Search for Supersymmetry at the LHC

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Outline

Open questions of the Standard Model

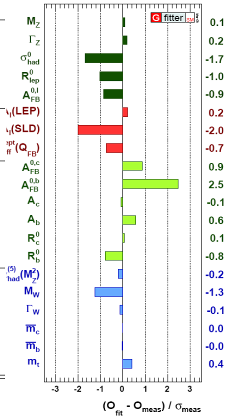
- Introduction to Supersymmetry
- Challenges in data analysis
- Tools for SUSY searches
- Detailed example for a SUSY search
- Outlook

The Standard Model

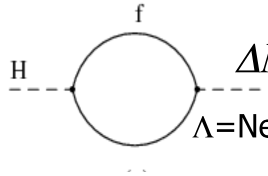
Finally complete!
Predictive!

Good agreement with data!

Parameter	Input value	Fit value
M_Z [GeV]	91.1875 ± 0.0021	91.1876 ± 0.0021
Γ_Z [GeV]	2.4952 ± 0.0023	2.4956 ± 0.0015
σ^0_{had}	41.540 ± 0.037	41.478 ± 0.014
R^0_l	20.767 ± 0.025	20.741 ± 0.018
$A^{0,l}_{FB}$	0.0171 ± 0.0010	0.01624 ± 0.0002
A_l (LEP)	0.1465 ± 0.0033	0.1473 ± 0.0009
A_l (SLD)	0.1513 ± 0.0021	$0.1465^{+0.0007}_{-0.0010}$
$\sin^2 \phi^l_{eff}(Q_{FB})$	0.2324 ± 0.0012	$0.23151^{+0.00010}_{-0.00012}$
$A^{0,c}_{FB}$	0.0707 ± 0.0035	0.0737 ± 0.0005
$A^{0,b}_{FB}$	0.0992 ± 0.0016	$0.1032^{+0.0007}_{-0.0006}$
A_c	0.670 ± 0.027	$0.6679^{+0.00042}_{-0.00036}$
A_b	0.923 ± 0.020	$0.93463^{+0.00007}_{-0.00008}$
R^0_c	0.1721 ± 0.0030	0.17225 ± 0.00006
R^0_b	0.21629 ± 0.00066	0.21577 ± 0.00005
$\Delta\alpha^{(5)}_{had}(M^2_Z)$	2768 ± 22	2764^{+22}_{-21}
M_W [GeV]	80.399 ± 0.023	$80.371^{+0.008}_{-0.011}$
Γ_W [GeV]	2.098 ± 0.048	2.092 ± 0.001
$\overline{m}_c$ [GeV]	1.25 ± 0.09	1.25 ± 0.09
$\overline{m}_b$ [GeV]	4.20 ± 0.07	4.20 ± 0.07
m_t [GeV]	173.1 ± 1.3	173.6 ± 1.2



Radiative corrections to Higgs mass:

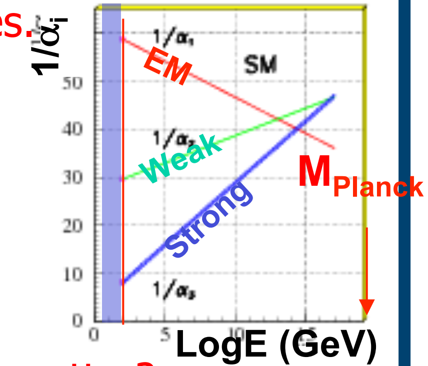


$$\Delta M^2 = \kappa \Lambda^2_{NP}$$

Λ=New Physics Scale

Neutrinos are massive.
Fermion masses stretch over 13 orders of magnitude (from neutrino to top quark).

(Non-)unification of the forces:

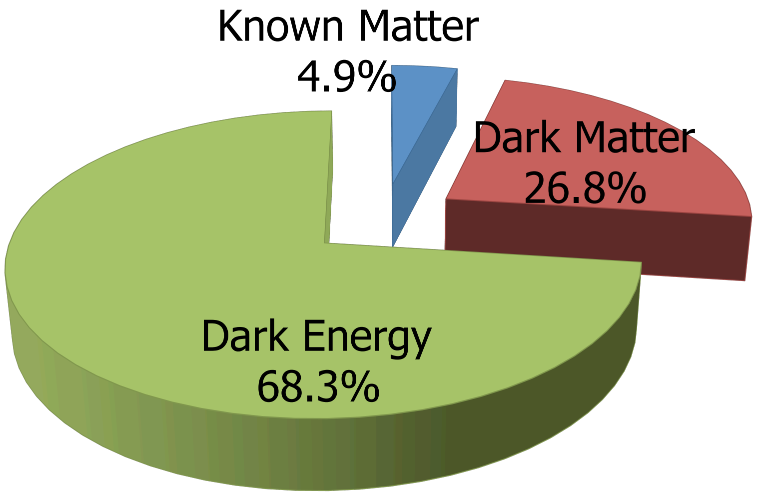


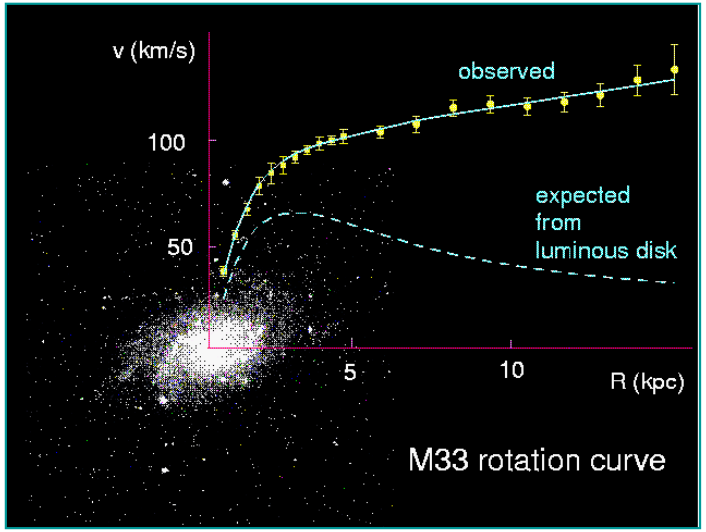
Dark matter?
Where is the anti-matter?
How to include gravity?

Dark Matter

We don't know much about the largest part of the universe!

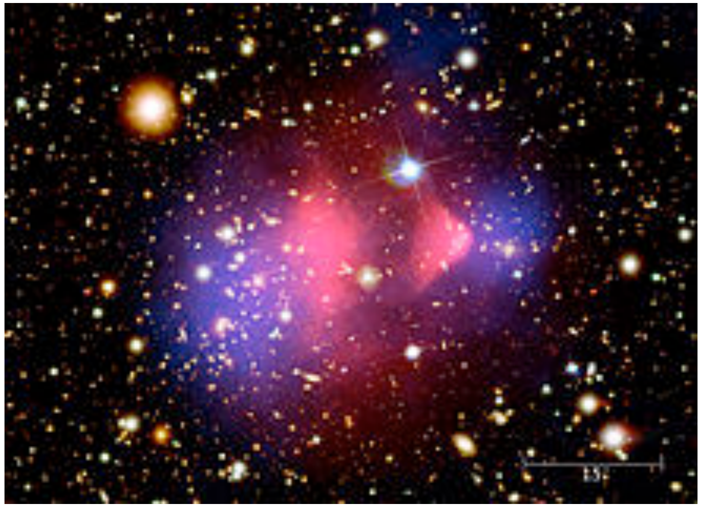
Galaxy rotation curves





Bullet cluster(1E 0657-558),
two colliding clusters of galaxies:

- Light-emitting matter
- Dark matter



Corrections to the Higgs Mass

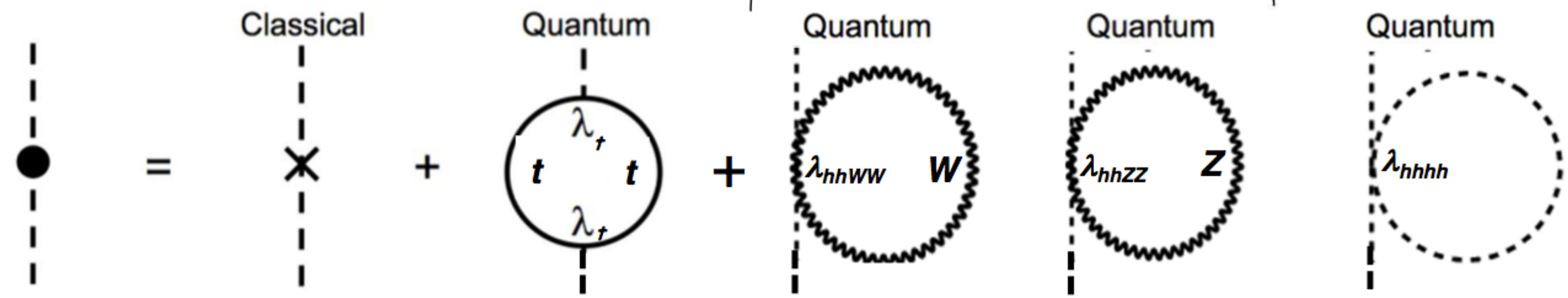
Up to 1-loop corrections

Most dangerous !

Fermion Yukawa coupling $\lambda_t = \sqrt{2}m_t/v \approx 1$

Gauge coupling $\lambda_{hhVV} = 2m_{W,Z}^2/v^2$

Self-coupling $\lambda_{hhhh} = 3m_h^2/v^2$

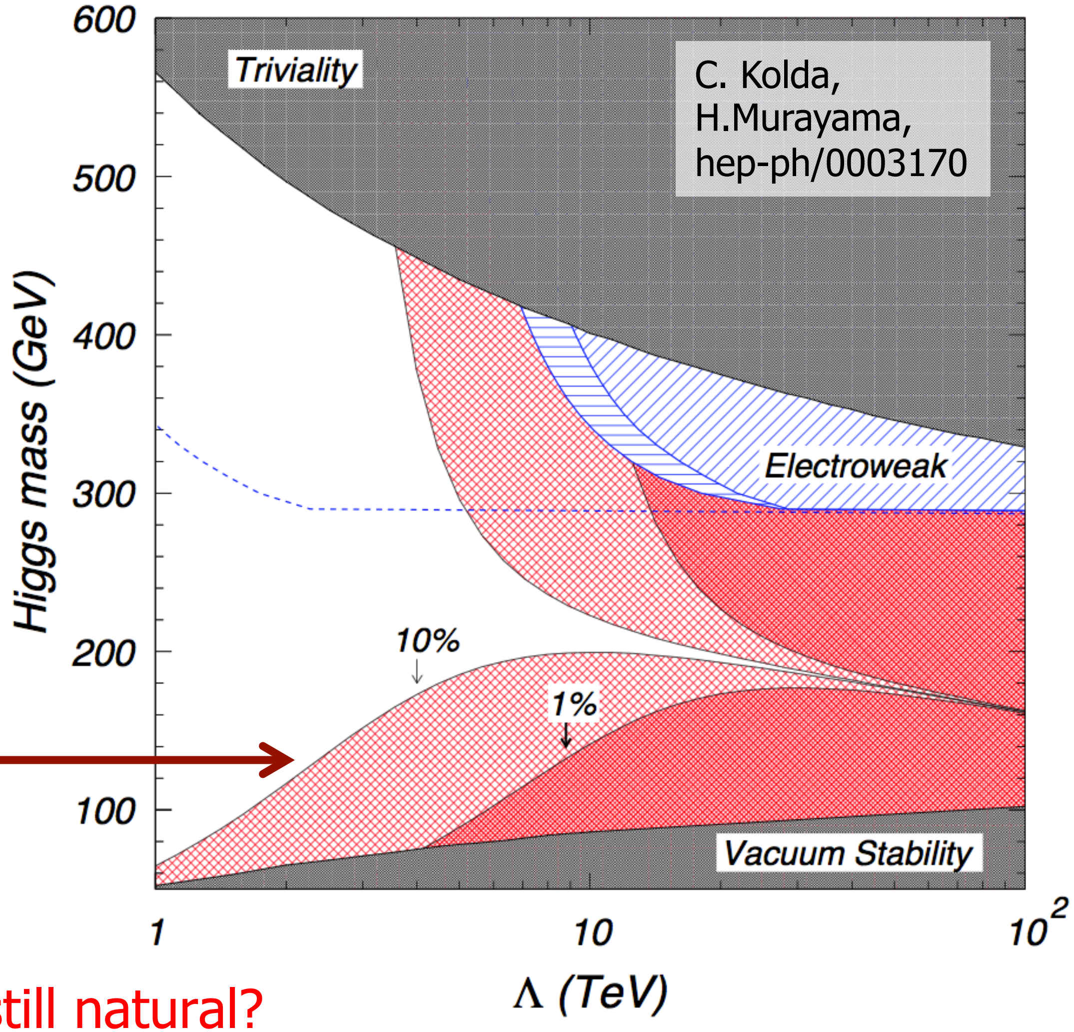


$$m_h^2 = (m_h^2)_0 - \frac{3G_F}{4\sqrt{2}\pi^2}(4m_t^2)\Lambda_{NP}^2 + \frac{3G_F}{4\sqrt{2}\pi^2}(2m_W^2 + m_Z^2 + m_h^2)\Lambda_{NP}^2 + O(\ln[\Lambda_{NP}/m_h])$$

$\Lambda_{NP}=M_{Pl} \rightarrow (125)^2 = 36{,}127{,}890{,}984{,}789{,}307{,}394{,}520{,}932{,}878{,}928{,}933{,}023 - 36{,}127{,}890{,}984{,}789{,}307{,}394{,}520{,}932{,}878{,}928{,}917{,}398$

Corrections to the Higgs Mass

Where do we expect Λ?

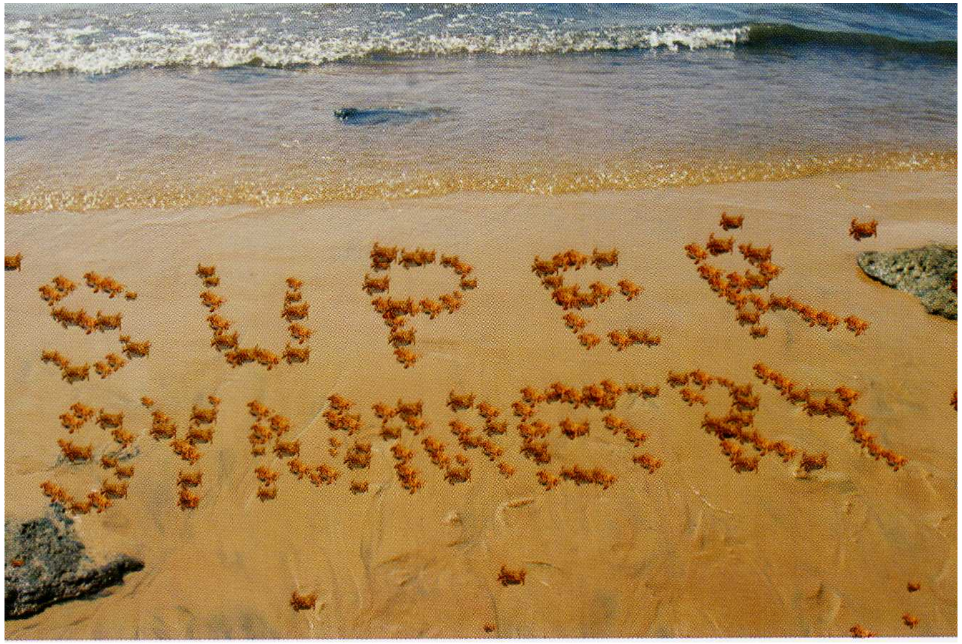


amount of fine tuning

How much finetuning is still natural?

Where we are...

- Open questions of the Standard Model
- **Introduction to Supersymmetry**
- Challenges in data analysis
- Tools for SUSY searches
- Detailed example for a SUSY search
- Outlook



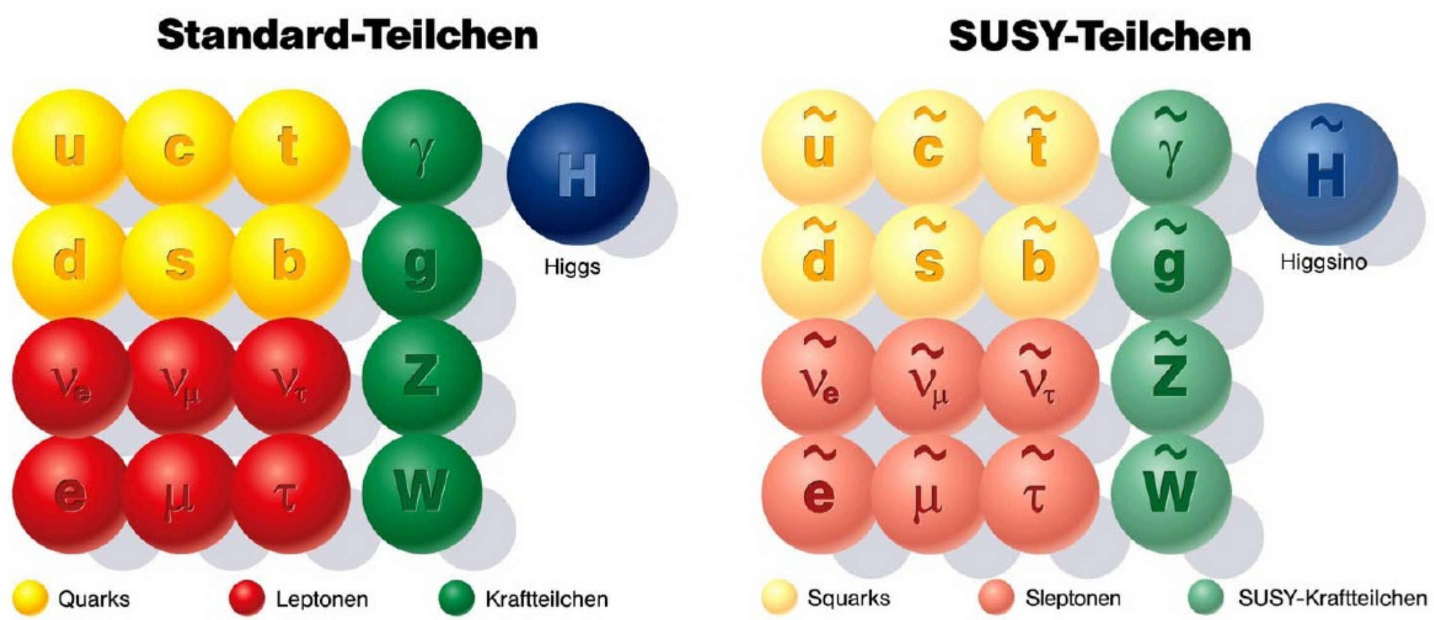
Supersymmetry

Each SM particle gets assigned a SUSY partner particle with spin differing by ½
SUSY transformation:

- Q |fermion> = |boson>
- Q |boson> = |fermion>

Name convention:

- Fermion ←→ S-fermion
- Boson ←→ bos(on)-ino



SUSY Particles

Overview of Particles

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)

5 physical Higgs bosons

$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$

$\tilde{\chi}_1^{+/-}\ \tilde{\chi}_2^{+/-}$

SUSY Mass Eigenstates

Mass eigenstates are calculated from gauge eigenstates, e.g. $f_1 = f_L \cos(M_f) + f_R \sin(M_f)$, where the mass matrix M_f depends on:

- M_1, M_2, $\tan\beta$, μ: SUSY masses and breaking
- m_Z, m_W, $\sin^2\theta_W$: EWSB mixing: B,W → Z, γ

Neutralino mixing: $(\tilde{B}, \tilde{W}, \tilde{H}_d, \tilde{H}_u) \rightarrow \tilde{\chi}^0_{1,2,3,4}$

$$\begin{pmatrix} M_1 & 0 & -m_Z c_\beta s_W & m_Z s_\beta s_W \\ 0 & M_2 & m_Z c_\beta c_W & -m_Z s_\beta c_W \\ -m_Z c_\beta s_W & m_Z c_\beta c_W & 0 & -\mu \\ m_Z s_\beta s_W & -m_Z s_\beta c_W & -\mu & 0 \end{pmatrix}$$

SUSY Mass Eigenstates

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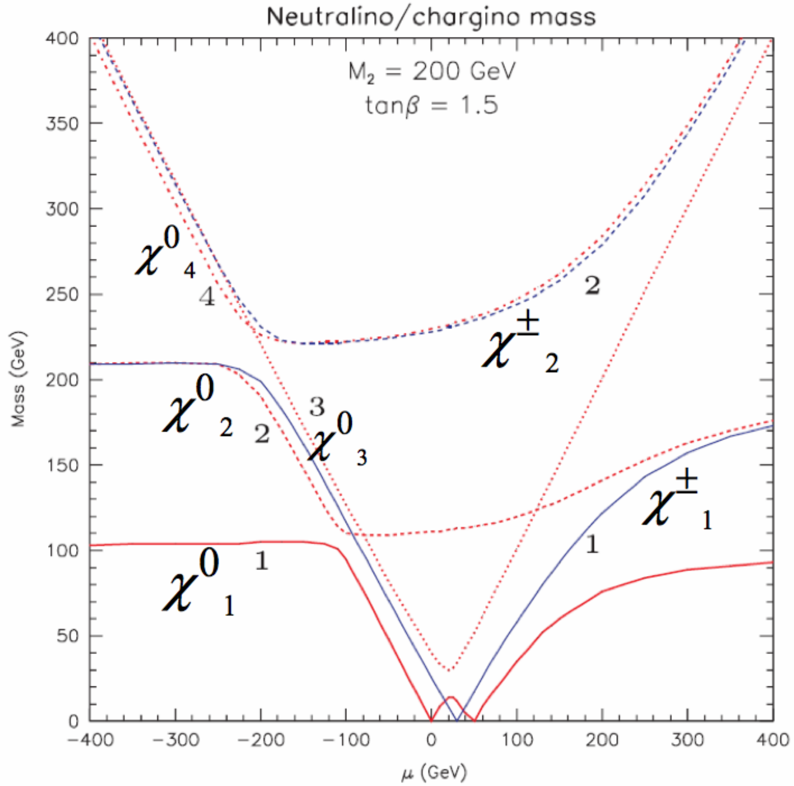
- M_1, M_2, $\tan\beta$, μ: SUSY masses and breaking
- m_Z, m_W, $\sin^2\theta_W$: EWSB mixing: B,W → Z, γ

Chargino mixing: $(\tilde{W}^\pm, \tilde{H}^\pm) \rightarrow \tilde{\chi}^\pm_{1,2}$

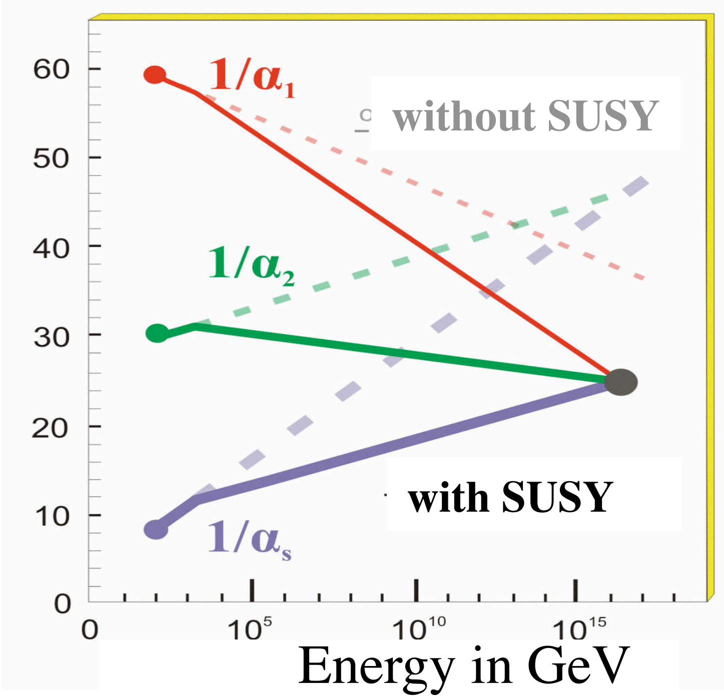
$$\begin{pmatrix} M_2 & \sqrt{2} m_W \sin\beta \\ \sqrt{2} m_W \cos\beta & \mu \end{pmatrix}$$



If the theory proceeds from a **GUT**, relation between M_1 and M_2: $\mathbf{M_2 \sim 2M_1}$

Supersymmetry – Advantages

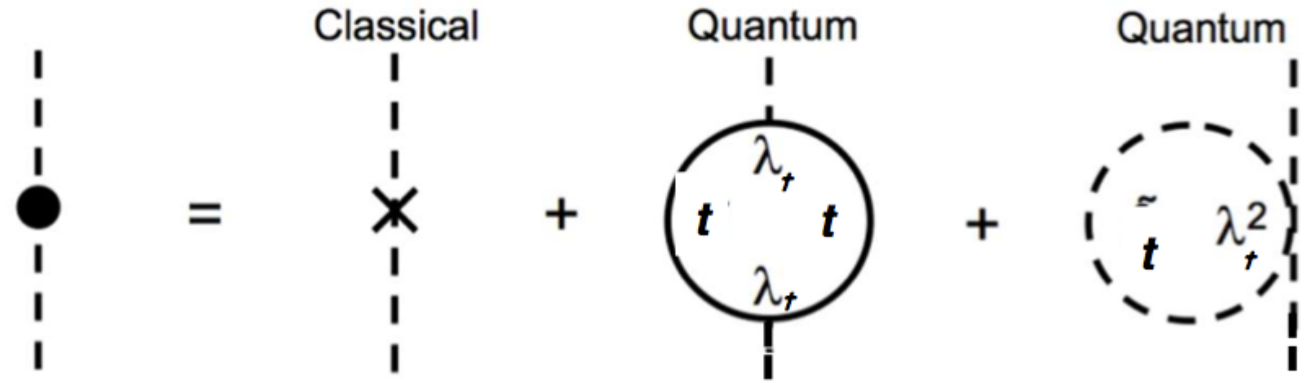
- Dark matter → lightest SUSY particle → viable Dark Matter candidate
- Gravity → can be included in SUSY
- Unification of forces at 10^{16} GeV:



- Neutrino masses: expected in SUSY

Corrections to the Higgs Mass

Corrections to the Higgs mass by scalar partner particles



Fermion Yukawa coupling

$y_t = \lambda_t = \sqrt{2}m_t / v$

$1/(\sqrt{2}G_F) = v^2$

$$m_h^2 = (m_h^2)_0 - \frac{3G_F}{4\sqrt{2}\pi^2}(4m_t^2)\Lambda_{NP}^2 + \frac{3G_F}{4\sqrt{2}\pi^2}(4m_{\tilde{t}}^2)\Lambda_{NP}^2 + O(\ln[\Lambda_{NP}/m_h])$$

$$+ \frac{3G_F}{\sqrt{2}\pi^2}(m_t^2 - m_{\tilde{t}}^2)\ln(\Lambda_{NP}/m_h)$$

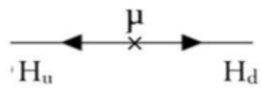
Note: to have 4, **two** mass-degenerate scalars needs to be considered ($\tilde{t}_R$ and $\tilde{t}_L$)

Complete cancellation only if masses are exactly the same, if not:
$\delta M_h^2 \sim \log(|M_B^2 - M_F^2|)$
To solve the hierarchy problem, expect at least a few SUSY masses below 1 TeV

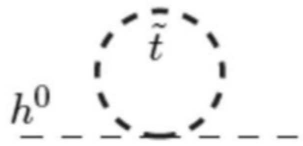
Corrections to the Higgs Mass

More SUSY particles protecting the Higgs mass:

$$m_Z^2 = -2(m_{h_u}^2 + |\mu|^2)$$

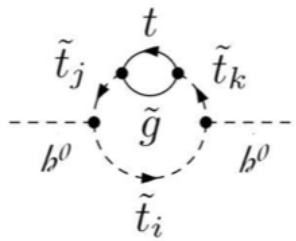


$$\delta m_{h_u}^2 = -\frac{3y_t^2}{4\pi^2} m_{\tilde{t}}^2 (1 + a^2/2) \log \frac{\Lambda}{m_{\tilde{t}}}$$



Guess the mass of the new particles

$$\delta m_{\tilde{t}}^2 = -\frac{8\alpha_s}{3\pi} M_3^2 \log \frac{\Lambda}{m_3}$$



Cornerstones of naturalness:

- Higgsino directly bound by Higgs mass parameter μ
- Top squark mass should not be heavier than 1 TeV (1-loop)
- Gluino can be a bit heavier (2-loops)

SUSY Breaking

Perfect symmetry: SUSY particles have same mass as SM particles

BUT: experimentally not found → broken symmetry can lead to higher masses

Allow all possible mass terms and couplings which don't violate gauge couplings:

squark masses (e.g. m_Q^2: 3x3 matrix, 6 real + 3 phases)

slepton / Higgs masses

gaugino masses (M1,M2,M3)

M': CP violation

qqH, llH couplings

Higgs masses

$$\begin{aligned}\mathcal{L}_{\text{soft}} = &-\Big[\tilde{Q}_i^\dagger \mathbf{m}^2_{\mathbf{Q}ij}\tilde{Q}_j + \tilde{d}^\dagger_{\mathrm{R}i}\mathbf{m}^2_{\mathbf{D}ij}\tilde{d}_{\mathrm{R}j} + \tilde{u}^\dagger_{\mathrm{R}i}\mathbf{m}^2_{\mathbf{U}ij}\tilde{u}_{\mathrm{R}j} \\ &+ \tilde{L}_i^\dagger \mathbf{m}^2_{\mathbf{L}ij}\tilde{L}_j + \tilde{e}^\dagger_{\mathrm{R}i}\mathbf{m}^2_{\mathbf{E}ij}\tilde{e}_{\mathrm{R}j} + m^2_{H_u}|H_u|^2 + m^2_{H_d}|H_d|^2\Big] \\ &-\frac{1}{2}\left[M_1\bar{\lambda}_0\lambda_0 + M_2\bar{\lambda}_A\lambda_A + M_3\bar{\tilde{g}}_B\tilde{g}_B\right] \\ &-\frac{i}{2}\left[M_1'\bar{\lambda}_0\gamma_5\lambda_0 + M_2'\bar{\lambda}_A\gamma_5\lambda_A + M_3'\bar{\tilde{g}}_B\gamma_5\tilde{g}_B\right] \\ &+\Big[(\mathbf{a_u})_{ij}\epsilon_{ab}\tilde{Q}_i^a H_u^b\tilde{u}^\dagger_{\mathrm{R}j} + (\mathbf{a_d})_{ij}\tilde{Q}_i^a H_{da}\tilde{d}^\dagger_{\mathrm{R}j} + (\mathbf{a_e})_{ij}\tilde{L}_i^a H_{da}\tilde{e}^\dagger_{\mathrm{R}j} + \text{h.c.}\Big] \\ &+\Big[(\mathbf{c_u})_{ij}\epsilon_{ab}\tilde{Q}_i^a H_d^{*b}\tilde{u}^\dagger_{\mathrm{R}j} + (\mathbf{c_d})_{ij}\tilde{Q}_i^a H^*_{ua}\tilde{d}^\dagger_{\mathrm{R}j} + (\mathbf{c_e})_{ij}\tilde{L}_i^a H^*_{ua}\tilde{e}^\dagger_{\mathrm{R}j} + \text{h.c.}\Big] \\ &+\left[b H_u^a H_{da} + \text{h.c.}\right], \qquad (8.1\end{aligned}$$

SUSY Breaking

We know SUSY is a broken symmetry – but how?
Different theories about the hidden sector on the market:

Hidden sector
SUSY breaking

Messenger

Visible sector
MSSM

Most known are:

SUGRA:

- Mediating interactions are gravitational → LSP is usually χ_1^0

GMSB:

- Mediating interactions are ordinary electroweak and QCD gauge interactions → LSP is usually the gravitino

AMSB, Gaugino-mediation:

- SUSY breaking happens on different brane in a higher-dimensional theory

Soft Supersymmetry Breaking: Give different masses to SM particles and their superpartners but preserve the structure of couplings of the theory

Gravitino in SUSY

- When standard symmetries are broken spontaneously → a massless boson appears for every broken generator
- If the symmetry is local, this boson is absorbed into the longitudinal components of the gauge boson, which becomes massive
- The same is true in SUSY → here, a massless fermion appears, called the Goldstino
- In the case of local supersymmetry, this Goldstino is absorbed into the Gravitino
- Coupling of the Goldstino (gravitino) to matter → proportional to
  $1/\sqrt{m_{\tilde{G}} M_{Pl}}$
- Mass of the gravitino in GMSB:

$$m_{\tilde{G}} \sim \frac{F}{M_{Pl}} \simeq 10^{-6} - 10^{-9}\mathrm{GeV}$$

SUSY Parameter Space

MSSM → 105 free parameters (masses, couplings, phases)
Key parameters are:

- μ = SUSY version of the SM Higgs mass
- $\tan\beta$ = Ratio of vacuum expectation values of H_u/H_d
- m_h = Mass of h^0 $m_h^2 \leq M_Z^2 + \Delta m_{rad}^2 (A_t, \tan\beta, \mu, m_{\tilde{t}\,1,2}, m_t, v^{**})$
- m_A = Mass of A^0 $\frac{1}{2}M_Z^2 = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - \mu^2 \approx -m_{Hu}^2 - \mu^2$
- m_{H^+} = Mass of $H^{+/-}$
- m_{Hu^2}, m_{Hd^2} from SUSY breaking
- M_{Q^2}= Squark 3x3 mass term
- M_{L^2}= Slepton 3x3 mass term

} $=m_0^2$ at GUT scale*

- M_1= Bino mass term
- M_2= Wino mass term
- M_3= gluino mass term

} $= m_{1/2}$ at GUT scale*

- $A_{u,d,e}$~Yukawa-like 3x3 matrix $=A_0$ at GUT scale*

* In Planck-scale mediated SUSY breaking models like mSUGRA
** $v=\sqrt{(v_{u^2}+v_{d^2})}$

SUSY Models

MSSM → 105 free parameters (masses, couplings, phases)

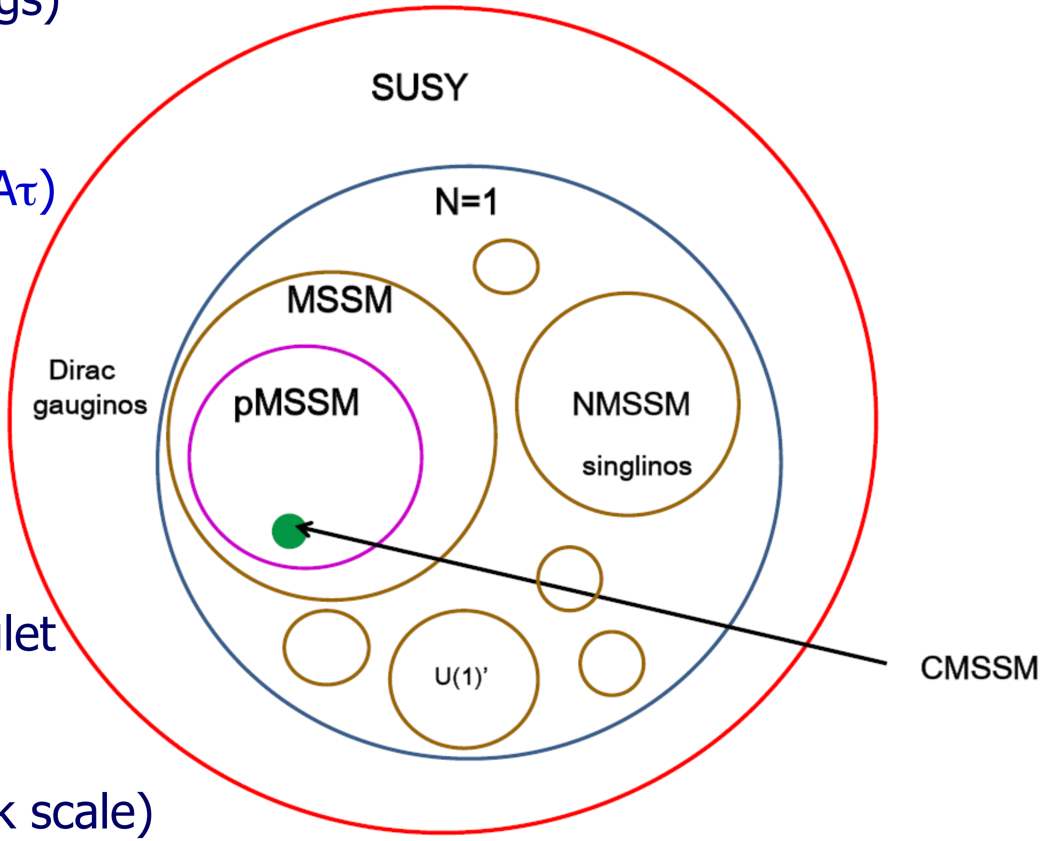
pMSSM → 19 free parameters (first two sfermion generations degenerate, and with negligible Yukawa couplings)

- 10 sfermion masses
- 3 gaugino masses
- 3 tri-linear couplings (A_b,A_t,$A\tau$)
- μ, M_A, tanβ

CMSSM → 4 free parameters + 1 phase

- tanβ, A_0, M_1, $M_{1/2}$, sign(μ)

NMSSM → contains one extra singlet chiral superfield
→ solves μ problem
(μ at EW and not Planck scale)

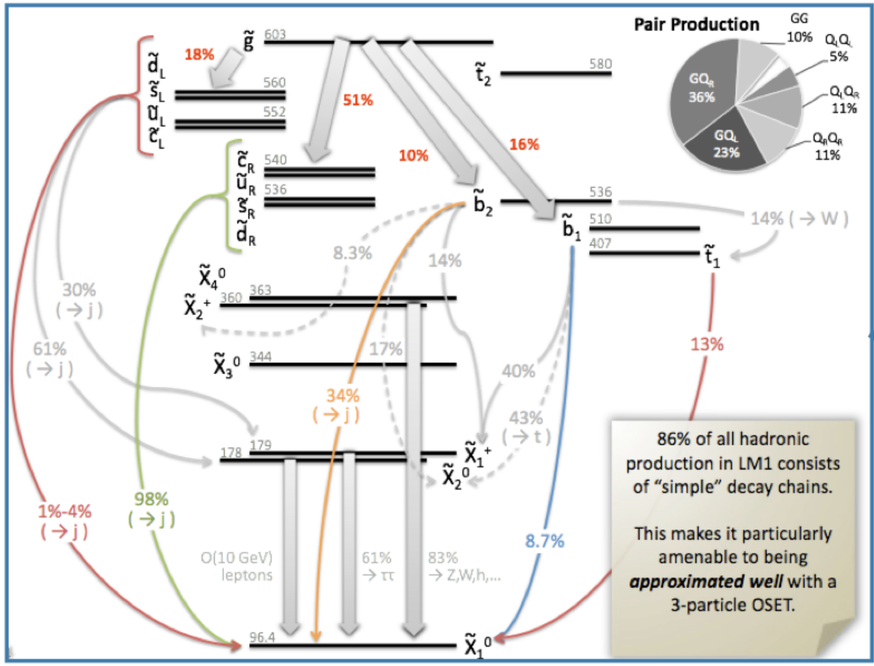


Full vs. simplified Model

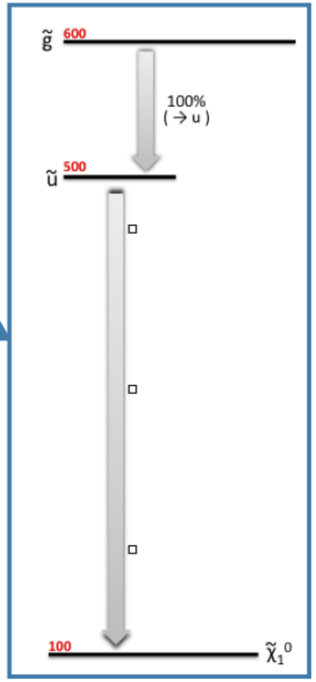
Past: interpretation in CMSSM

Present: try to make it more easier for theorists to compare their model to our result → use simplified model!

CMSSM



What we put in: much simpler…

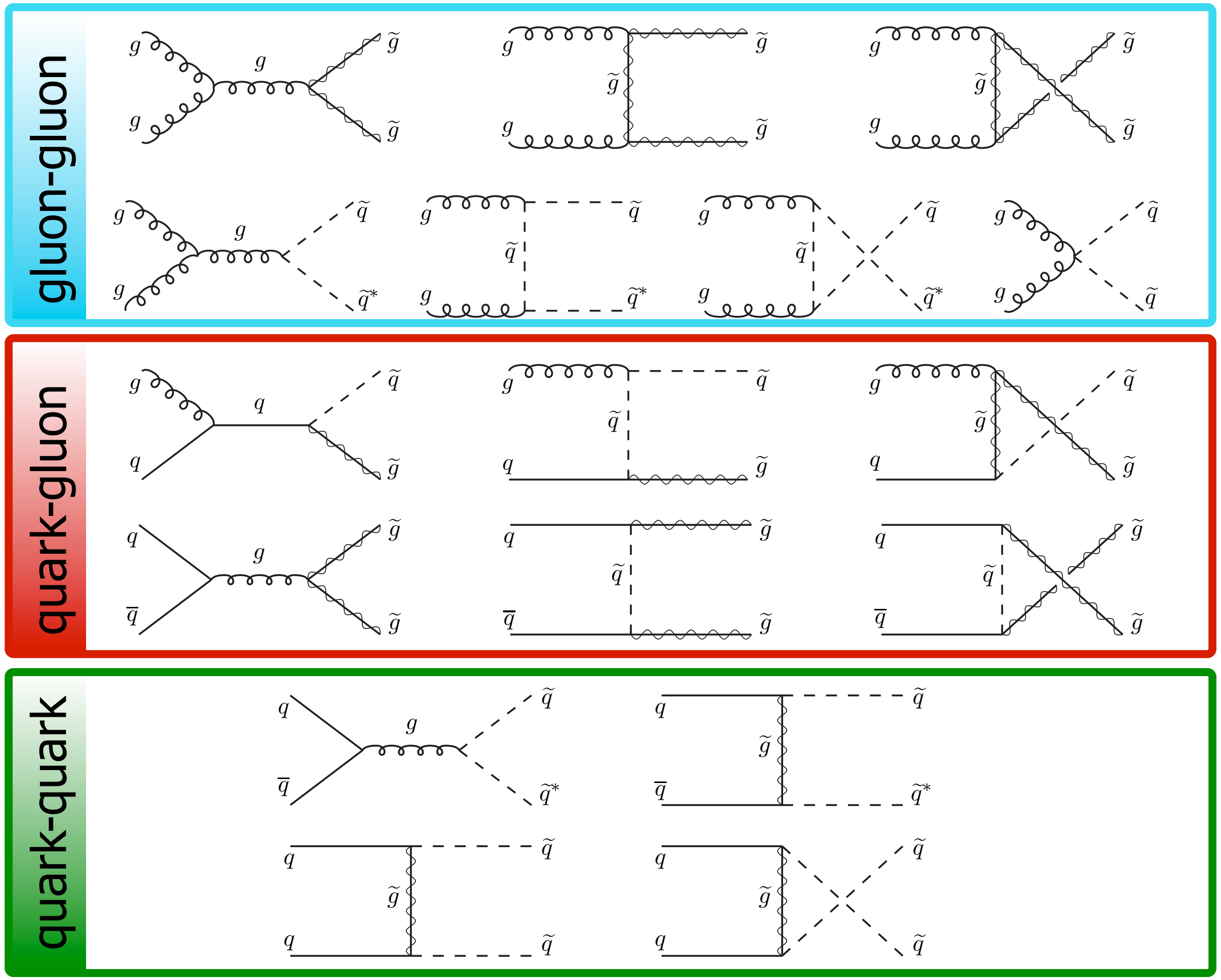


Simplified Model Spectrum (SMS) with 3 particles, 2 decay modes

Future: ???

SUSY Production (Squarks and Gluinos)

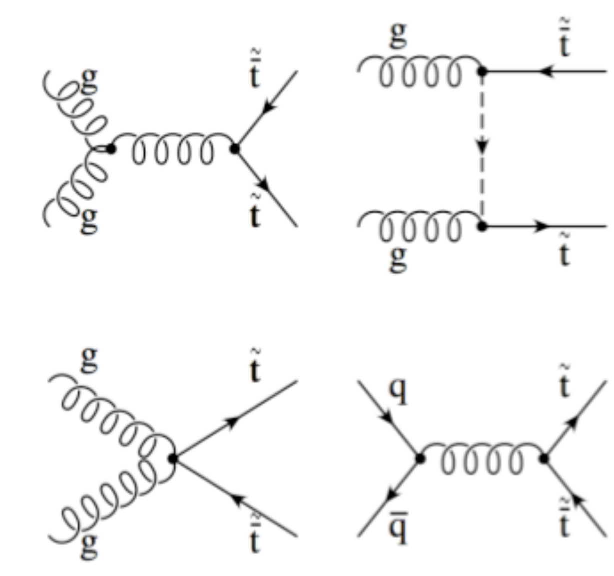
Colored production has highest cross section at the LHC (if colored particles are not too heavy)

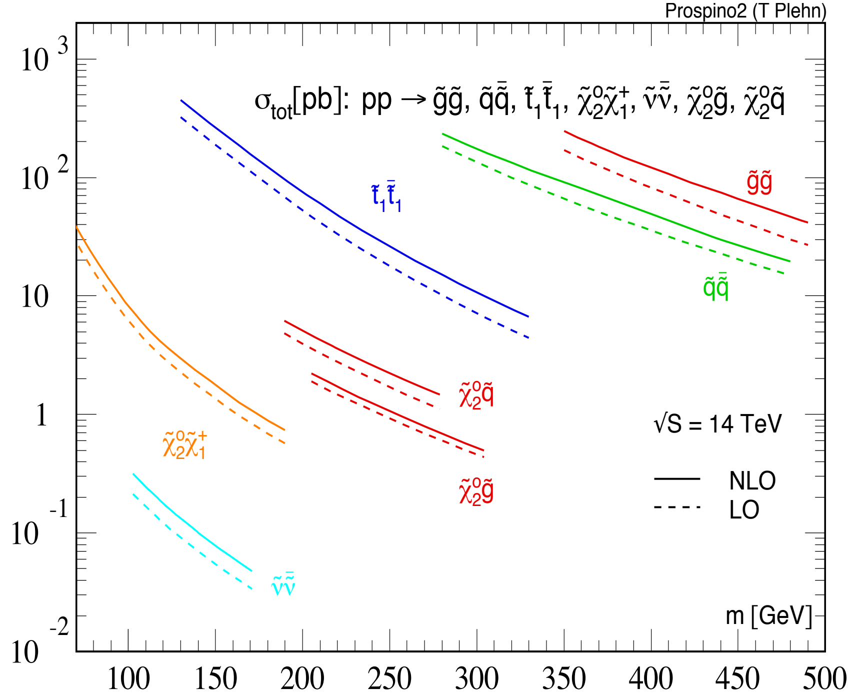


SUSY Production (3^{rd} Generation and Chargino-Neutralino)

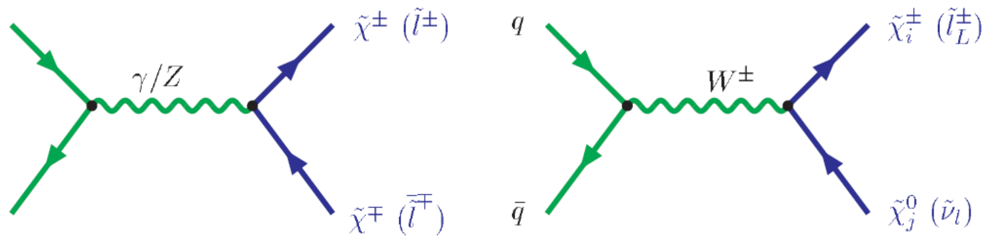
Stop and EWKino cross sections lower

quark-quark & gluon-gluon





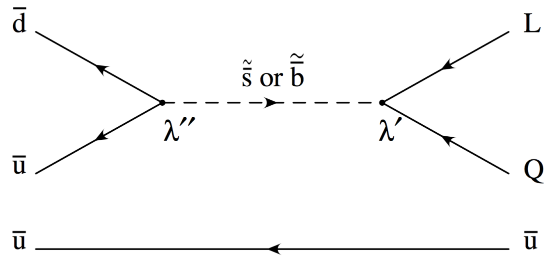
annihilation



(similar to e^+e^- channels)

Proton Decay and R-Parity

In the MSSM, **proton could decay** through SUSY particle exchange with new couplings W = $\lambda' \, LQD + \lambda \, LLE + \lambda'' \, UDD$:



Solution: *R*-parity conservation, with *R* defined as:

$R = (-1)^{2s+3B+L}$ with s: Spin, B: baryon number, L: lepton number

R=1: SM particle
R=-1: SUSY particle

If ***R*-parity is conserved** (**RPC**):

→ Single SUSY particle cannot decay into just SM particles
→ Lightest SUSY particle (LSP) absolutely stable
→ LSP candidates are: lightest neutralino, gravitino

Other option: **small violation of B or L** (aka **RPV** models)

Summary: Introduction to Supersymmetry

SUSY: a beautiful and straight-forward extension of the SM…

- Only possible extension of the Poincare group
- Solves most SM questions (Includes gravity, Dark Matter, unification of the forces
- Predicts a light Higgs
- Perturbative → predictive

- Predicts many new scalar particles
- We don't know their masses
- Hard to find (at least up to now…)
- Adds new quantum number to prevent p decay, but otherwise not theoretically motivated…

- Escaped 30 years of searches!
- SUSY breaking not understood (soft breaking in hidden sector?)
- We are flowed by 105 new parameters…

Where we are…

- Open questions of the Standard Model
- Introduction to Supersymmetry
- ⇨ **Challenges in data analysis** ⇦
- Tools for SUSY searches
- Detailed example for a SUSY search
- Outlook

Experimental Challenges

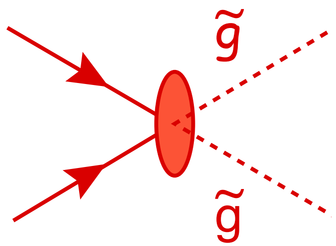
How to find direct evidence of (weak-scale) SUSY at LHC?

- SUSY cross-section is weak (pb-fb) and SM background is huge
- SUSY mass spectrum is a priori unknown (well, we can use naturalness as guide…)
- SUSY signatures can be numerous and (more or less) striking
- Long decay chains difficult to reconstruct

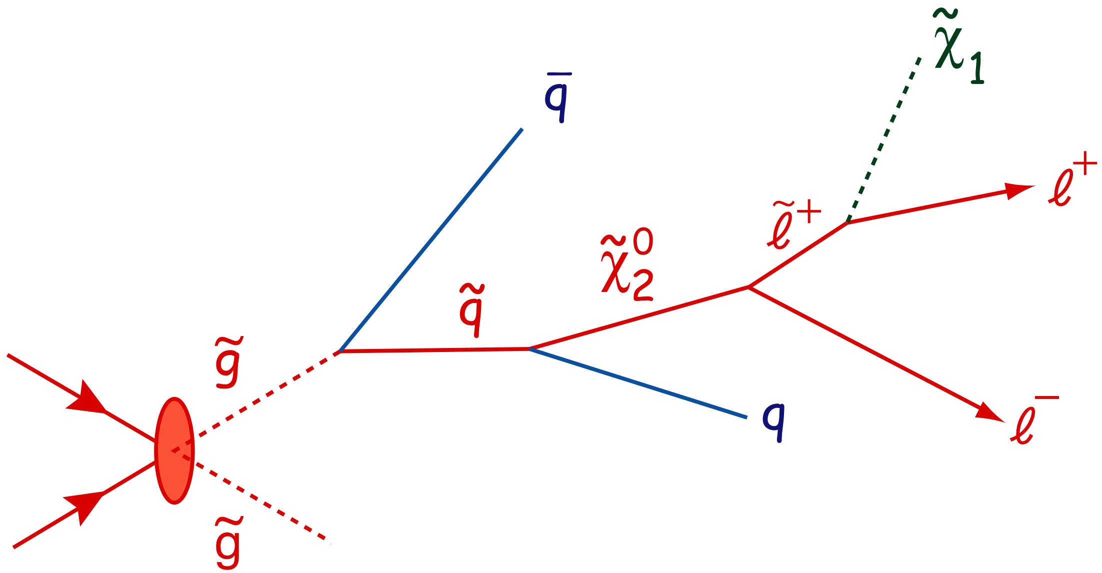
Experimental challenges = systematics = search sensitivity

- Changing LHC conditions (especially pile-up) and experiments
- Trigger can kill the signal …
- Object reconstruction in hadronic environment
- Detector understanding (timing, …) crucial for non-standard SUSY
- Data/Monte-Carlo (dis-)agreement in hadronic environment

Example SUSY Decay



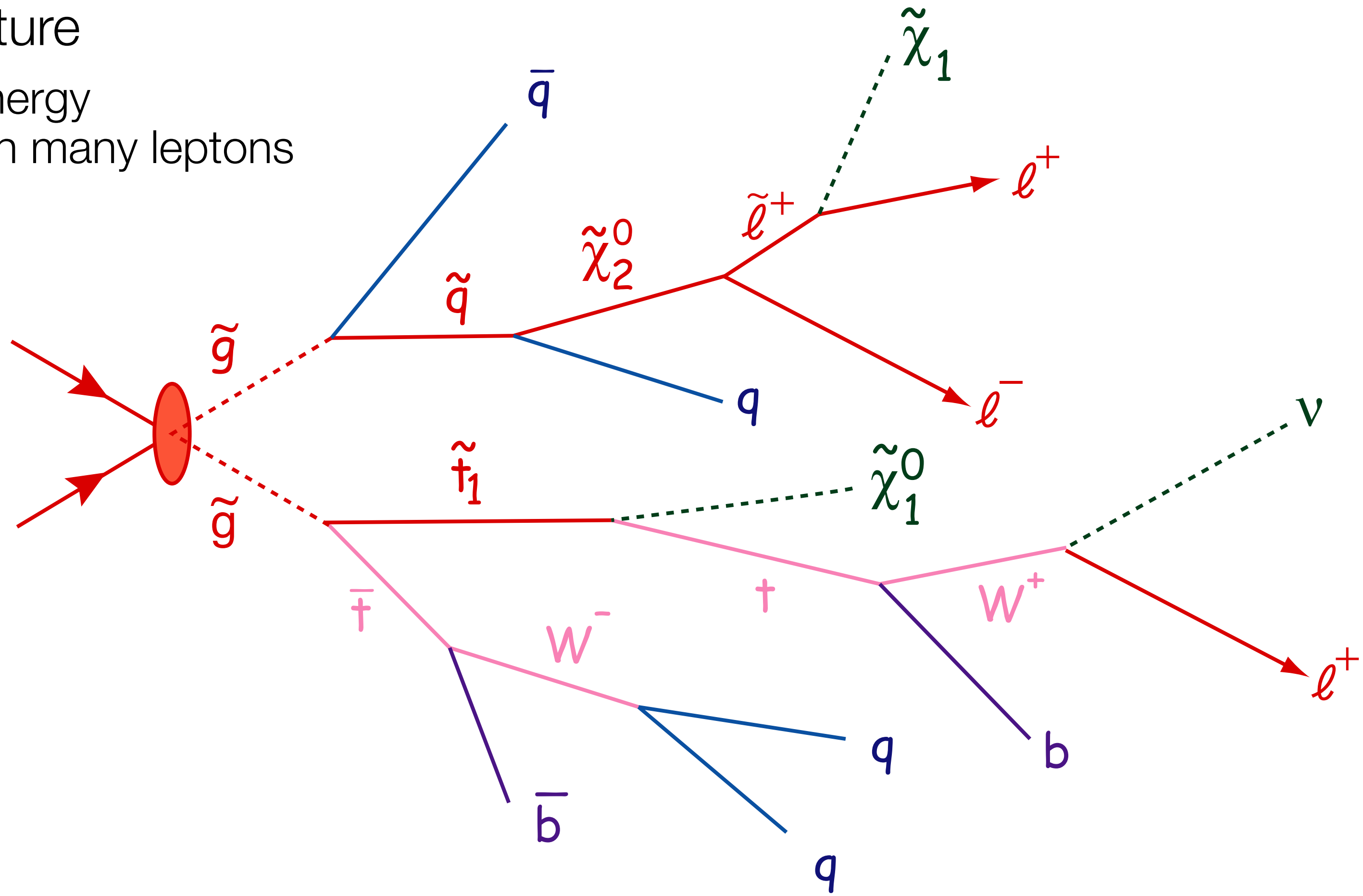
Example SUSY Decay



Example SUSY Decay

Pairwise production;
clear signature

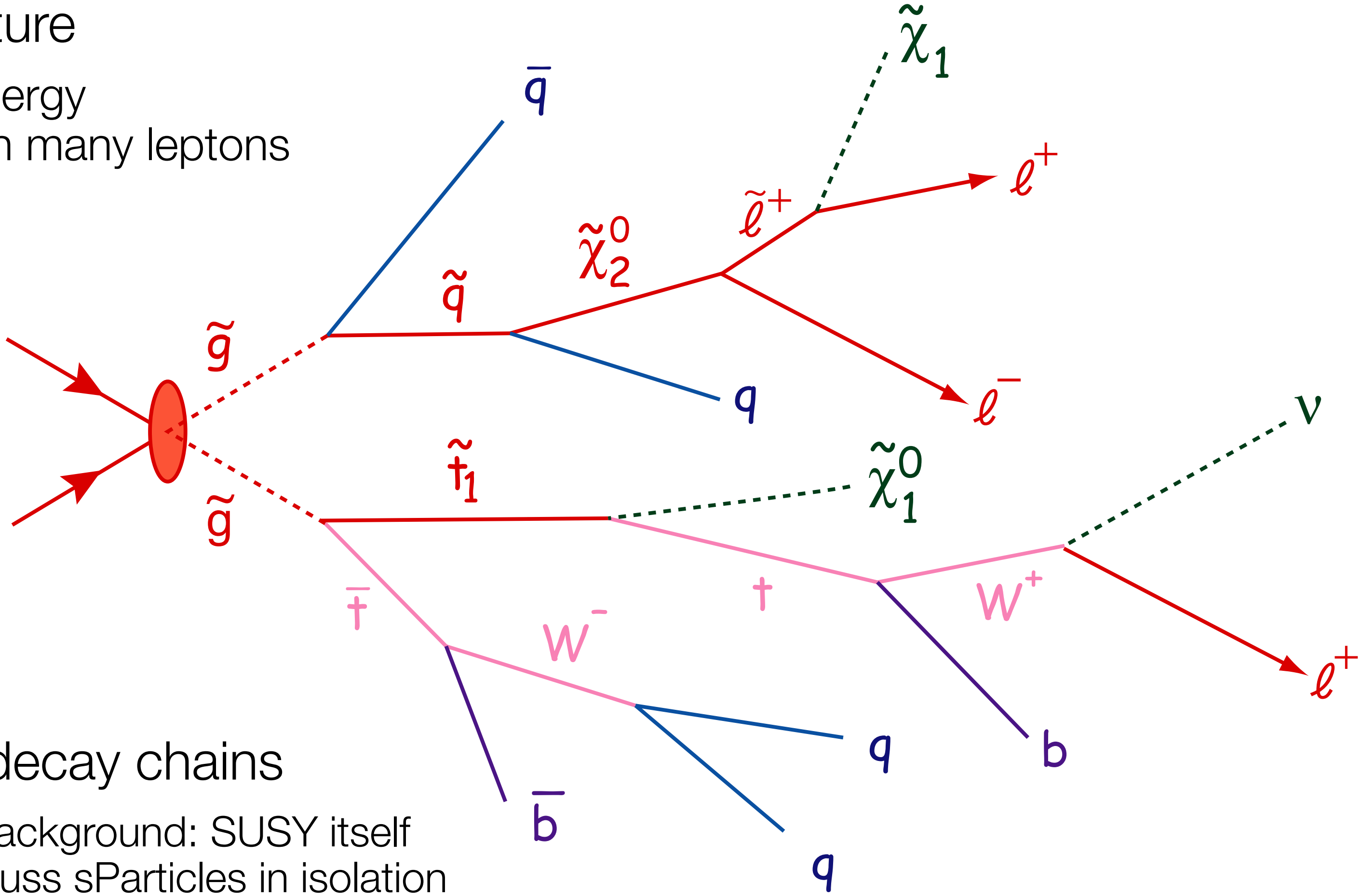
- missing energy
- events with many leptons
- and jets.



Example SUSY Decay

Pairwise production;
clear signature

- missing energy
- events with many leptons and jets.



But: Long decay chains

- dominant background: SUSY itself
- cannot discuss sParticles in isolation
- use consistent model for simulation

Example SUSY Decay

Pairwise production; clear signature

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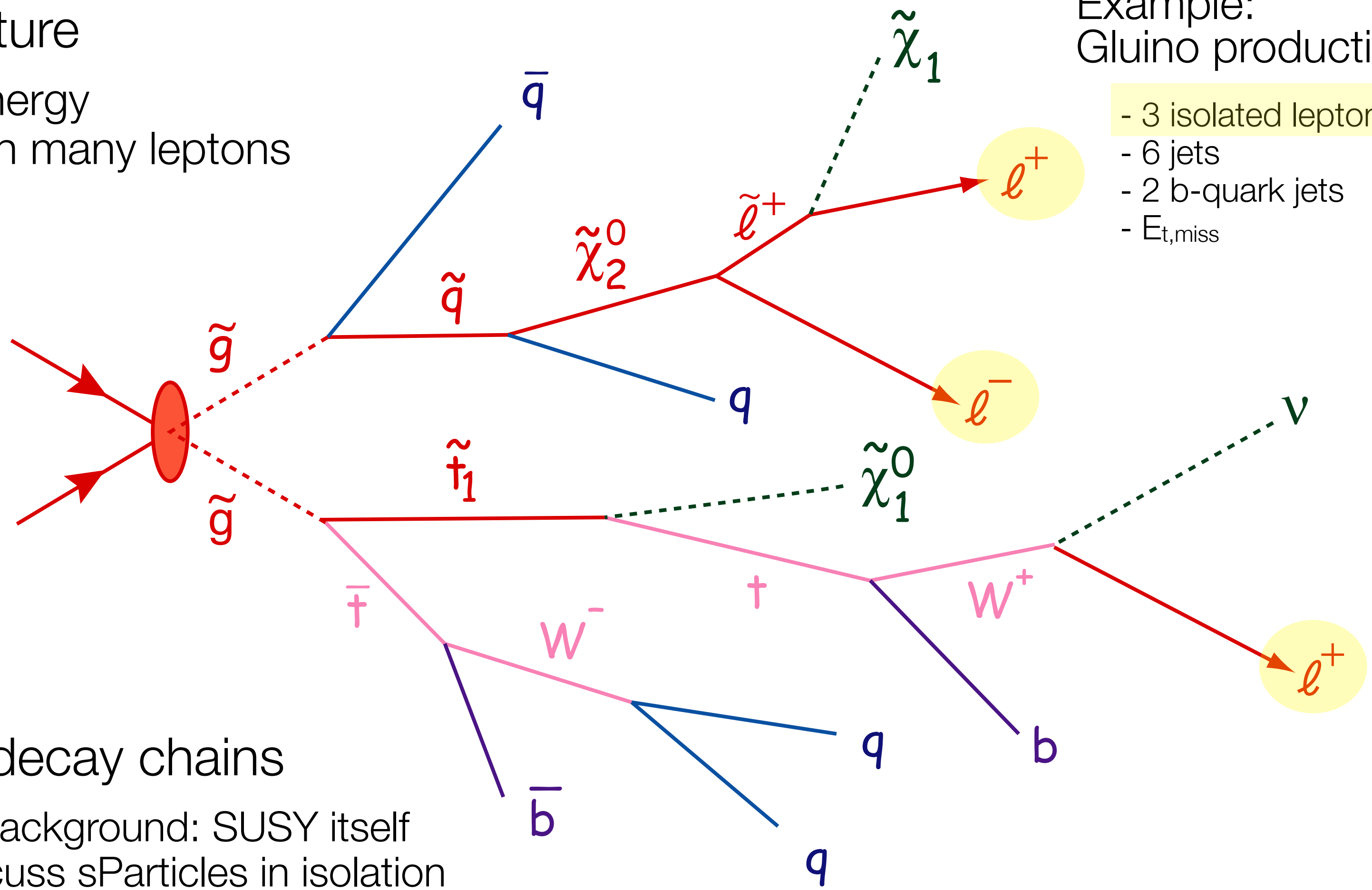
events with many leptons
and jets.

Example:
Gluino production

- 3 isolated leptons
- 6 jets
- 2 b-quark jets
- $E_{t,miss}$



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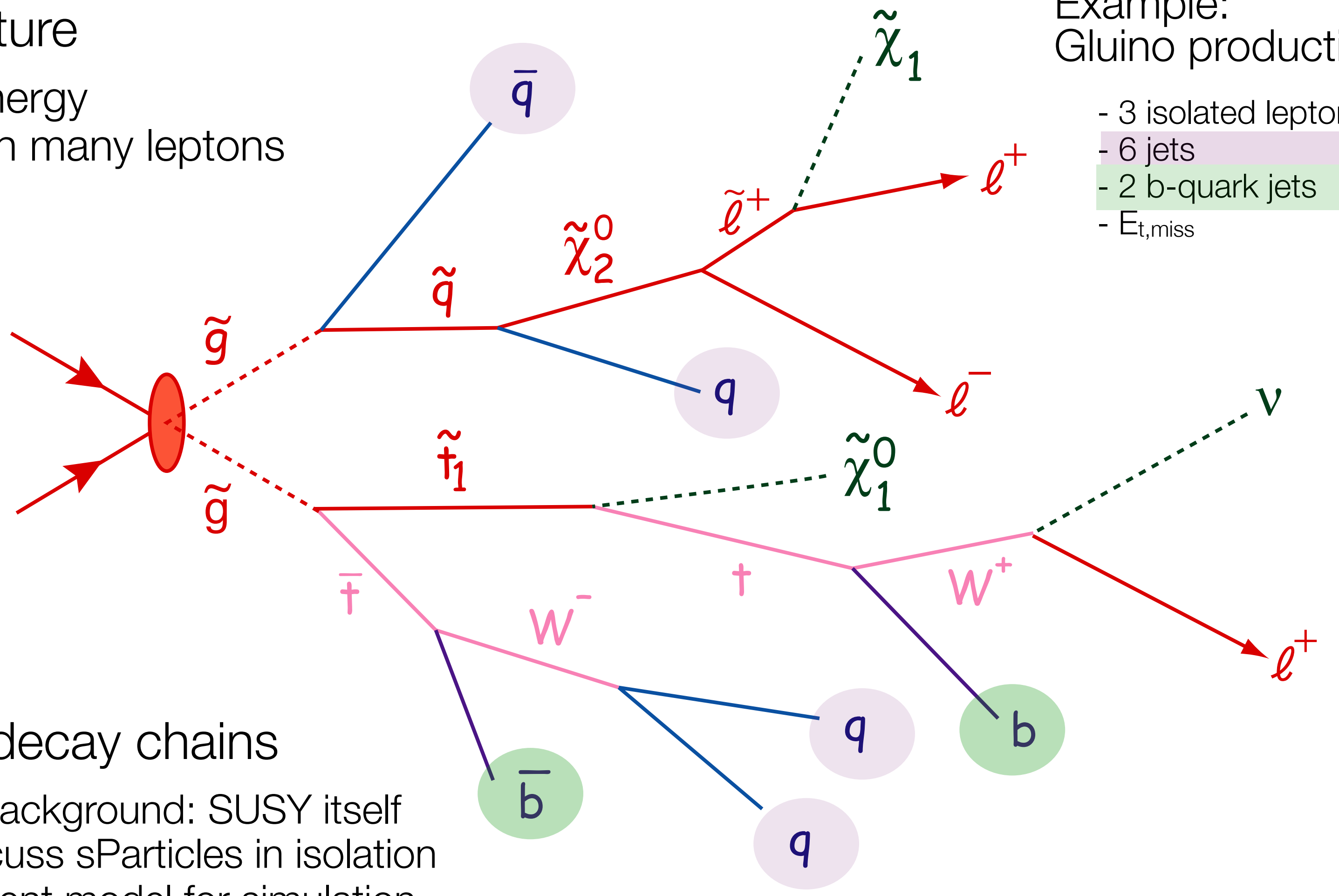

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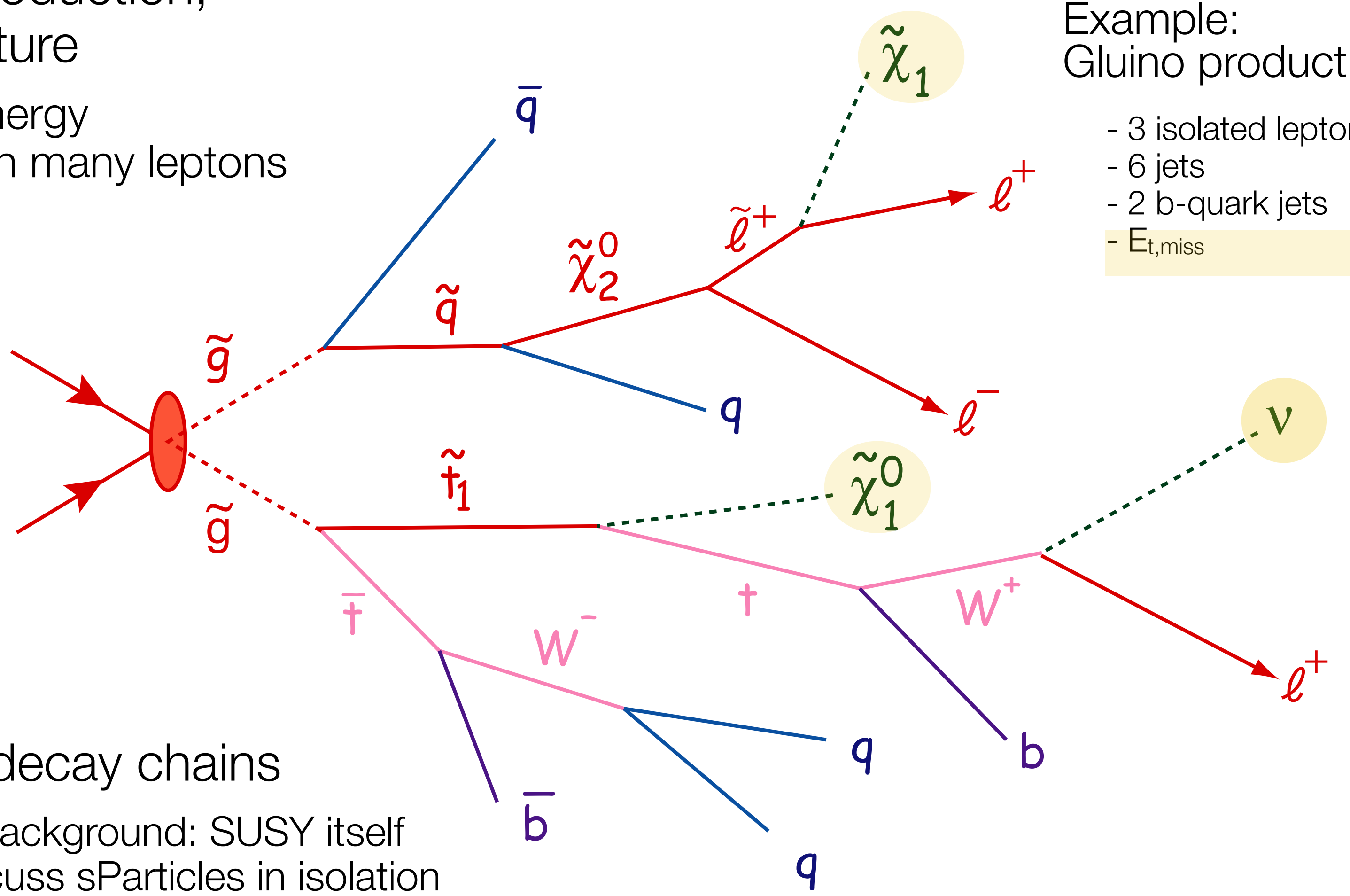
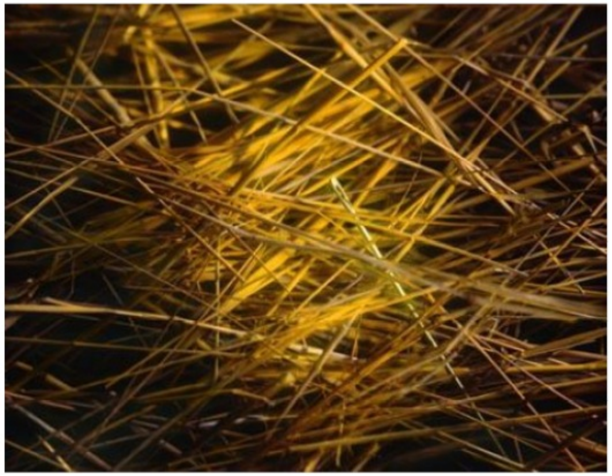


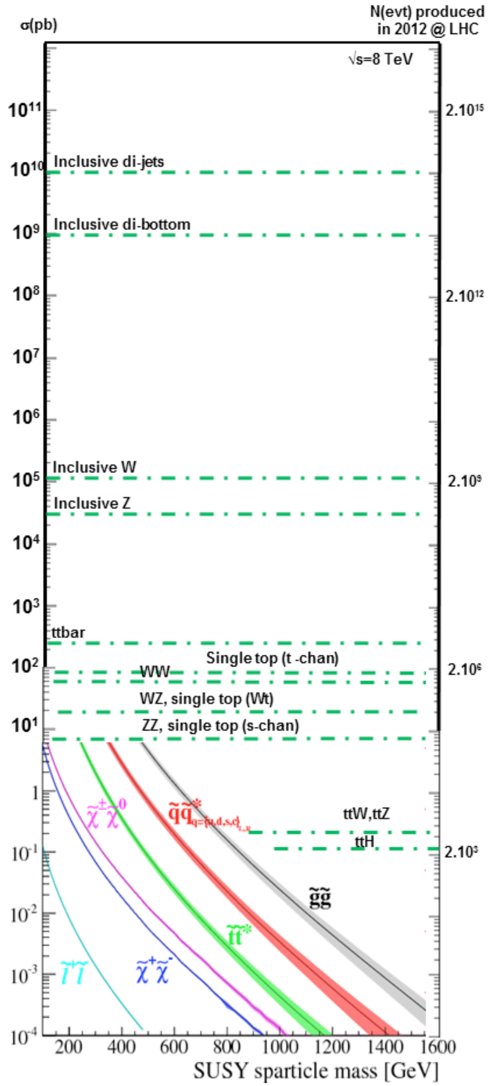
But: Long decay chains

dominant background: SUSY itself
cannot discuss sParticles in isolation
use consistent model for simulation

Event Selection needed!

Problem:
Signals much smaller
than background!





Big challenge
to find the rare
exciting events!!

Where we are...

- Open questions of the Standard Model
- Introduction to Supersymmetry
- Challenges in data analysis
- ⇨ **Tools for SUSY searches** ⇦
- Detailed example for a SUSY search
- Outlook

Interesting Observables

Need to find variables that **distinguish BSM from SM** signatures!

- **Missing transverse energy** (expected for only weakly interacting neutral particles leaving the detector)
  - Calculated from all energies in calorimeter or all Particle Flow objects: E_T^{miss} (or MET)
  - Calculated from all jets: H_T^{miss} (or MHT)
- **ΔΦ**: angle between E_T^{miss} and leading jet(s)
- **M_{T2}, Razor**: two heavy particles in two hemispheres decaying to LSP
- **Transverse mass** calculated from lepton p_T and E_T^{miss}: M_T
- Sum of transverse energies of all jets above certain p_T threshold:

$$H_T = \sum_{jets} p_T^{jet}$$

- **Effective mass** of all objects: M_{eff}

$$M_{eff} = \sum_{jets} p_T^{jet} + p_T^{lepton} + E_T^{miss}$$

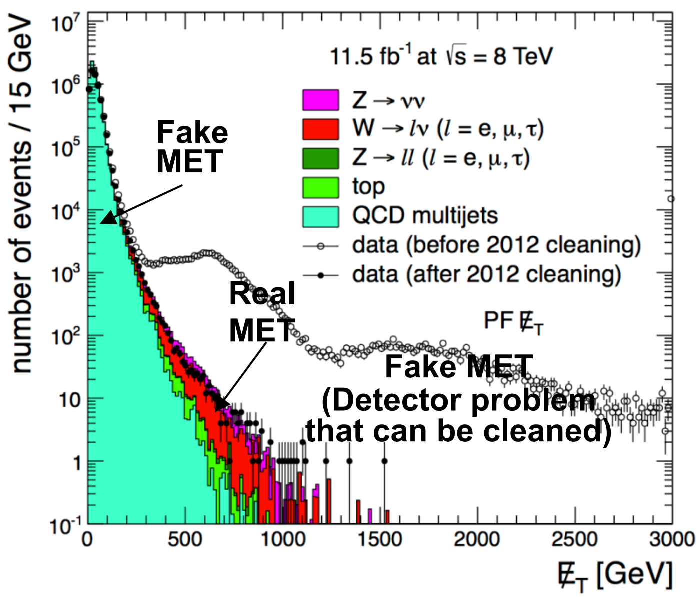
(typically peaks at $1.8(M^2_{SUSY} - M^2_{LSP})/M_{SUSY}$

Interesting Variables: E_T^{miss}

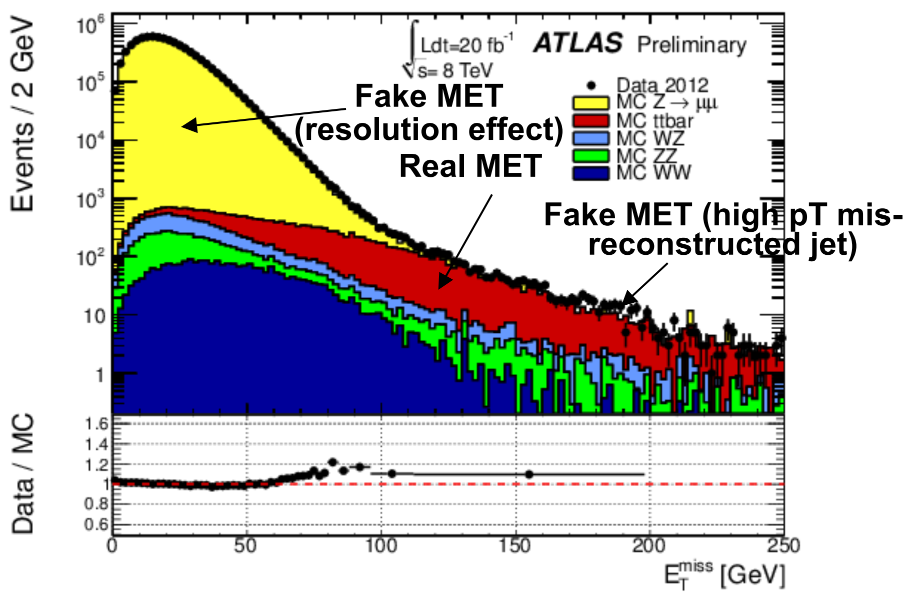
Crucial for all SUSY searches (and experimentally very challenging)

- **Real MET:** Presence of a neutral weakly interacting particle in the event (i.e. ν)
- **Fake MET:** Mismeasurement + detector malfunctions, poorly instrumented regions

DiJet



Z→μμ



→ Agreement data – Monte Carlo key for SUSY searches

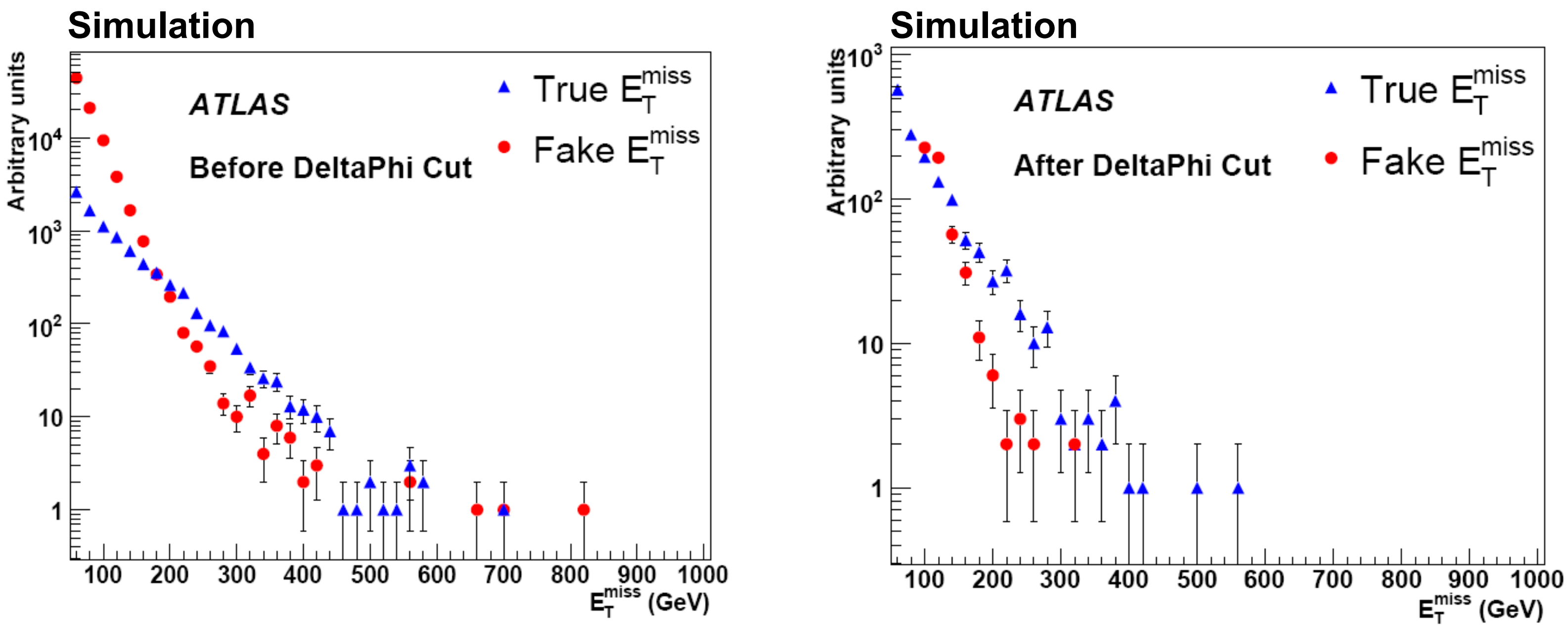
Interesting Variables: $\Delta\Phi(\text{jet, MET})_{min}$

High MET might be caused by **high p_T mismeasured jets**

→ $\Delta\Phi$: angle between E_T^{miss} and leading jet(s)

$\Delta\Phi(\text{jet, MET})_{min}$>0.2-0.5 (0-lepton events)

QCD sample (0.5<p_T<1.1 TeV)



Reverting this cut provides a very nice QCD enriched sample for background studies…

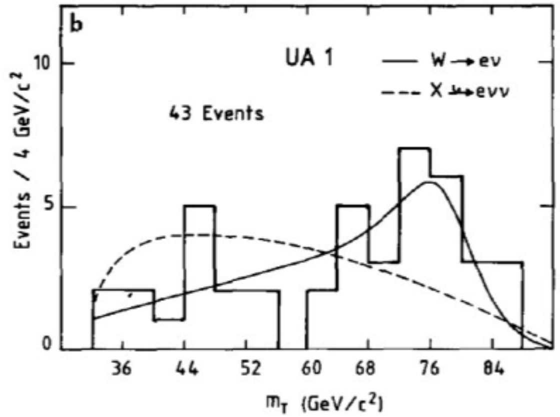
Interesting Variables: M_{T2}

In W → lν decay, transverse mass $\mathbf{M_T}$ has an **endpoint at the true W mass:**

$$m_W^2 = m_l^2 + m_\nu^2 + 2(E_T^l E_T^\nu \cosh\Delta\eta - \mathbf{p}_T^l \cdot \mathbf{p}_T^\nu) \geq$$

$$m_T^2 = m_l^2 + m_\nu^2 + 2(E_T^l E_T^\nu - \mathbf{p}_T^l \cdot \mathbf{p}_T^\nu)$$

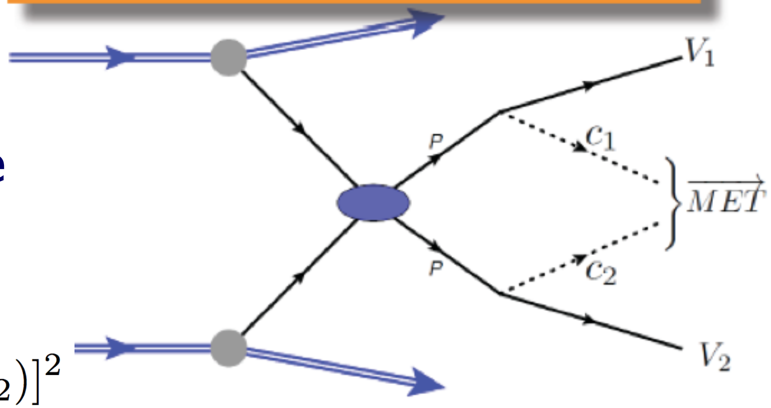
Phys. Lett. B 129 (1983) 273-282



In **RPC SUSY: two decay chains** with an unobserved child (c1 and c2) at each end. The "stransverse" mass M_{T2}: extension of M_T for the SUSY case of two unobserved particles:

$$M_{T2}(m_c) = \min_{p_T^{c(1)} + p_T^{c(2)} = p_T^{miss}} \left[\max\left(m_T^{(1)}, m_T^{(2)}\right)\right]$$

Lesters & Summers, hep-ph/9906349



If m_c were known, the endpoint of M_{T2} could be used to calculate the parent mass M_p

Simpler, but with similar efficiency: $\mathbf{M_{CT}}$

$$m_{\mathrm{CT}}^2(v_1, v_2) = [E_{\mathrm{T}}(v_1) + E_{\mathrm{T}}(v_2)]^2 - [\mathbf{p}_{\mathrm{T}}(v_1) - \mathbf{p}_{\mathrm{T}}(v_2)]^2$$

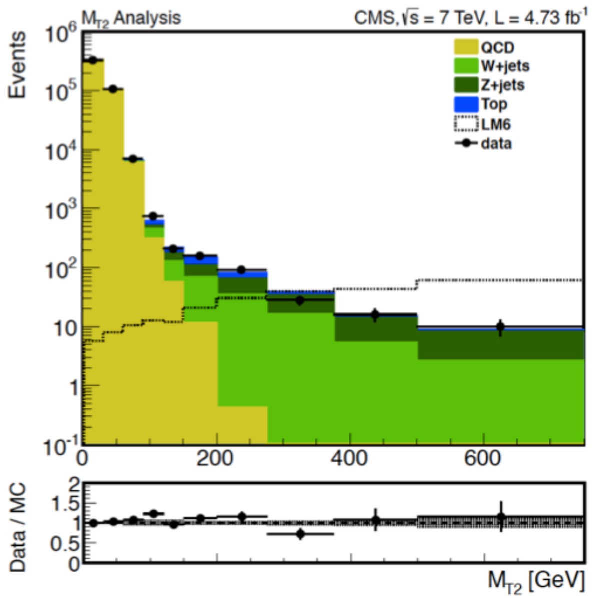
Interesting Variables: M_{T2}

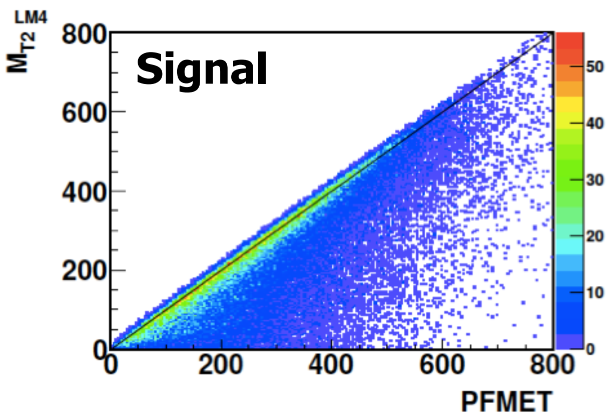
Interpretation of M_{T2}

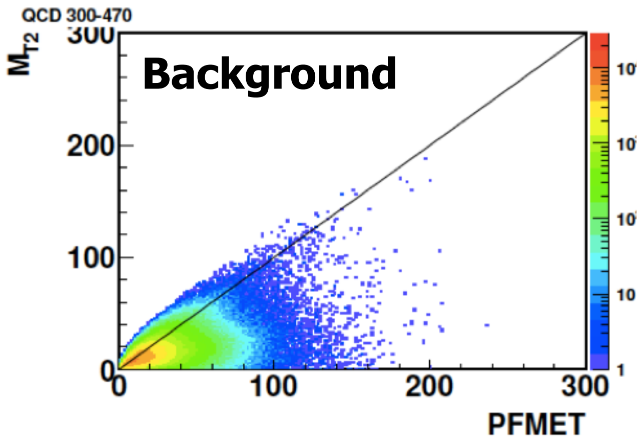
- Simplest case: no extra jets (ISR/FSR); m_c=0:

$$(M_{T2})^2 = 2p_T^{vis(1)} p_T^{vis(2)} (1 + cos\phi_{12})$$

- For **signal with symmetric systems**, $p_T^{vis(1)} = p_T^{vis(2)}$:
  - M_{T2}~MET
- For **background**:
  - Well-measured back-to-back dijets: M_{T2}~0
  - Mis-measured events: $M_{T2} < E_T^{miss}$
- Multi-jet events → divided into 2 pseudo-jets

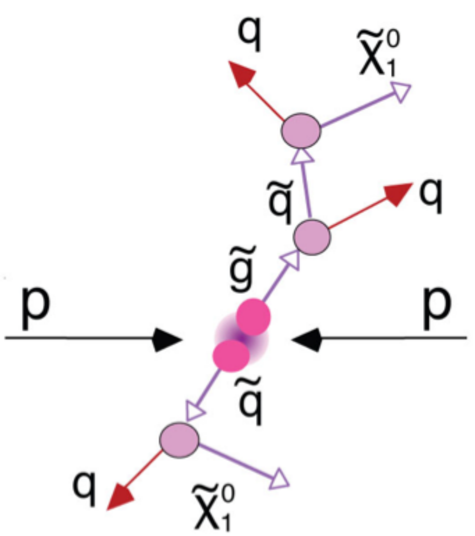


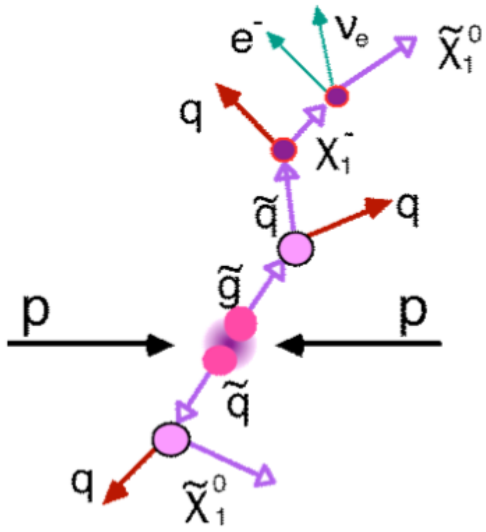


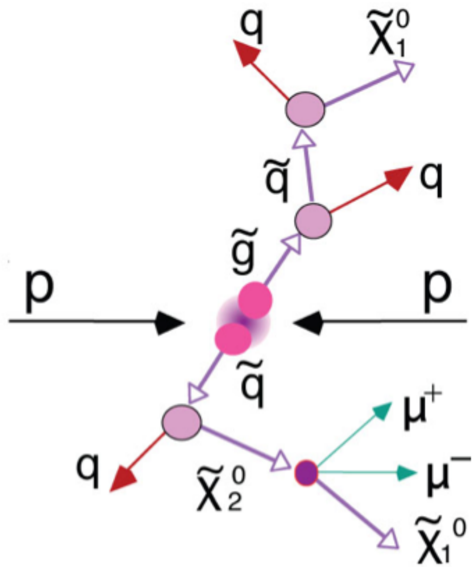


Main Backgrounds

Background differ depending on the final state:







QCD multijets
Z(→νν)+ jets
(W,t)+jets; W→τν

QCD: small
W/Z(→lν)+jets
t(→lν)+jets

W/Z(→lν)+jets
WW, WZ
tt(→llν)+jets

Where we are…

- Open questions of the Standard Model
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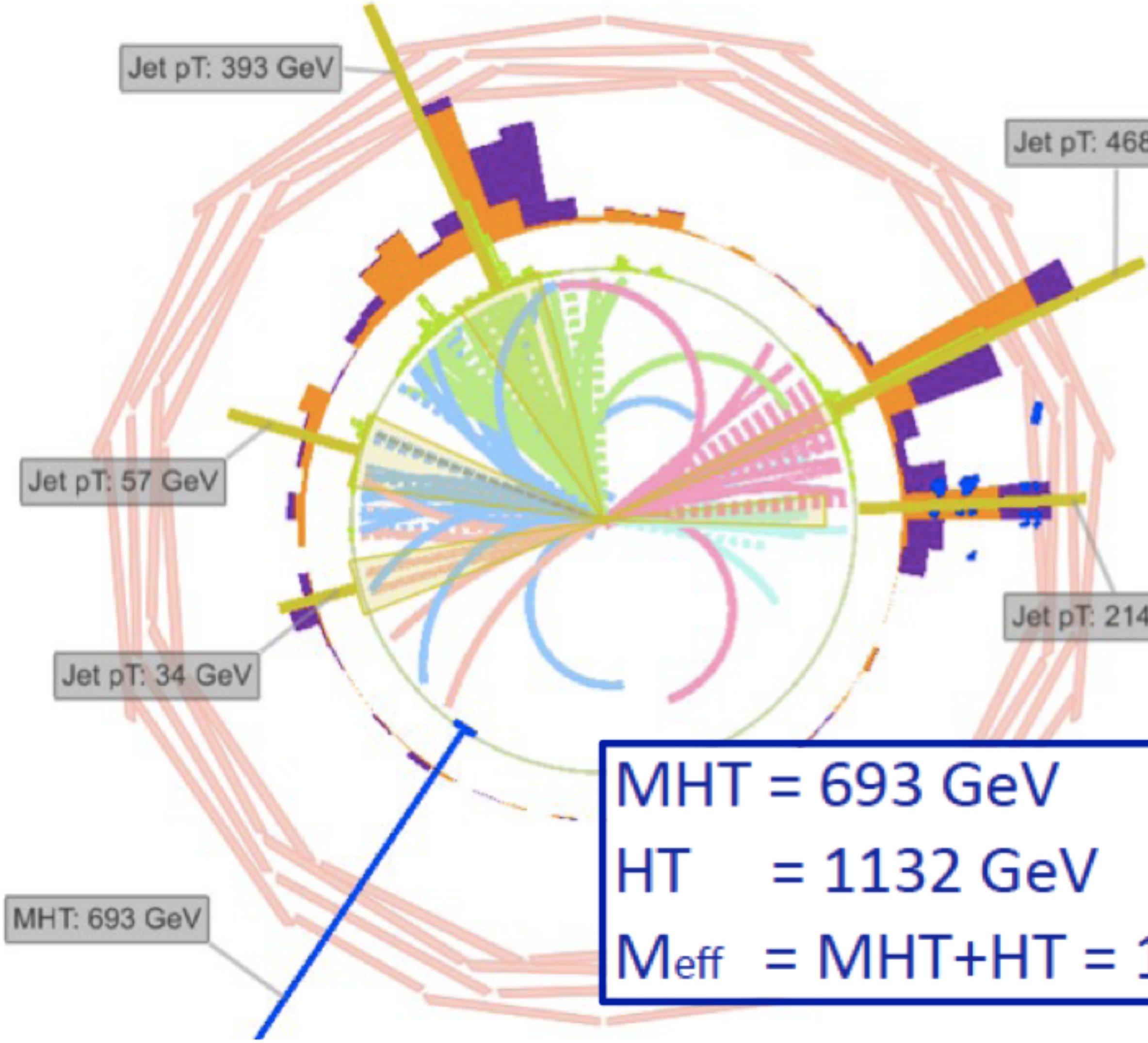
- Challenges in data analysis
- Tools for SUSY searches
- **Detailed example for a SUSY search**
- Outlook

Example: Inclusive All-Hadronic Search Event Display



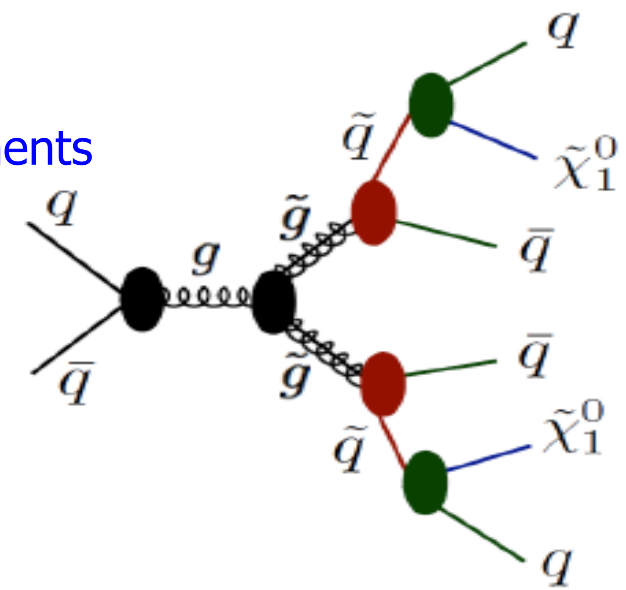
MHT = 693 GeV
HT = 1132 GeV
M_{eff} = MHT+HT = 1.83 TeV

Inclusive All-Hadronic Search: Introduction

SUS-13-012
JHEP 06 (2014) 055
arXiv:1402.4770

Signature:
Many jets and large missing transverse energy

- Least model-dependent analysis
- Large backgrounds:
  - Z+jets with Z→ $\nu\nu$ (irreducible)
  - W+jets and ttbar with W → lν and lost lepton or τ → hadrons + ν
  - QCD multijet events with large missing transverse momentum due to:
    - Leptonic decays of heavy flavor hadrons inside jets
    - Jet energy mismeasurement
    - Instrumental noise
    - Non-functioning detector components

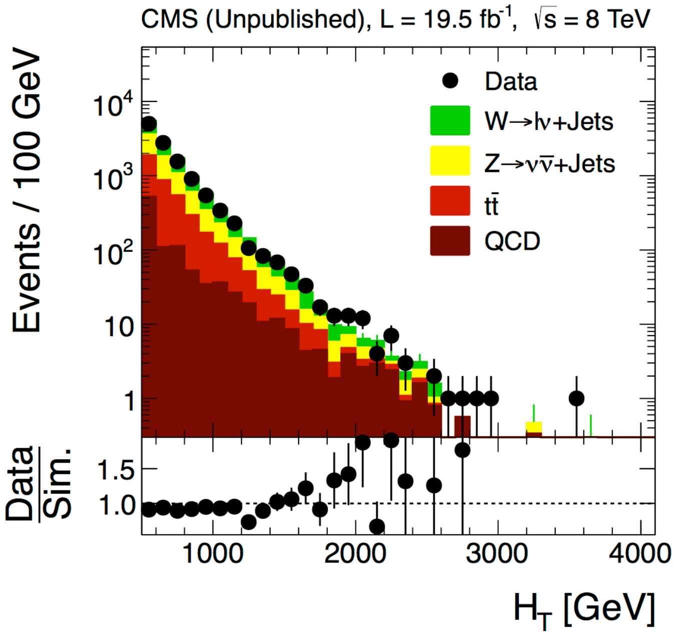


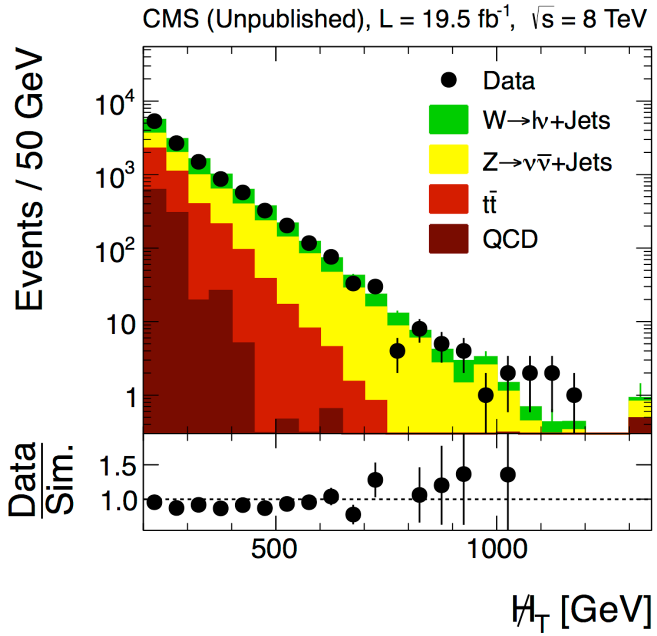
Inclusive All-Hadronic Search: Event Selection

SUS-13-012
JHEP 06 (2014) 055
arXiv:1402.4770

Baseline selection

- At least 3 jets with $p_T^{jet} > 50$ GeV and $|\eta| < 2.5$
- $H_T > 350$ GeV
- $H_T^{miss} > 200$ GeV
- $|\Delta\Phi(J_{1,2}, H_T^{miss})| > 0.5$ and $|\Delta\Phi(J_3, H_T^{miss})| > 0.3$ to veto events where H_T^{miss} is aligned in transverse plane with one of the 3 leading jets
- Veto on isolated muons and electrons





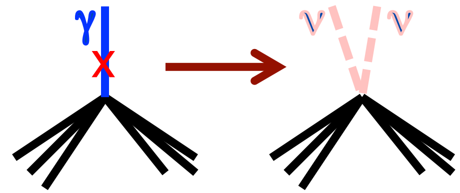
Inclusive All-Hadronic Search: Background Estimation for Z → νν

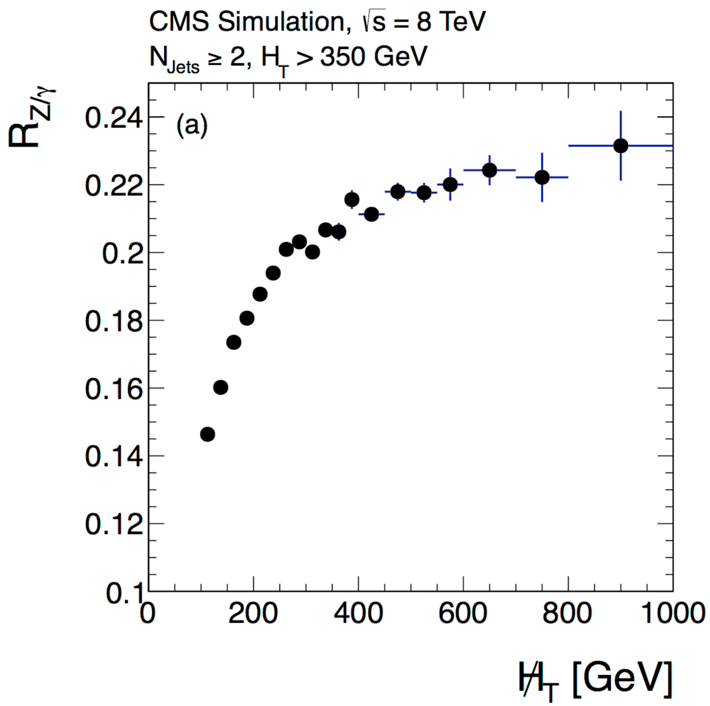
SUS-13-012
JHEP 06 (2014) 055
arXiv:1402.4770

Background estimation with γ+jets :

Strategy:

- **Declare photon invisible** to emulate neutrinos
- **Then re-calculate H_T^{miss}** for this event
- **Correct** for the photon reconstruction efficiency and neutrino branching ratio
- Then **scale** the result with the production cross section ratio $R_{Z/\gamma}$





SUSY signals could bias the prediction!

→ Cross check with Z→μμ+jets:

→ **Drawback: Low statistics** in signal region, but comparable result in baseline selection

Inclusive All-Hadronic Search: W and Top Background Estimation

SUS-13-012
JHEP 06 (2014) 055
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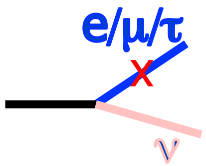
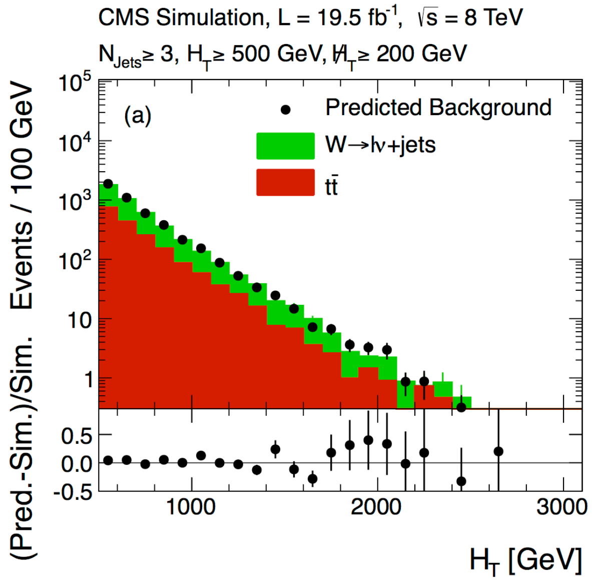
Lost Lepton Background Estimation

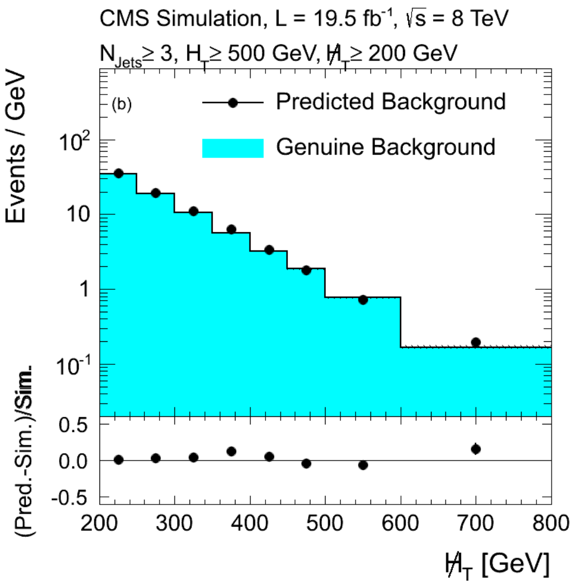
- Muon control sample with $M_T < 100$ GeV with $M_T=\sqrt{(2p_T^{\mu}\, E_T^{miss}\, (1-\cos\phi))}$ used to model:
  - Non-isolated (but identified) leptons
  - Non-identified leptons (ratio id/non-id taken from Monte Carlo)





τ Background Estimation

- Determined with a muon control sample
- Substitute μ with τ jet using response template to model the fraction of visible momentum
- Recalculate all quantities like H_T, H_T^{miss}



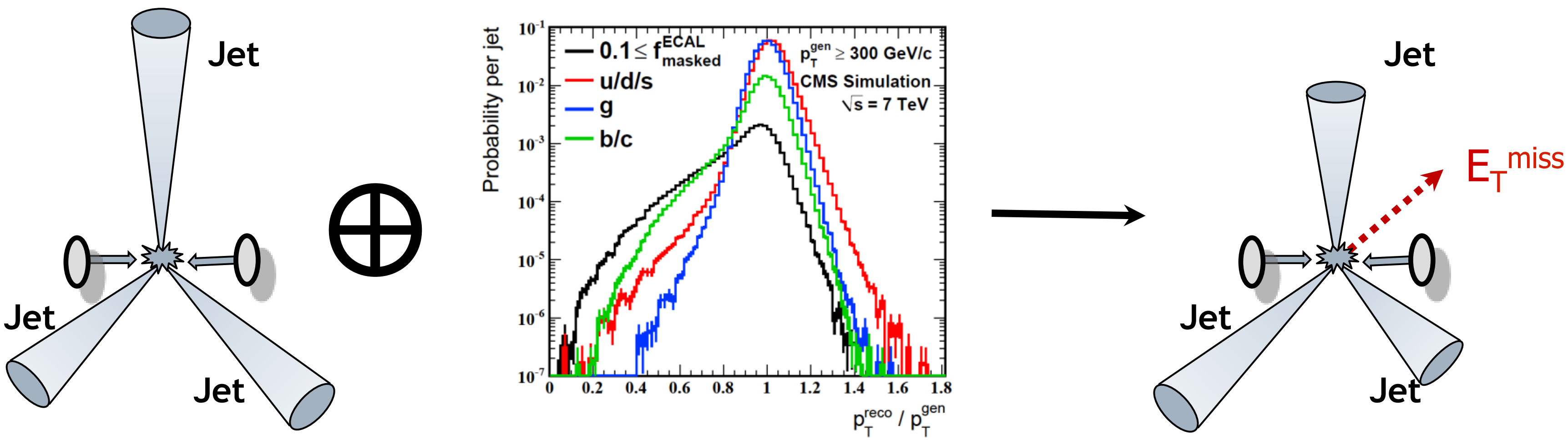
Inclusive All-Hadronic Search: QCD Background Estimation

SUS-13-012
JHEP 06 (2014) 055
arXiv:1402.4770

Most difficult background, derived here by '**Rebalance & Smear**' method:

- Rebalance all jets to overall p_T balance (=kind of 'generator level jet', robust against seed jet mismeasurements and non-QCD processes)
- Smear p_T of each seed jet by a factor derived from jet resolution distribution (from simulation, and corrected for data/MC differences)

Smearing of the jets results in artificially created E_T^{miss} used to estimate the real E_T^{miss} distribution



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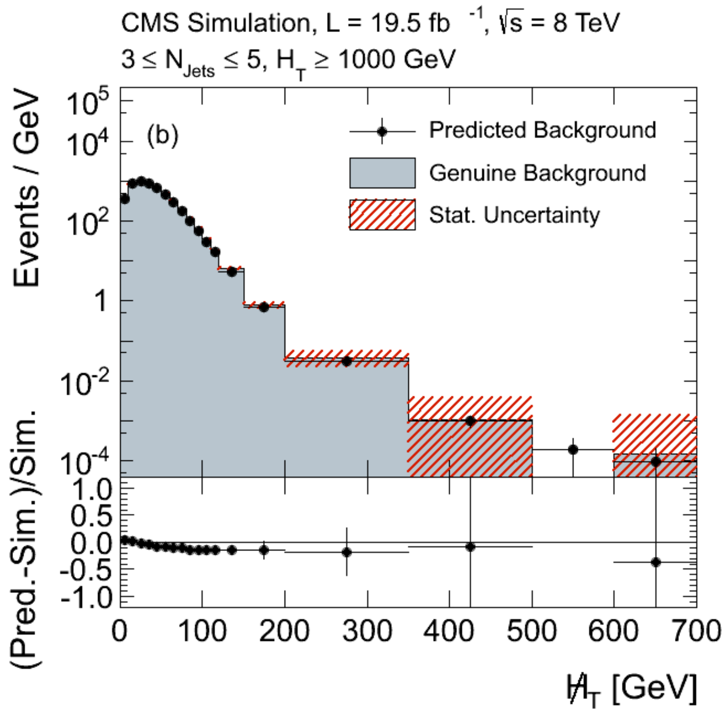
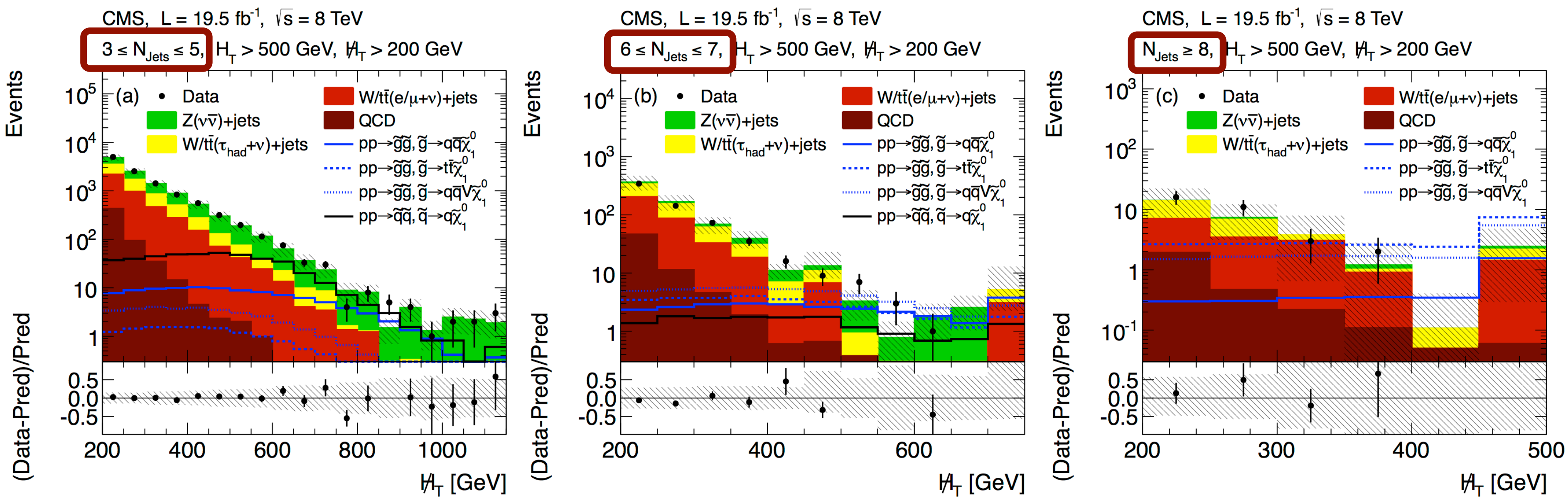


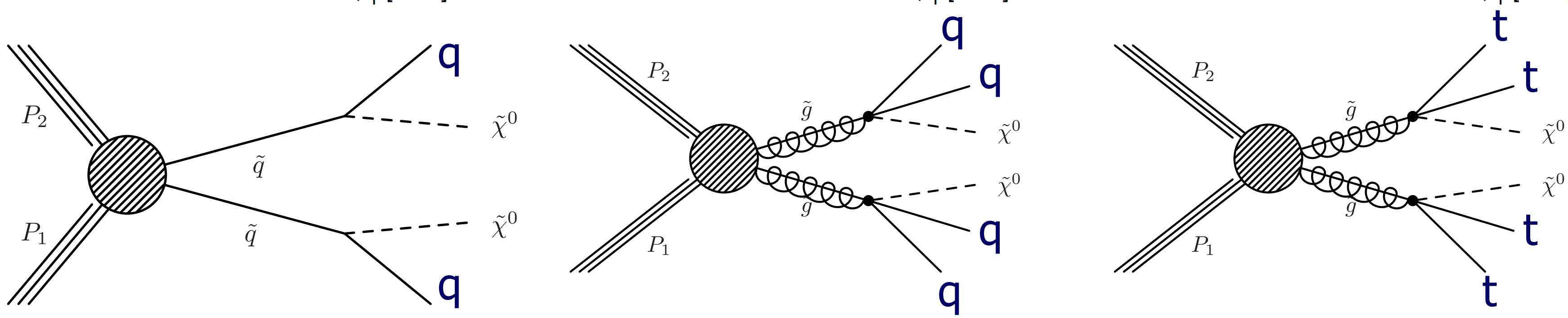
Inclusive All-Hadronic Search: Results

SUS-13-012
JHEP 06 (2014) 055
arXiv:1402.4770

Result measured in bins of **H_T, H_T^{miss} and Njets**

Different search regions sensitive to different signals





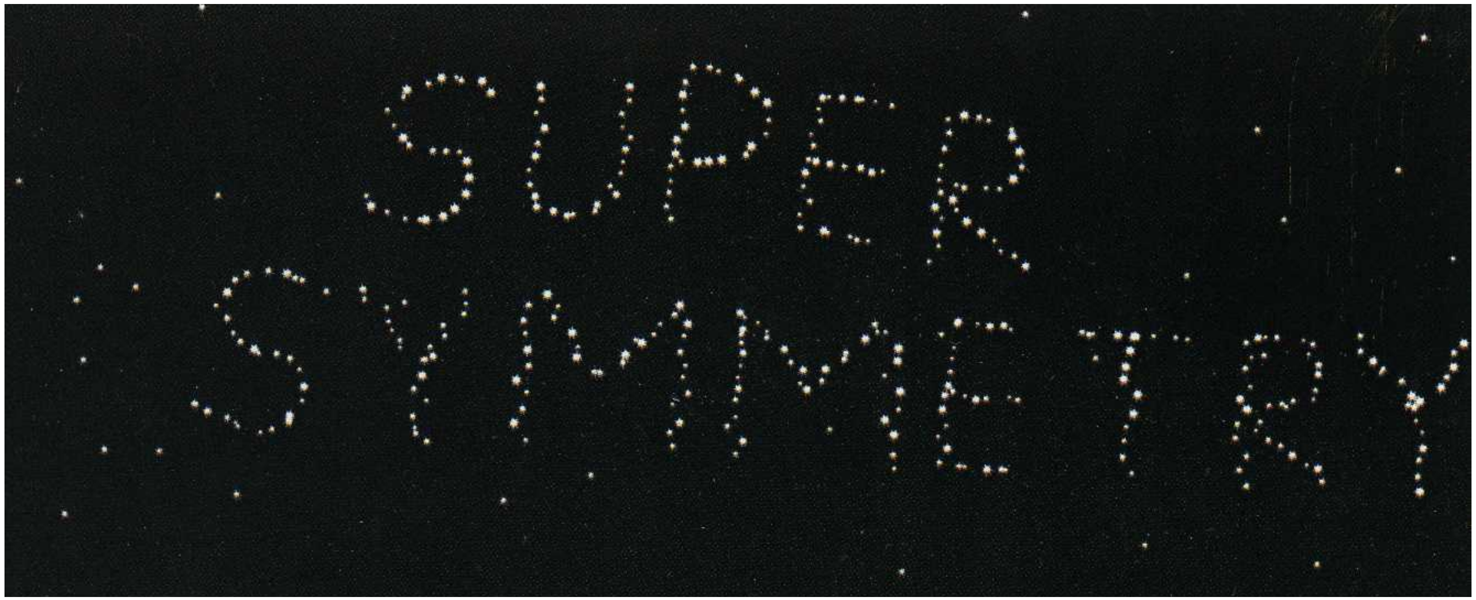
Recap

Today we discussed:

- Introduction to Supersymmetry
- Challenges in data analysis
- Tools for SUSY searches
- Detailed example for a SUSY search

Next:

- Overview over other SUSY searches
- Outlook



Understanding the Background – Example

Event selection done – but still some backgrounds left

Reconstruction of physics objects [e.g. muons]

- Suppose SUSY Model XYZ implies that we should be looking for a signature of one muon, plus 3 jets – to do:
  - Use a combination of Monte Carlo simulation of all known processes [e.g. W+3 jets with W→$\mu\nu$] that give this signature plus data events with 1μ+3jets
  - But what about another background: Z+3 jets, for which we lose one lepton from the Z→$\mu\mu$ decay?!

Problem: we can only get a feeling for the size of the effect from Monte Carlo and detector simulation, MC+simulation will never get the answer completely right

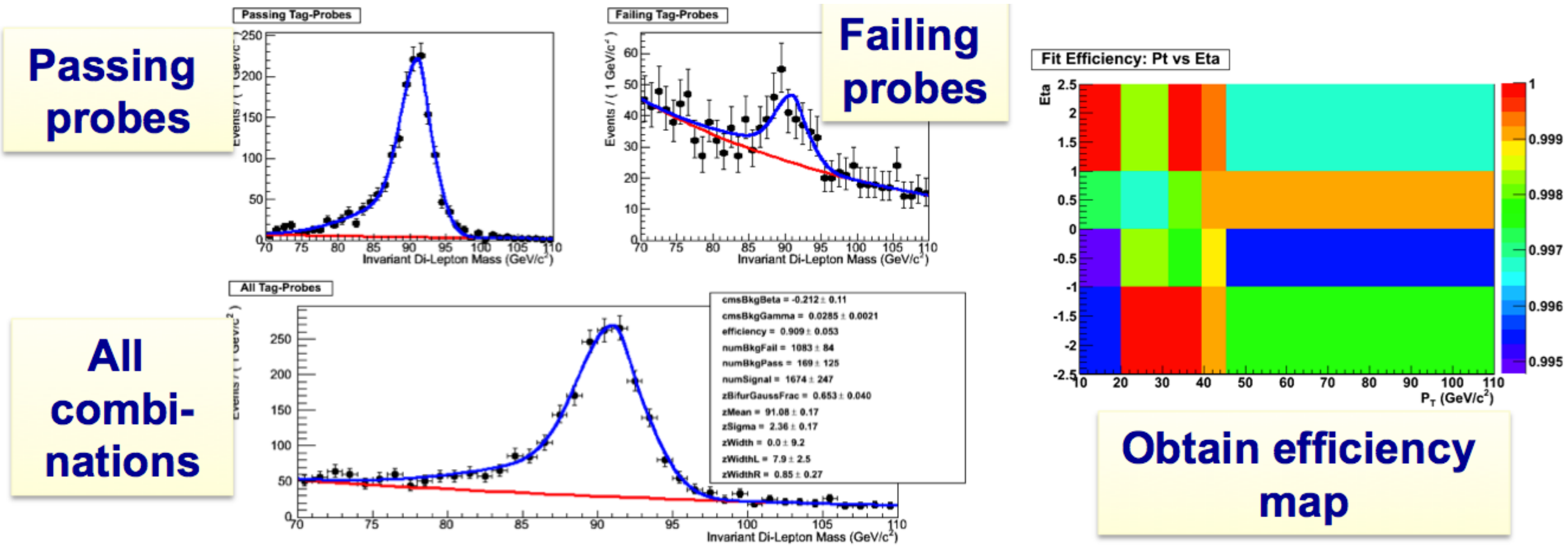
→ One needs to find a way of calculating this efficiency from the only source that speaks the absolute truth: the **data**!

→ Need to apply "data-driven" methods / techniques

Obtaining (in)efficiencies from data

Tag-and-probe method, e.g. with Z → μμ events:

- Make a selection based on one muon that "tags" the type of event (e.g. passes tight cuts; or passes the trigger)
- Then demand that second muon does the same



Basic Variables

- Number (N) of
  - Jets
  - Leptons

  } Model dependence, e.g. mean N_{jet} can vary from 0 to 4 for 1-lepton events in mSUGRA (CMS LM points)

- Transverse momentum (p_T) of
  - Jets
  - Leptons

  } Model dependence (softer or harder spectra possible)

- Angle ϕ : no (large) ϕ dependence expected – good crosscheck
- Pseudorapidity $\eta = -\ln(\tan\theta/2)$
- Relative isolation within a cone ΔR defined as:

  $\Delta R = \mathrm{sqrt}\,(\Delta\eta^2 + \Delta\Phi^2)$