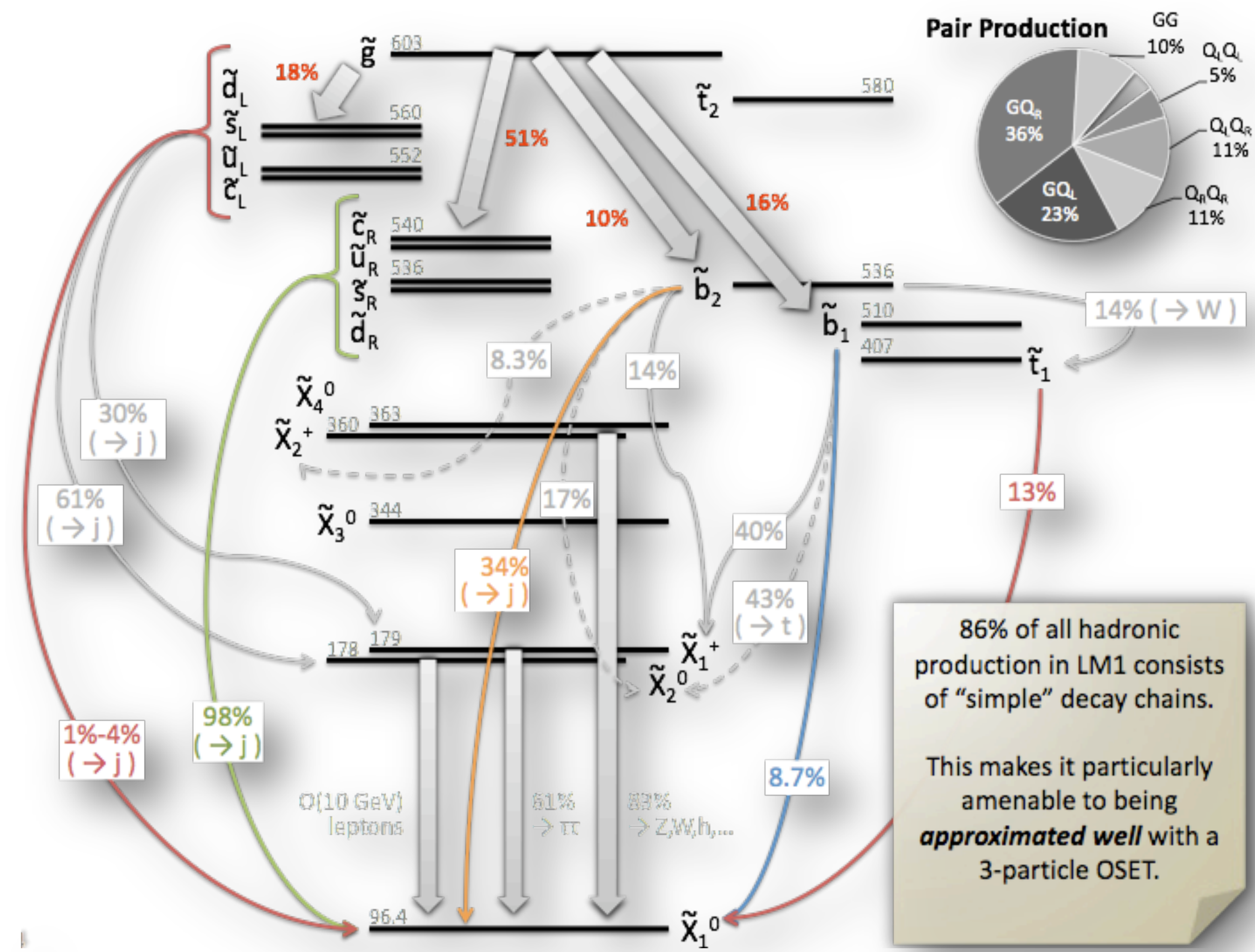


The LHC has pushed the mass scale in constraint SUSY models to a new level!

O. Buchmüller, EPS-HEP 2013

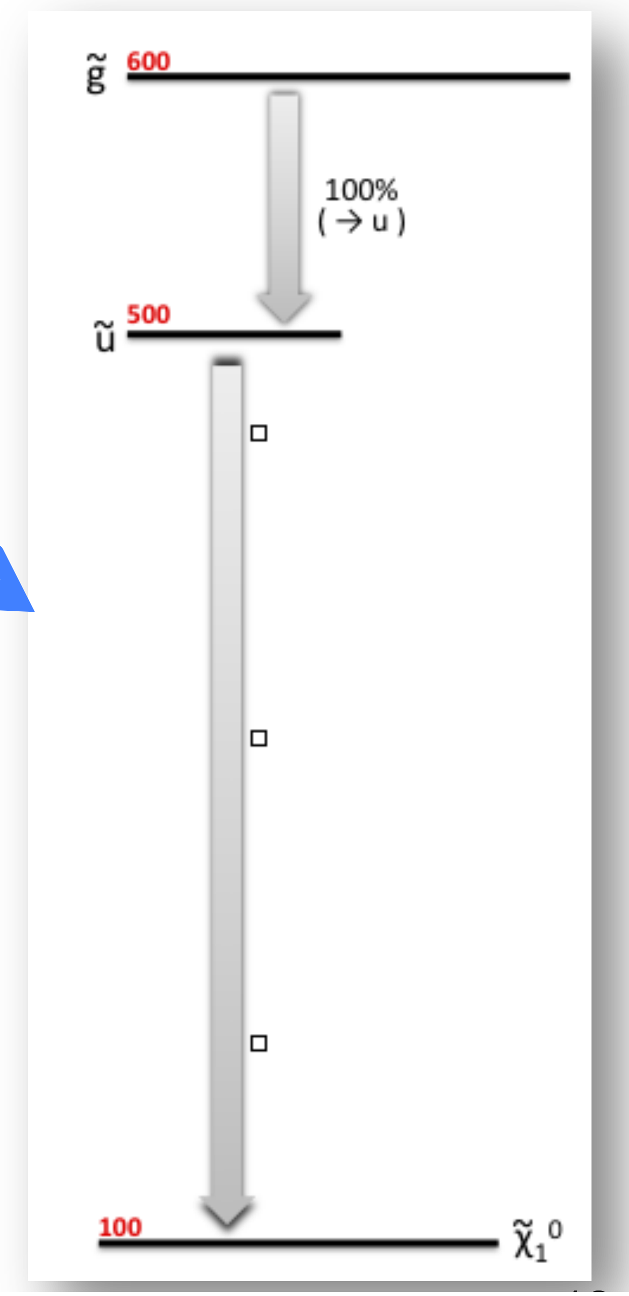
Interpretation of Results - Simplified Models

CMSSM



Simplified model spectrum (SMS)
with 3 particles, 2 decay modes

What the individual searches are sensitive to is much more simple…



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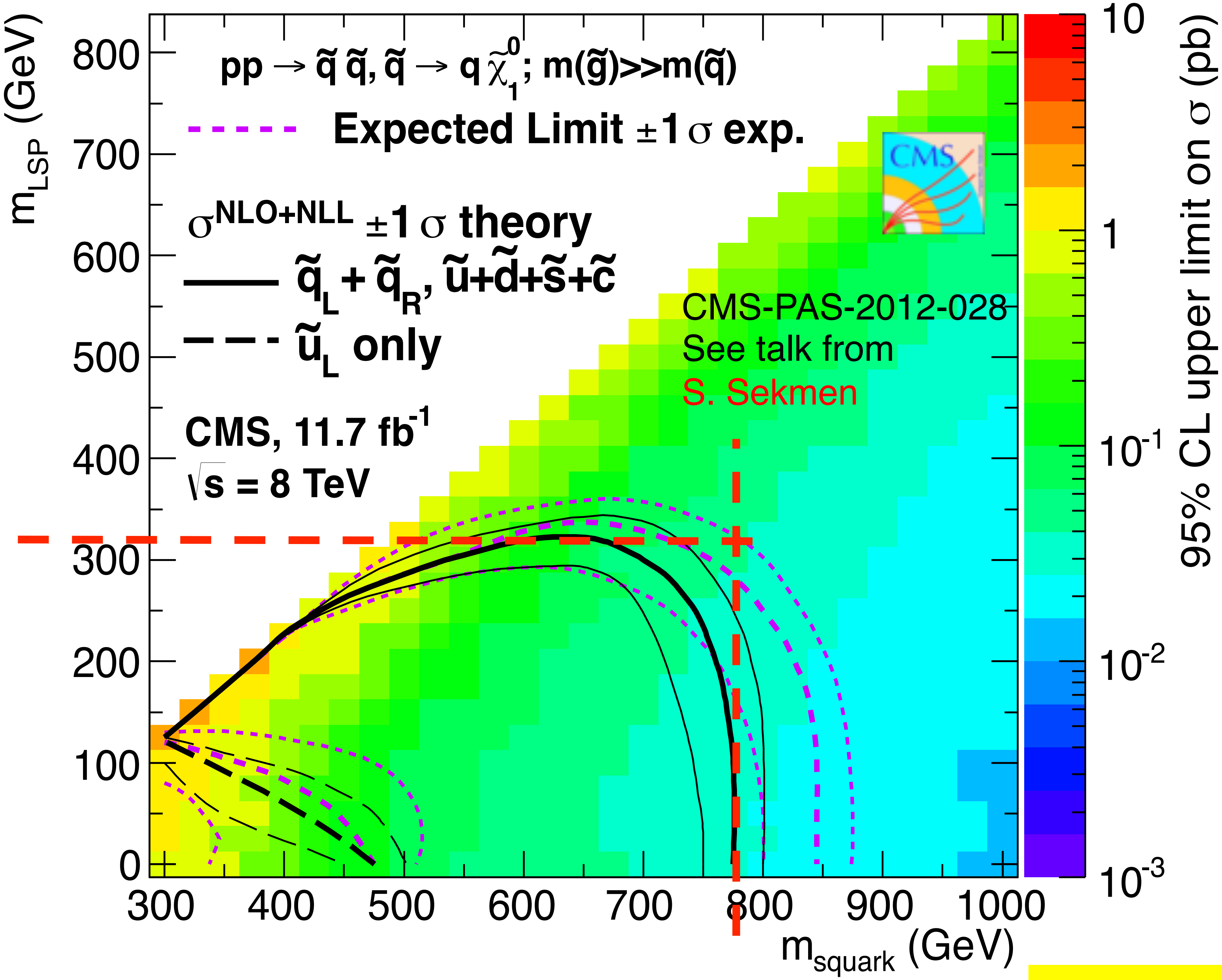
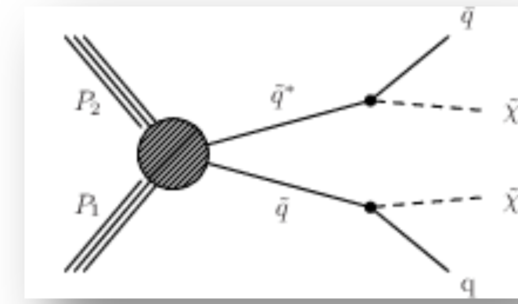
Interpretation of Results - Simplified Models

$m_{LSP}^{max} \approx 0.3$ TeV : LSP mass above which there is NO limit anymore



$m_G^{max} \approx 0.8$ TeV : Best limit in plane



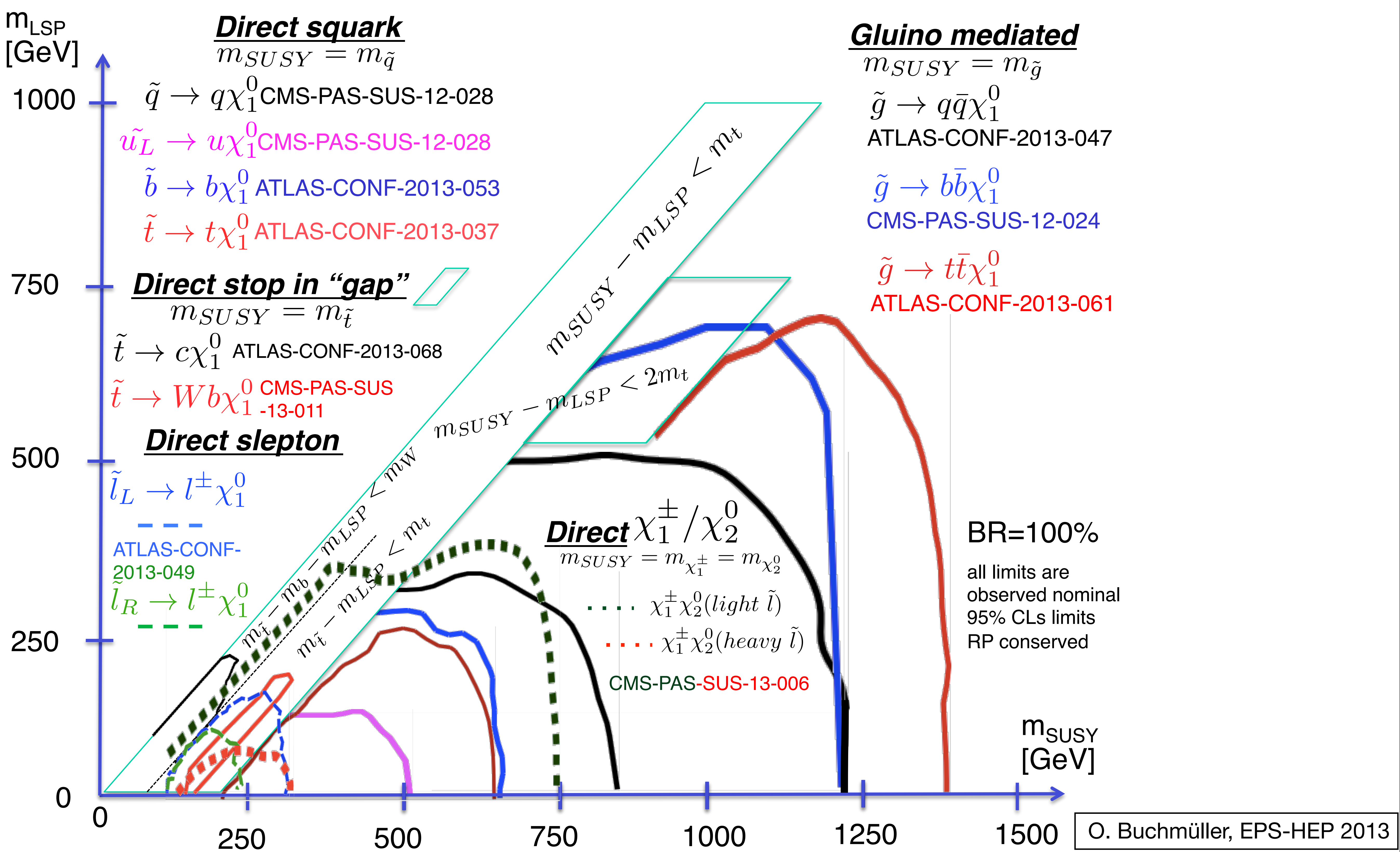
$\tilde{q}\bar{\tilde{q}} \rightarrow q\tilde{\chi}^0\bar{q}\tilde{\chi}^0$

Limits are obtained by comparing the highest cross section for a signal still allowed by the measurement with the expectation for a particular particle mass

Assumes 100% BR for decay chain considered.

O. Buchmüller, EPS-HEP 2013

Interpretation of Results - Putting it all together



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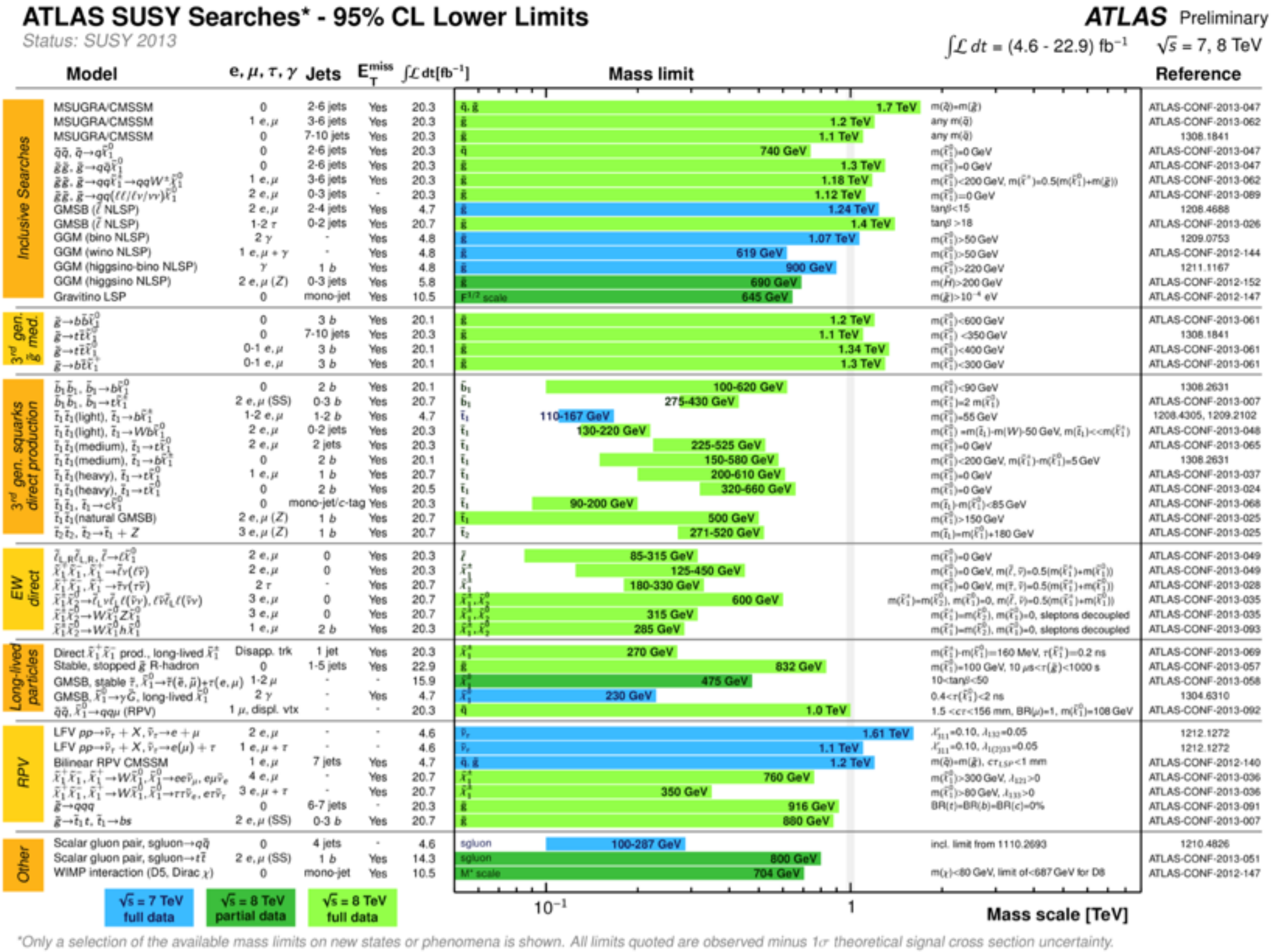

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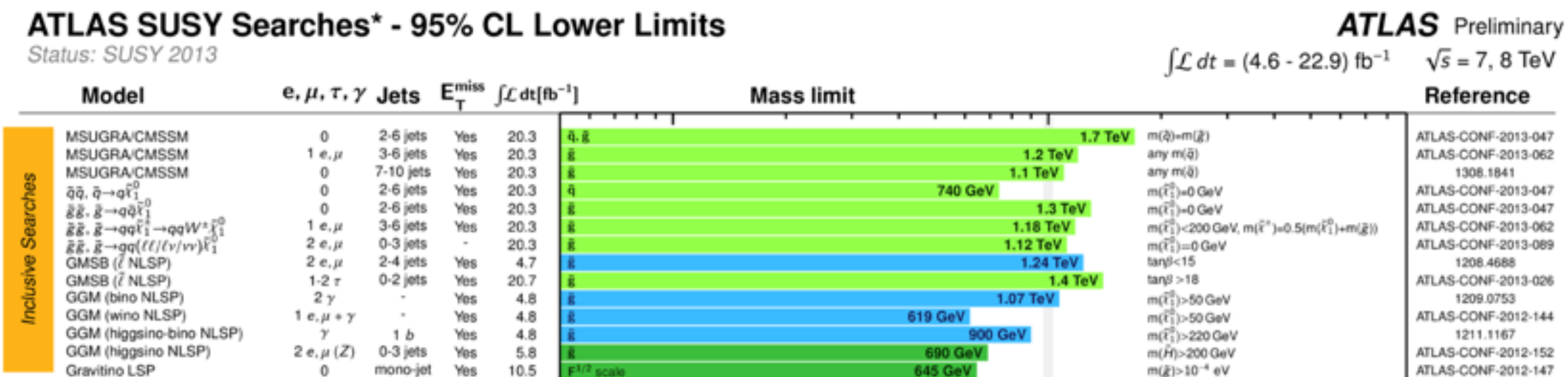
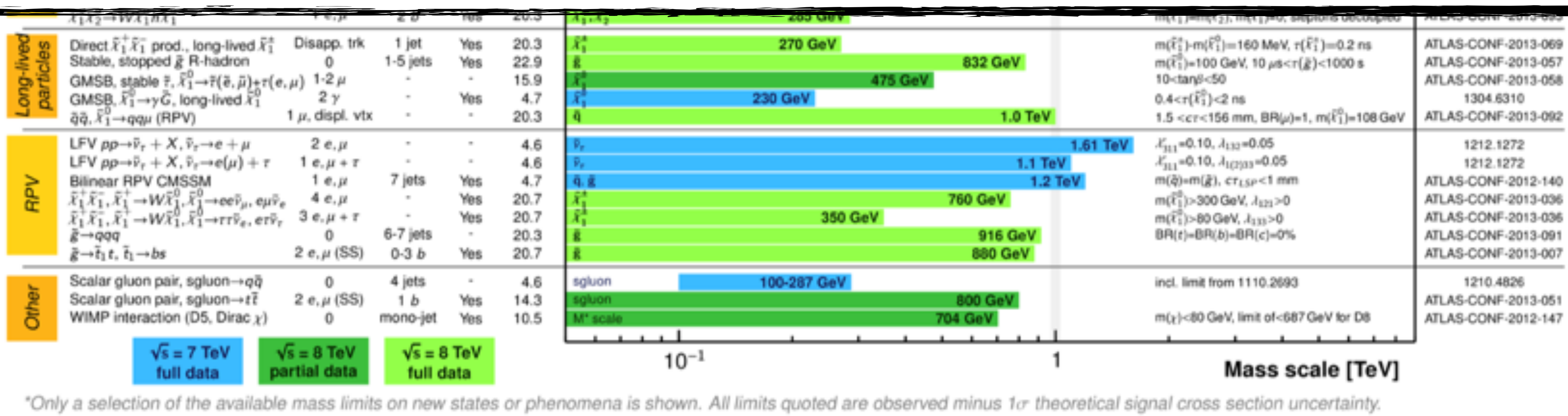
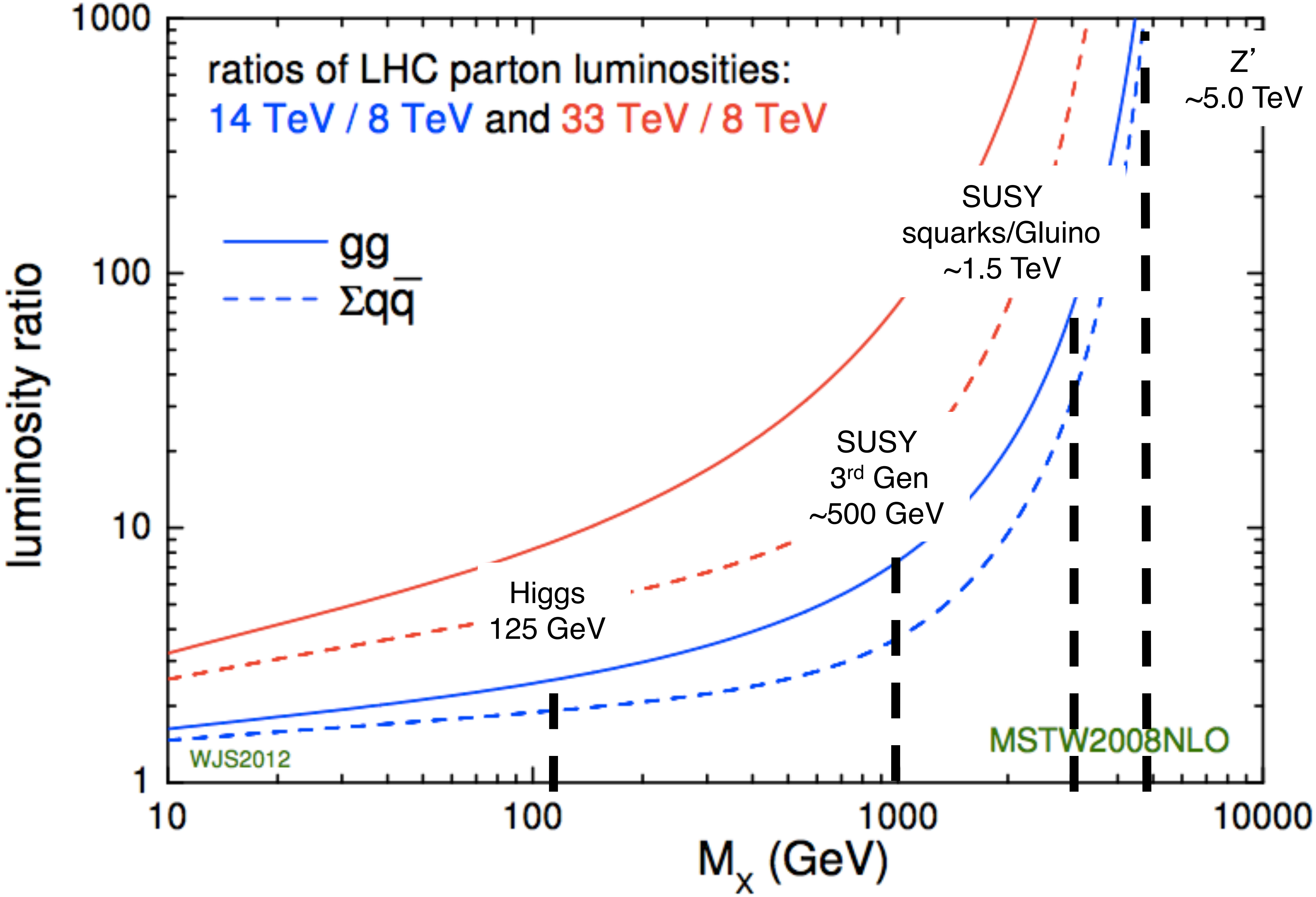


No observation so far - all consistent with the Standard Model.
The limits are getting close to (and in some cases surpassing) the TeV scale.
The constrained (rather naive) SUSY models are under quite some pressure now - but the phase space is huge, and in more general models many limits are still extremely weak.



Is there Hope?

- The increase in energy at the LHC to 14 TeV (will happen 2015) provides enormous potential:



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- for lighter 3rd gen. quarks the increase is a factor of 5

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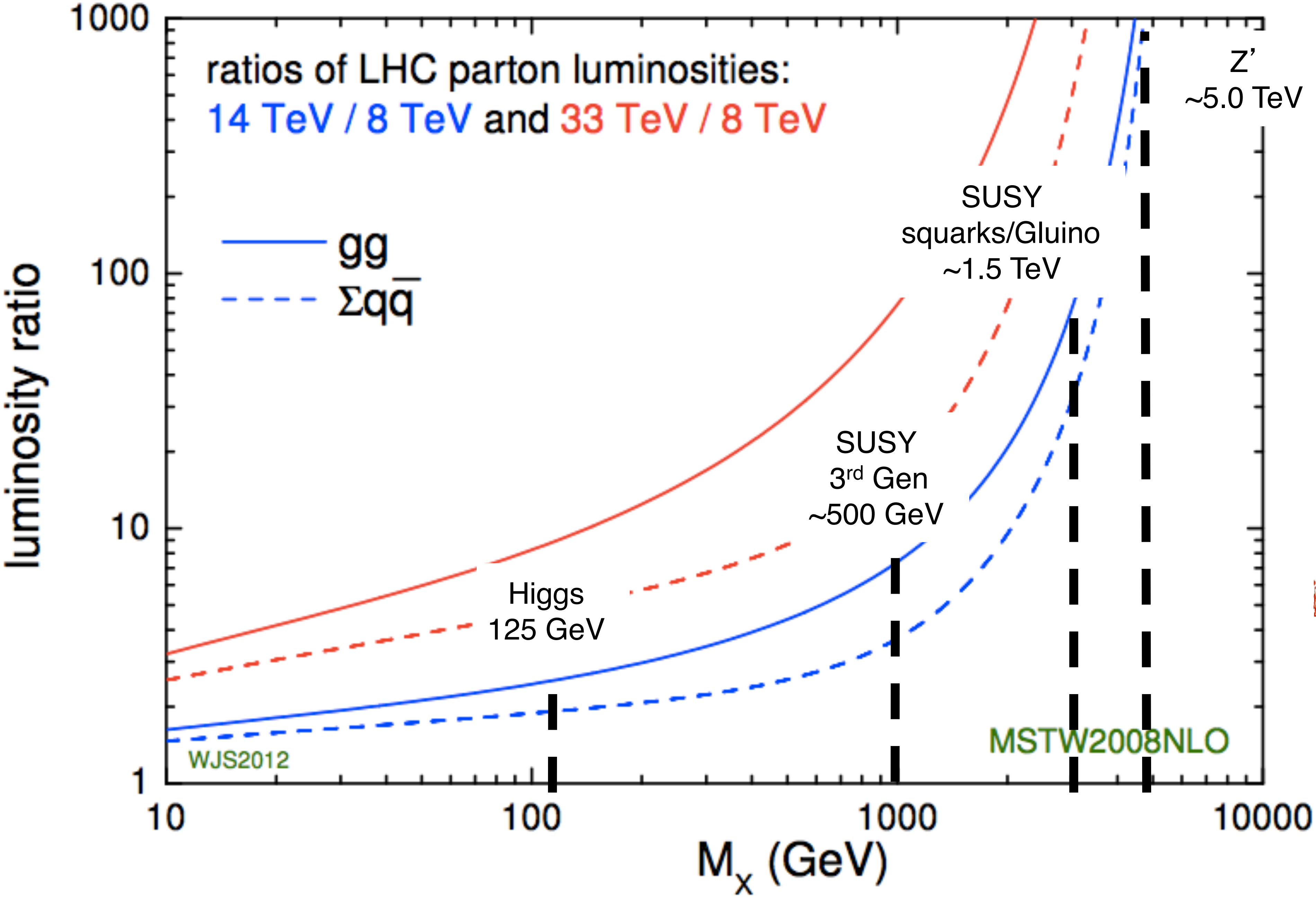

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The story is far from over!

Zusammenfassung

- The Standard Model alone cannot be the final theory of particle physics
  - The quest for an all-encompassing theory: GUTs (Grand Unified Theories): The main idea is the unification of the electroweak and the strong interaction - That alone does not yet solve all problems of the SM
- The most-studied extension of the SM: Supersymmetry, prediction of new particles at the TeV scale
  - SUSY has to be broken: So for not a single superpartner has been observes
  - SUSY provides a good Dark Matter candidate: The LSP
- Experimental search for SUSY:
  - Final states with highly energetic jets (and leptons), missing transverse energy
- High discovery potential at the LHC: If there are SUSY particles in the region up to a few TeV the chances are high that LHC will discover them - But nothing so far!

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Next Lecture: Exotics (Black Holes, Extra Dimensions) and Outlook, S. Bethke 03.02.2014

Time Plan

1.	Einführung; Stand der Teilchenphysik	14.10.
2.	Hadronenbeschleuniger: Tevatron und LHC	21.10.
3.	Standard-Modell Tests	28.10.
4.	Teilchendetektoren an Tevatron und LHC (I)	04.11.
5.	Trigger, Datennahme und Computing	11.11.
6.	Teilchendetektoren an Tevatron und LHC (II)	18.11.
7.	Monte Carlo Generatoren und Detektor Simulation	25.11.
8.	QCD, Jets, Strukturfunktionen	02.12.
9.	Top Quark	09.12.
10.	Higgs-Physik (I)	16.12.
	----------- no lecture -------------	**23.12.**
	-----------Christmas ---------------------	
11.	Higgs-Physik (II)	13.01.
	----------- no lecture -------------	**20.01.**
12.	SUSY, Physik jenseits des Standard-Modells	27.01.
13.	Andere Modelle jenseits des SM, Ausblick	03.02

Literature

- Theoretical background:
  - Stephen Martin, “A Supersymmetry Primer”, arXiv:hep-ph/9709356
    http://arXiv.org/abs/hep-ph/9709356