Search for Supersymmetry in Hadronic Final States with M_{T2} with the CMS Detector

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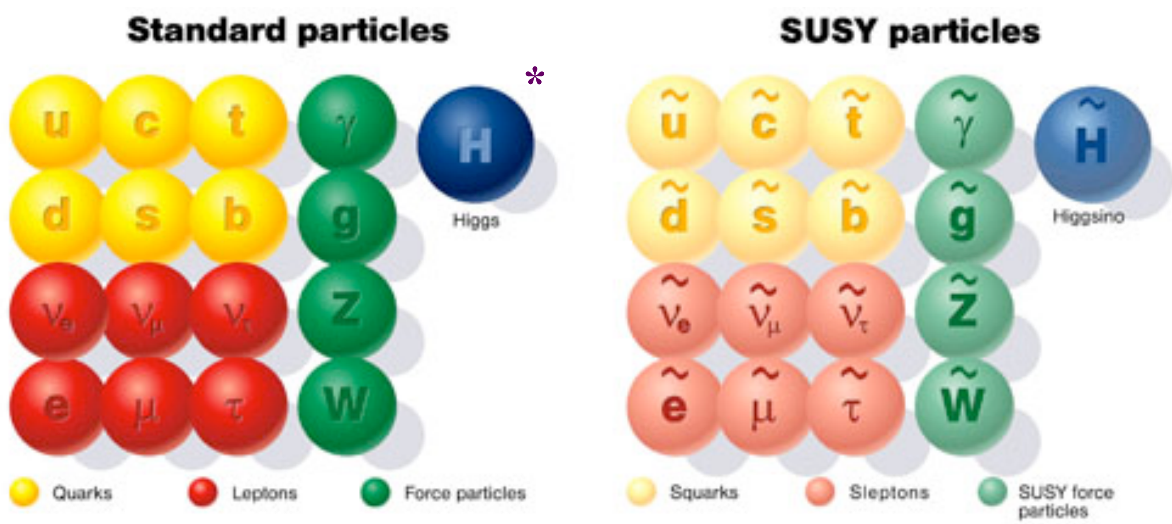
Supersymmetry

- Supersymmetry (SUSY) is a possible extension of the standard model (SM):
  - For each SM particle there is at least one supersymmetric partner particle (sparticle) – differing only in spin by ½:

$$Q_\alpha \left|\text{fermion}\right\rangle = \left|\text{boson}\right\rangle \qquad Q_\alpha \left|\text{boson}\right\rangle = \left|\text{fermion}\right\rangle$$

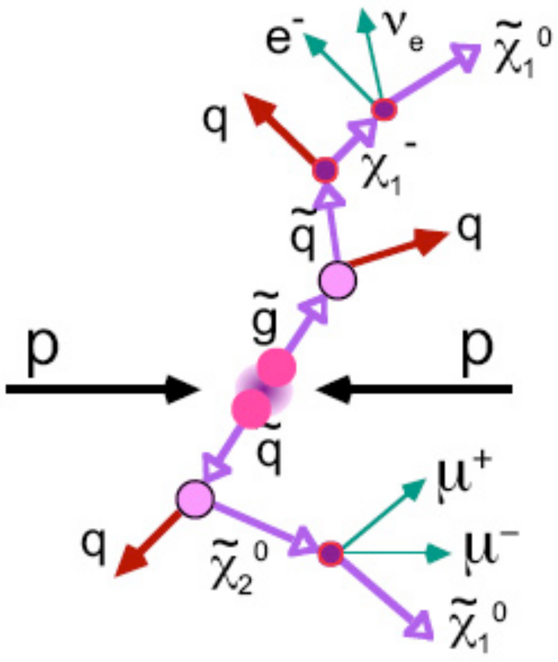


(*) Actually two Higgs doublets needed → five Higgs bosons

  - The degrees of freedom and couplings for particles and sparticles are the same.
  - Due to SUSY breaking the masses of these superpartners become much larger than those of the SM particles.

Supersymmetry

- Supersymmetry (SUSY) has several nice features:
  - The enlarged particle spectrum stabilizes e.g. the Higgs mass and therefore solves the hierarchy problem between electroweak (10^2 GeV) and Planck (10^{19} GeV) scale.
  - SUSY allows for grand unification of forces (strong and electroweak forces).
  - In many scenarios sparticles have to be produced in pairs.
  - The lightest sparticle (LSP) is weakly interacting and stable → dark matter candidate.



Hadronic supersymmetry

- Why searching for SUSY in fully hadronic channel (i.e. with no leptons) at the LHC?
- Only rely on strong production of gluinos and squarks → highly sensitive
- If SUSY comes with a stable sparticle this will not be observed by the CMS detector
  - Large missing transverse momentum E_T^{miss}.
- Therefore we can motivate a search based on two variables:

$$H_T = \sum_{jets} |\vec{p}_T| \qquad E_T^{miss} = \left| - \sum_{particles} \vec{p}_T \right|$$

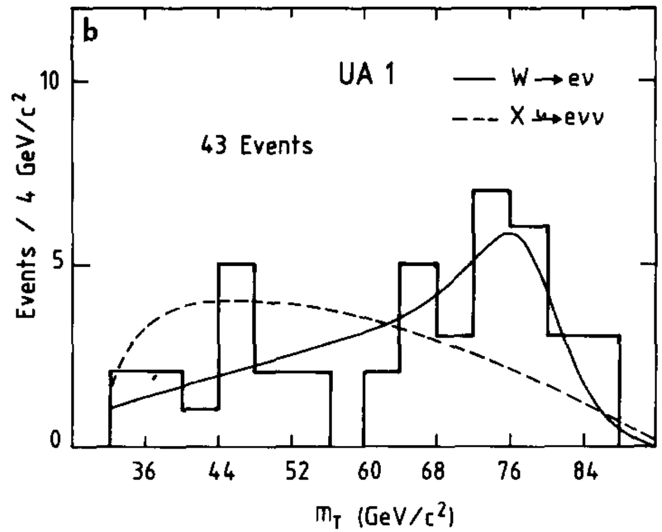
Hadronic activity — Missing transverse momentum

- Think about clever kinematical variables reflecting these properties:
  - One possible idea: M_{T2} (other existing variables: Razor, α_T, M_{eff}, …)

The search variable M_{T2}

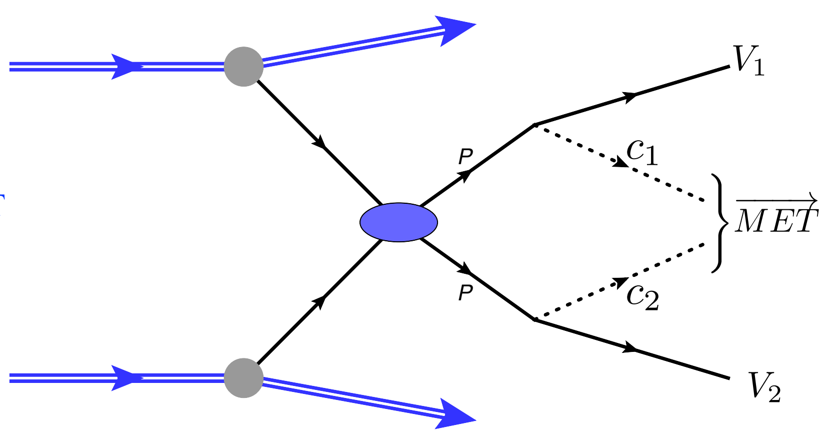
- Discovery of W-boson in UA1 (1983)
  - in the decay W(eν), the mass of the W boson is accessible via its transverse projection M_T.
  - M_T has an endpoint at the true W-mass.

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



- In events involving sparticles expect two decay chains with unobserved particles c_1 and c_2

$$M_{T2}(m_c) = \min_{\vec{p}_T^{c(1)} + \vec{p}_T^{c(2)} = \vec{p}_T^{miss}} \left[\max\left(M_T^{(1)}, M_T^{(2)} \right) \right]$$



- M_{T2} is a generalization of the transverse mass M_T with one unobserved particle for each chain.
  - If the child mass m_c is known M_{T2} would have an endpoint at the parent mass.

Interpretation of M_{T2}

- In case of no initial state radiation and zero masses

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

$p_T^{(i)}$: the transverse momenta of the visible systems.

- $M_{T2} \approx E_T^{miss}$ for symmetric systems:

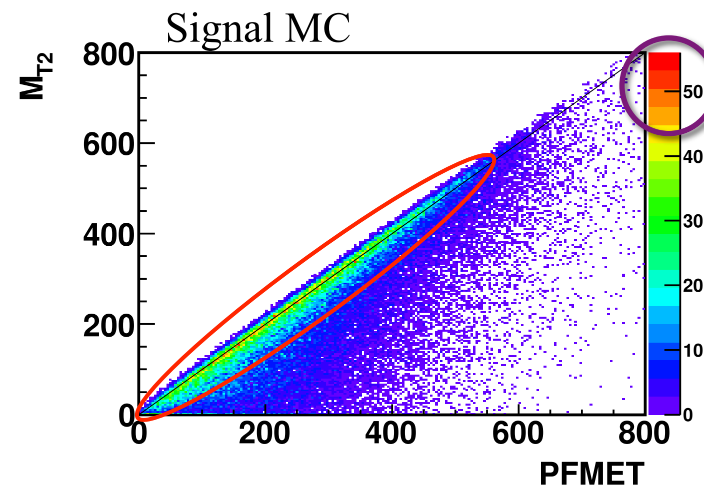
$$(E_T^{miss})^2 = (p_T^{(1)} - p_T^{(2)})^2 + 2 p_T^{(1)} p_T^{(2)} (1 + \cos\phi_{12})$$

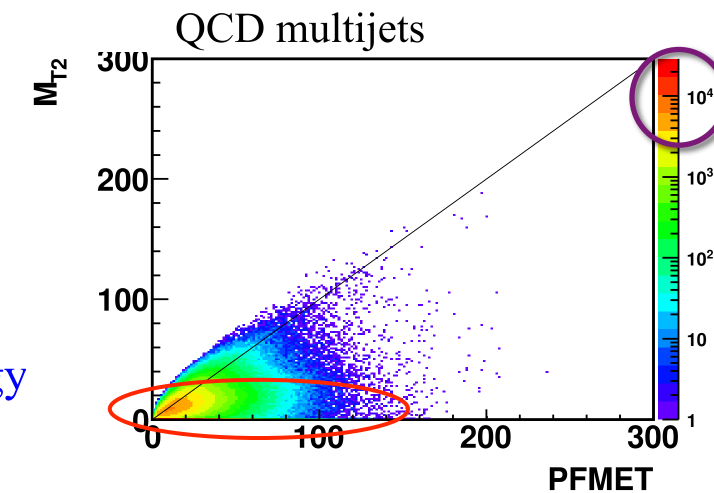
- $M_{T2} = 0$ GeV for back-to-back systems

→ M_{T2} is similar to E_T^{miss} in search region,

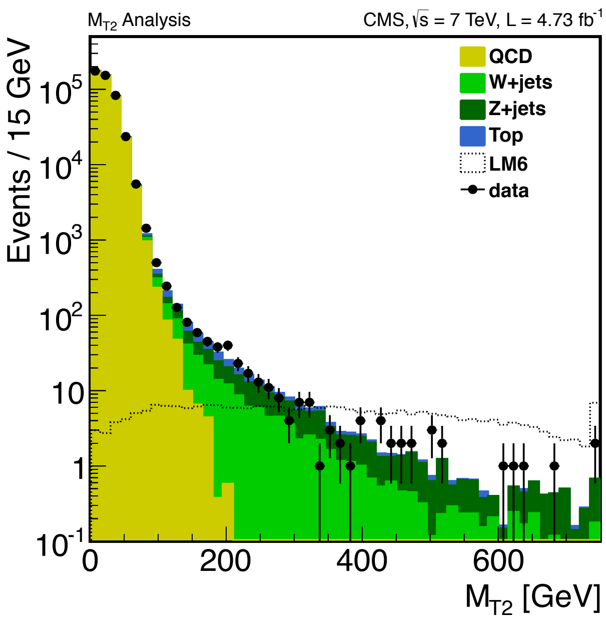
→ more robust against jet energy mismeasurements than E_T^{miss}.

- Multijet events are divided into a 2 pseudo-jet topology using a hemisphere algorithm.



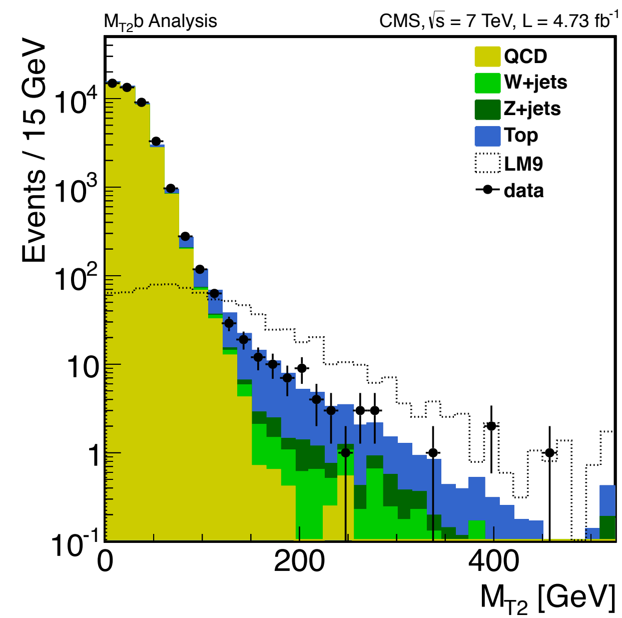


Analysis strategy



Baseline selection

$H_T \geq 750$ GeV
electron and muon veto
filters against detector noise



Two channels

M_{T2} analysis

At least 3 jets
min$\Delta\phi$(jets, E_T^{miss}) > 0.3
M_{T2} > 150 GeV

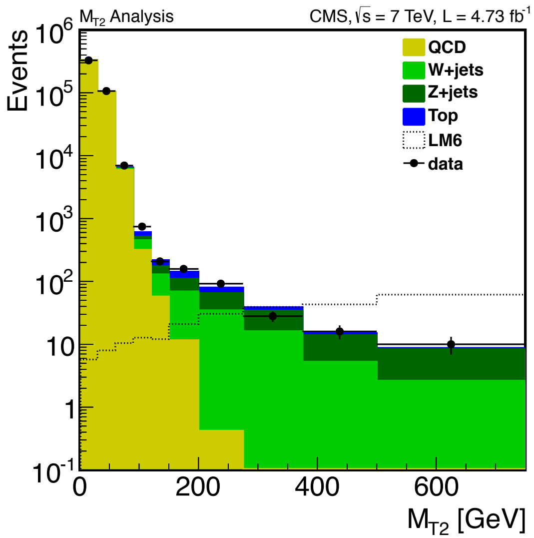
sensitive to high/medium squark and gluino masses

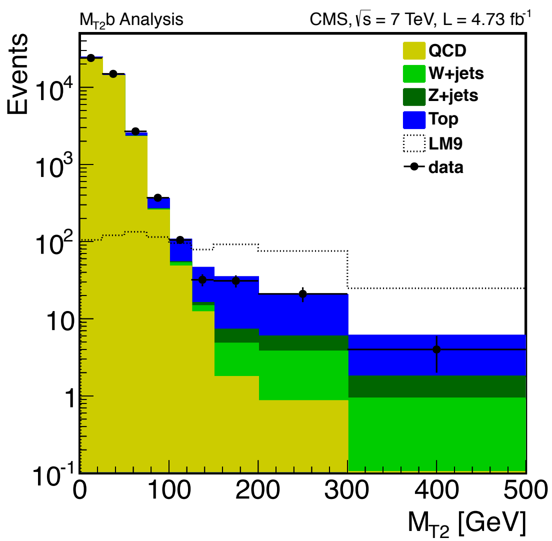
sensitive to light gluinos with heavy squarks

$M_{T2}b$ analysis

At least 4 jets
At least one jet b-tagged
min$\Delta\phi$(j_1-j_4, E_T^{miss}) > 0.3
M_{T2} > 125 GeV

Analysis strategy





- This analysis uses shape information in the search variables M_{T2} and H_T by using exclusive bins:
- For the **M_{T2} analysis** we define two H_T bins and five M_{T2} bins, with lowest bin starting at $M_{T2} > 150$ GeV.
- For the **$M_{T2}b$ analysis** we define two H_T bins and four M_{T2} bins, with lowest bin starting at $M_{T2} > 125$ GeV.

- These exclusive bins are combined in a likelihood.

→ Including this shape information increases sensitivity to larger phase spaces where signal does not only show up in the tail of the M_{T2} distribution.

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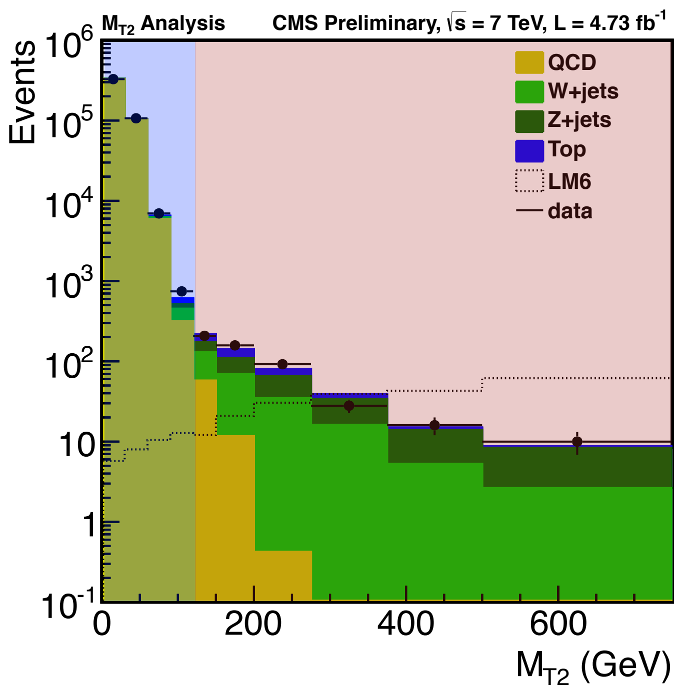
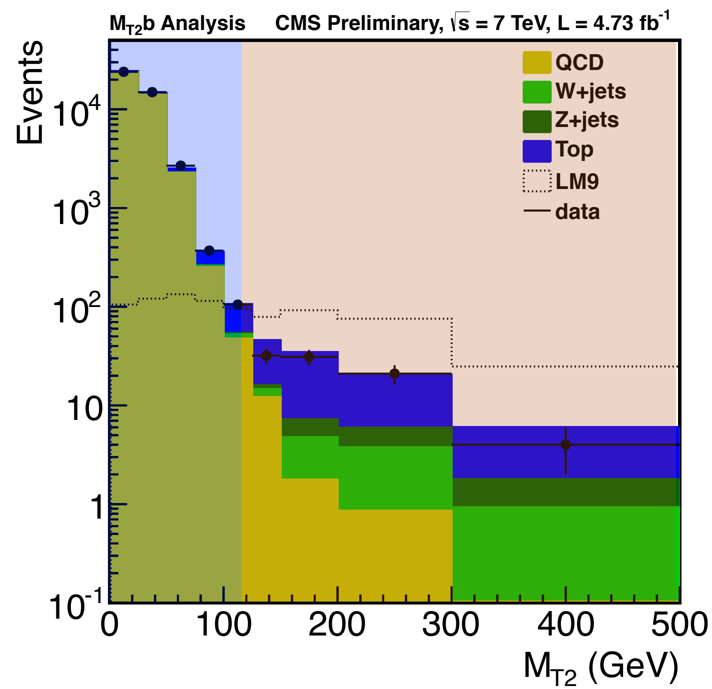
Backgrounds

M_{T2} analysis



QCD multijets	W+jets, Z+jets minor: Top

$M_{T2}b$ analysis



QCD multijets	Top minor: W+jets, Z+jets

Backgrounds: Estimations

- **QCD multijets** have no genuine E_T^{miss} → small M_{T2}.
- Mismeasured jets can lead to larger M_{T2}. These jets are aligned with E_T^{miss}. Use correlation of min$\Delta\phi$(jets, E_T^{miss}) and M_{T2} to predict this very small background.

- **Z bosons decaying into neutrinos** are signal like with large E_T^{miss}.
- This background is predicted by using photon + jets and W(→μν)+jets events.
- The visible vector boson p_T is added to the E_T^{miss} to mimic Z(→νν)+jets events.

- **Leptonic W+jets and Top+jets events** have real E_T^{miss}. Largely reduced due to lepton veto.
- Enter signal region if electrons or muons is not reconstructed or out of acceptance (= is *lost*), or taus decaying into hadrons.
- Estimate from one lepton sample and probability of reconstructing respective *loosing* a lepton.

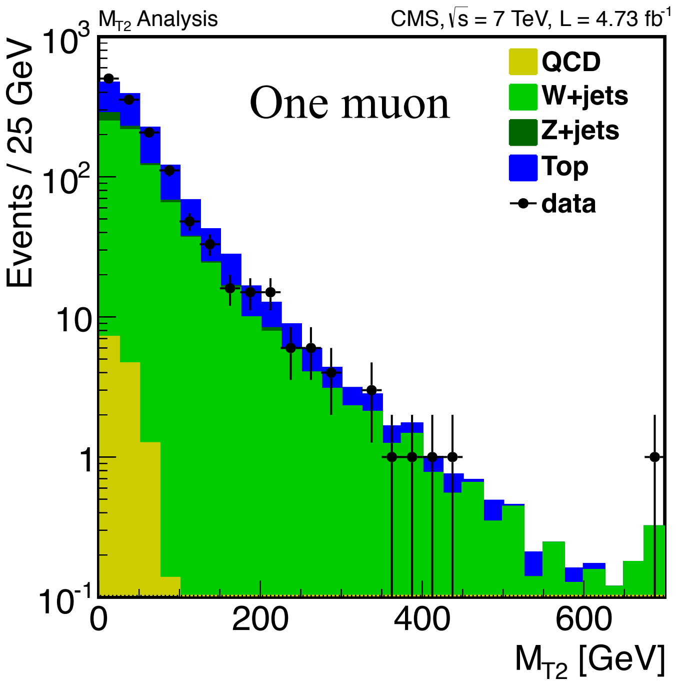
Robust estimation of the SM background contribution to all signal bins.

Example: W+jets and $t\bar{t}$+jets

- W+jets and Top+jets events have real E_T^{miss}, if W decays leptonically. Enter our event selection if
  - an electron and muon is not reconstructed or out of acceptance (= is *lost*),
  - taus decaying into hadrons.
- The *lost* leptons are estimated from the one lepton sample and the probability of identifying a produced lepton: ε

$$N_{e,\mu}^{pass\ veto} = (N_{e,\mu}^{reco} - N_{e,\mu}^{bg})\frac{1}{\varepsilon_{e,\mu}} - (N_{e,\mu}^{reco} - N_{e,\mu}^{bg})$$

$$= (N_{e,\mu}^{reco} - N_{e,\mu}^{bg})\frac{1-\varepsilon_{e,\mu}}{\varepsilon_{e,\mu}}$$

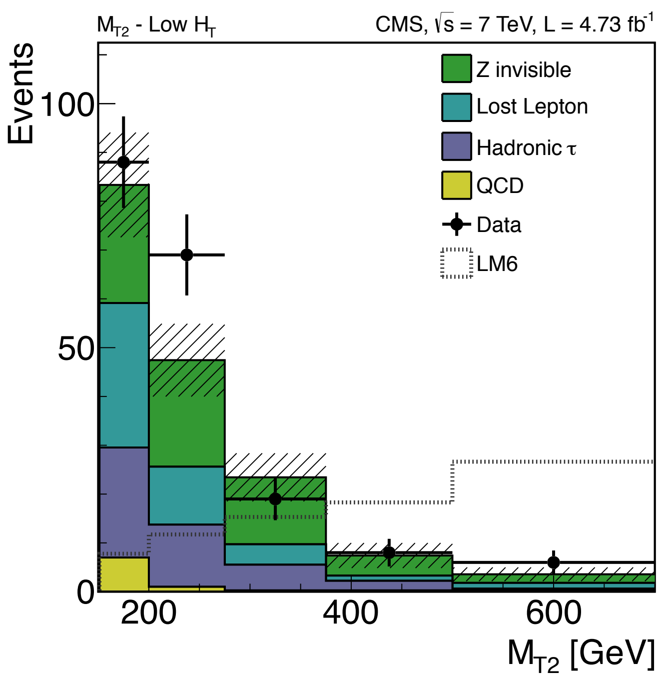


- The amount of background due to hadronically decaying taus are validated by tau-tagging. Due to low statistics taken from simulation.

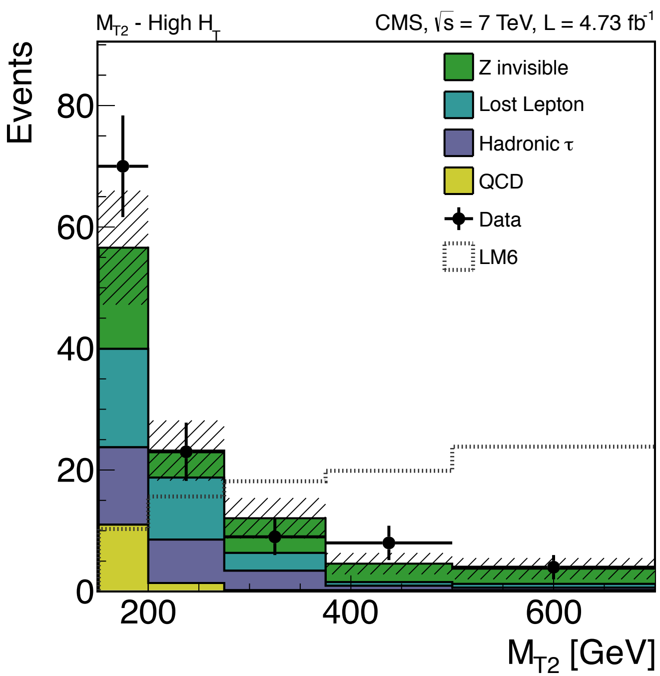
Results: M_{T2} analysis

- The background estimates for the **M_{T2} analysis** are summarized here.
- Shaded region is uncertainty on the background estimation.
- Data of 2011 pp collisions at 7 TeV collected by CMS, corresponding to 4.73 fb^{-1}.
- A possible SUSY signal is overlaid to show sensitivity of search region.

750 GeV < H_T < 950 GeV



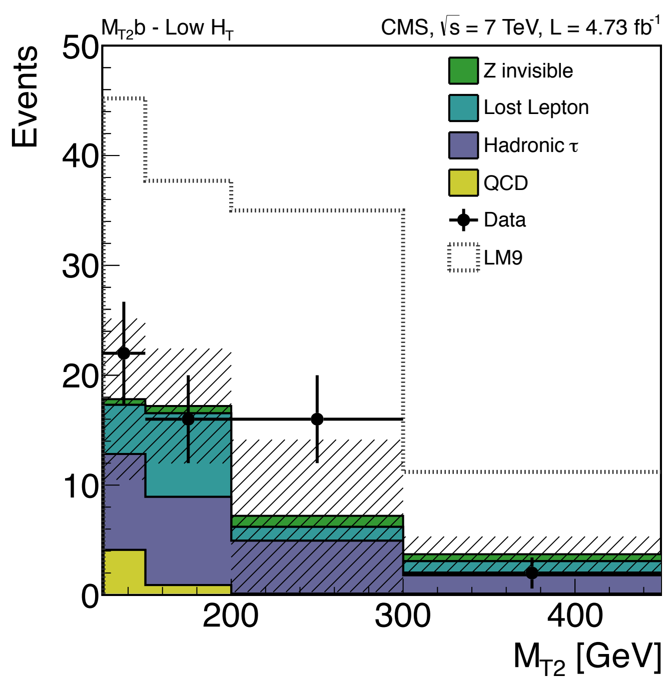
H_T > 950 GeV



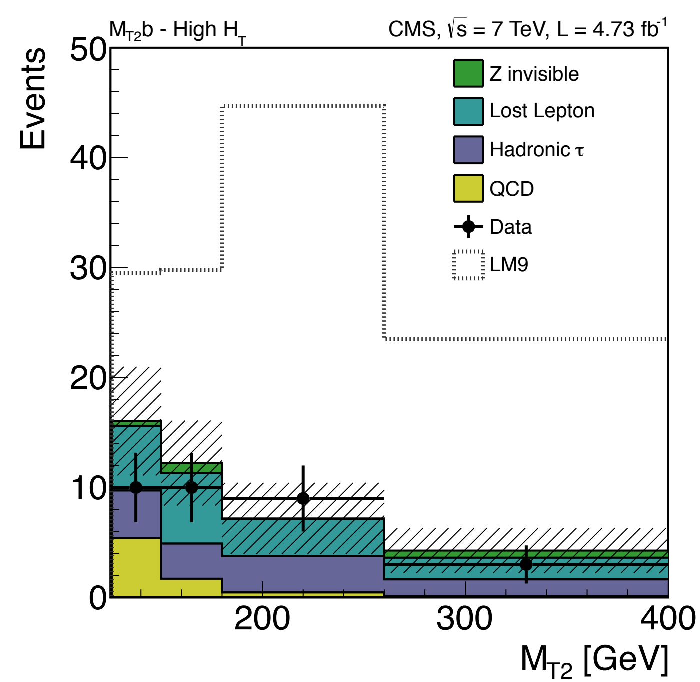
Results: $M_{T2}b$ analysis

- The background estimates for the **$M_{T2}b$ analysis** are summarized here.
- Shaded region is uncertainty on the background estimation.
- Data of 2011 pp collisions at 7 TeV collected by CMS, corresponding to 4.73 fb^{-1}.
- A possible SUSY signal is overlaid to show sensitivity of search region.

750 GeV < H_T < 950 GeV

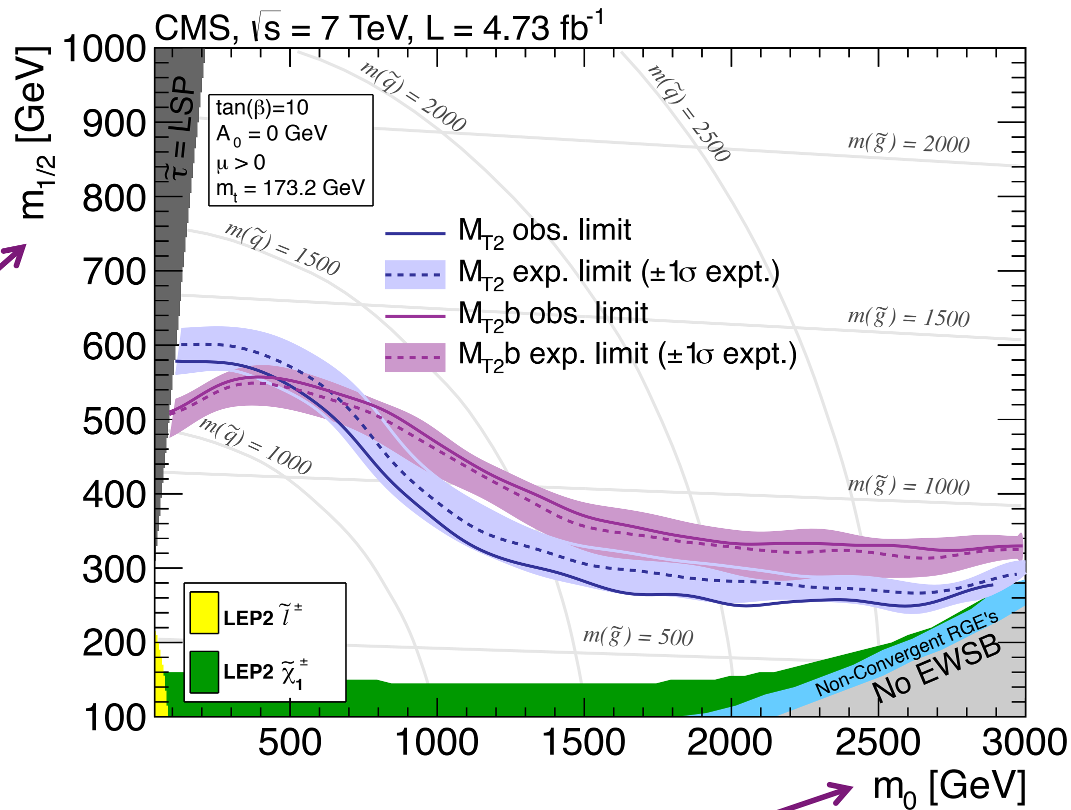


H_T > 950 GeV



Interpreting results

- The results are interpreted in a full SUSY model constrained to five parameters.
  - In the plane below three of those parameters are fixed: $A_0 = 0$, $\tan\beta = 10$, $\mu>0$

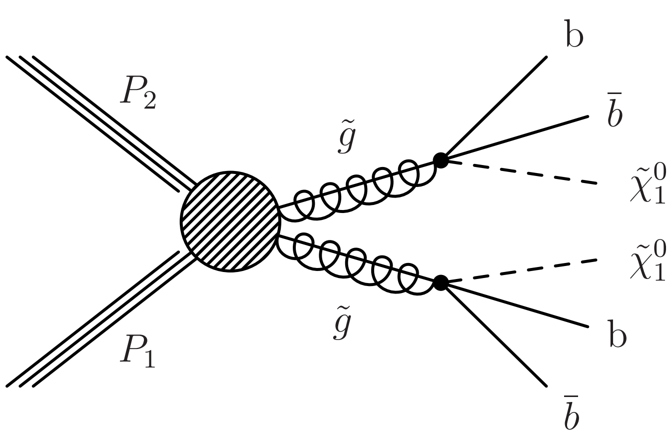


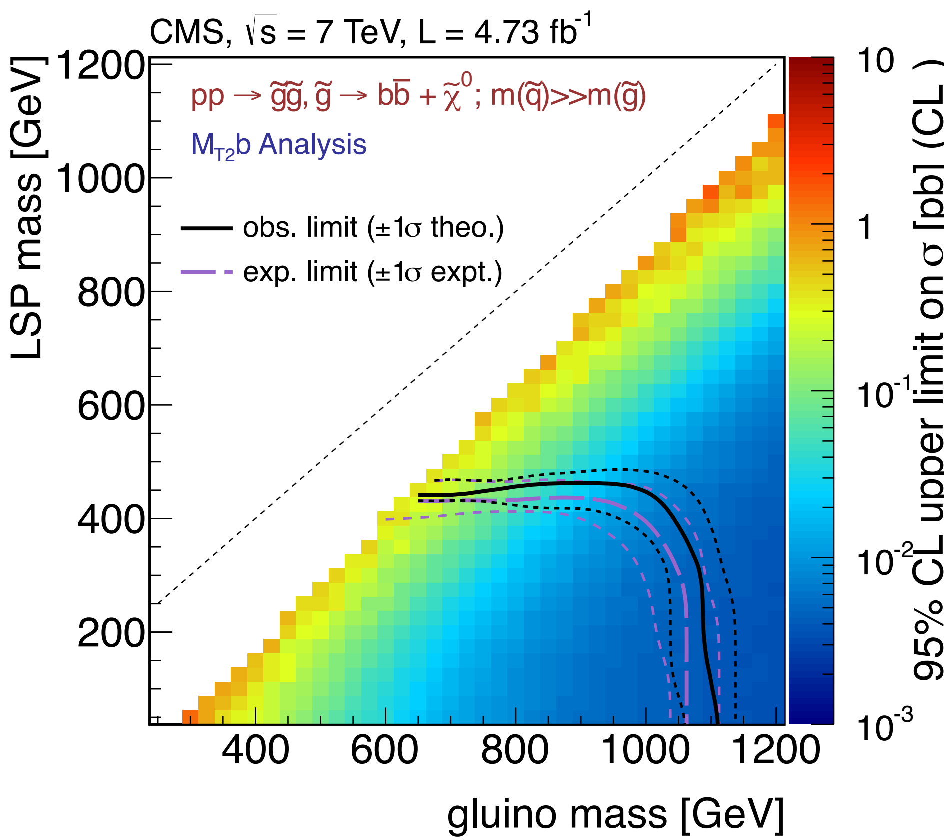
Gaugino mass parameter

Scalar mass parameter

Interpreting results

- The analyses are also interpreted in simplified models.
  - Models are reduced to one SUSY decay chain only.
- Other model interpretations are in the back-up.



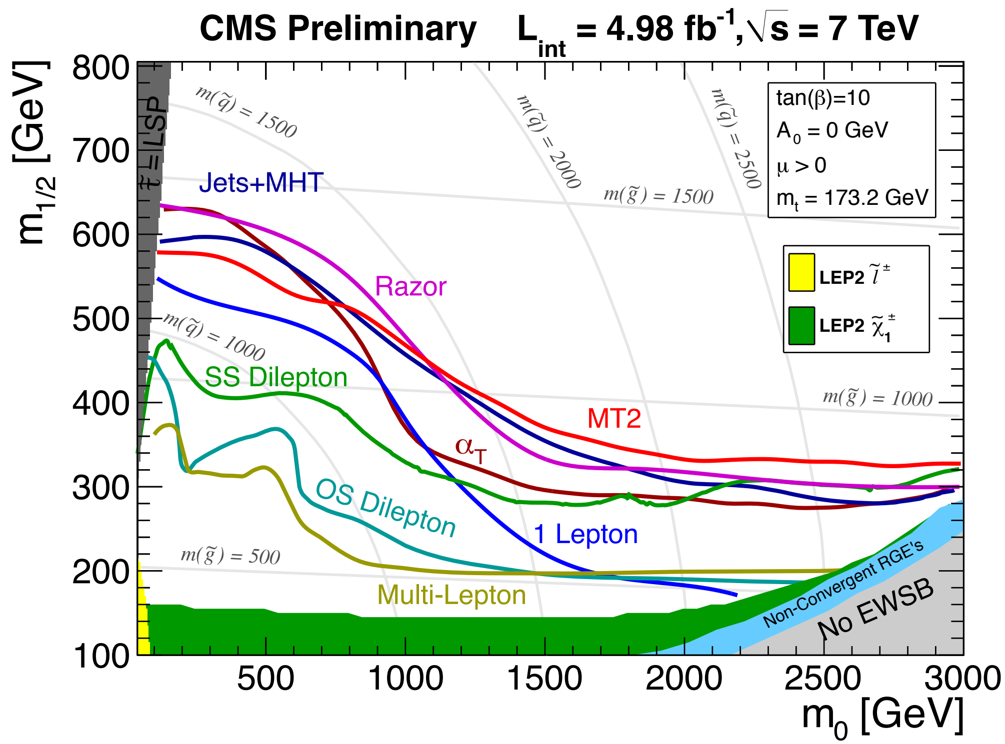


Summary

- A search for supersymmetry in fully hadronic final states in 2011 pp collision data collected by the CMS detector has been performed.

- No excess over the predicted background has been found.
- Limits in various signal model spaces have been set.

- For more details: arXiv:1207.1798



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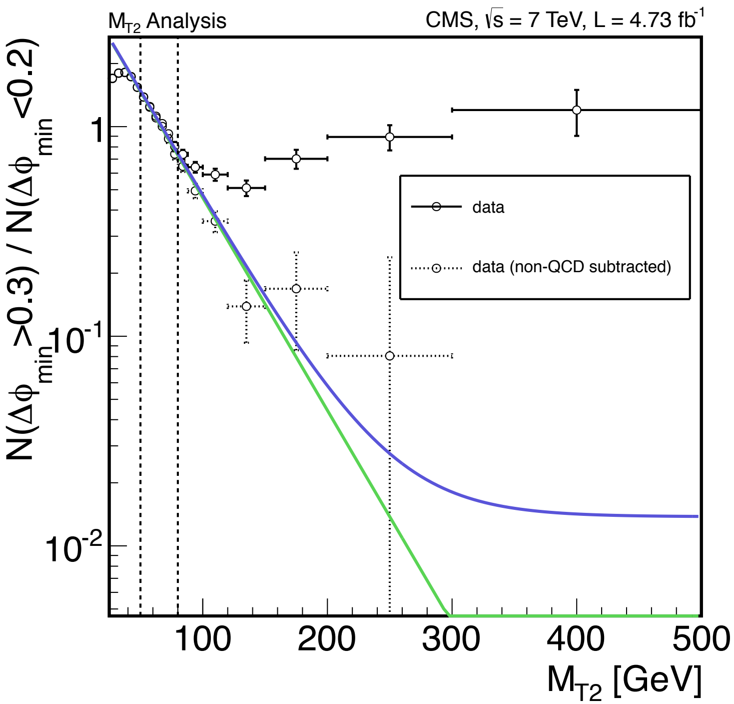
Backup

Backgrounds: QCD multijets

- Multijet events have no genuine E_T^{miss}. However, mismeasured jet energies can lead to larger E_T^{miss} and M_{T2}.

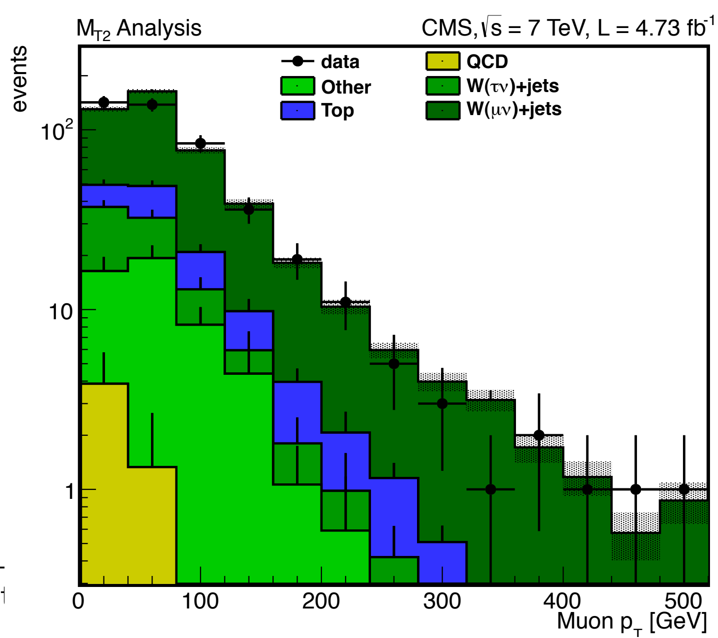
- Mismeasured jets are aligned with E_T^{miss}.
  - Use correlation of min$\Delta\phi$(jets, E_T^{miss}) and M_{T2} to predict amount of background due to mismeasured jets.

$$\frac{N(\min\Delta\phi(\text{jets},\text{E}_\text{T}^\text{miss}) > 0.3)}{N(\min\Delta\phi(\text{jets},\text{E}_\text{T}^\text{miss}) < 0.2)} = e^{a-b\cdot M_{T2}} + c$$



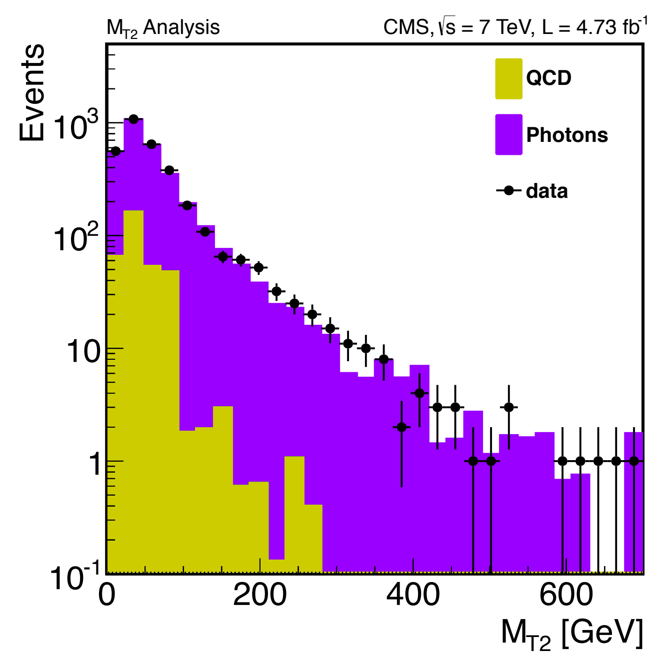
Backgrounds: $Z(\rightarrow \nu\bar{\nu})$+jets

- Z bosons decaying into neutrinos are signal like with large E_T^{miss}.
- Two methods have been developed to predict this background using photon + jets or $W(\rightarrow\mu\nu)$+jets.
- In both method the visible vector boson p_T is added to the E_T^{miss}, and the relevant event quantities (like M_{T2}) are recalculated.
- The event yield is scaled by cross section ratio and corrected for reconstruction efficiencies/kinematical differences.



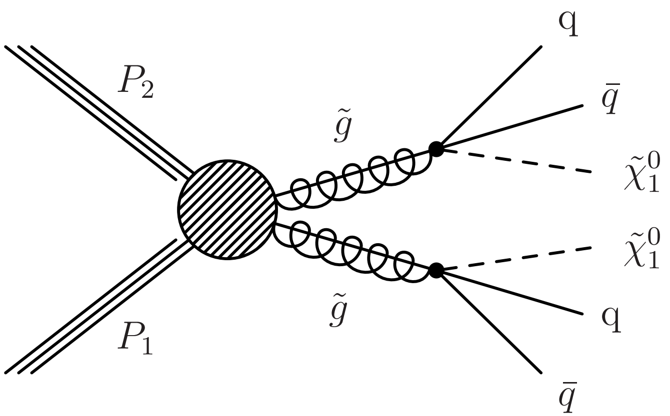
$\leftarrow W(\rightarrow l\nu)$

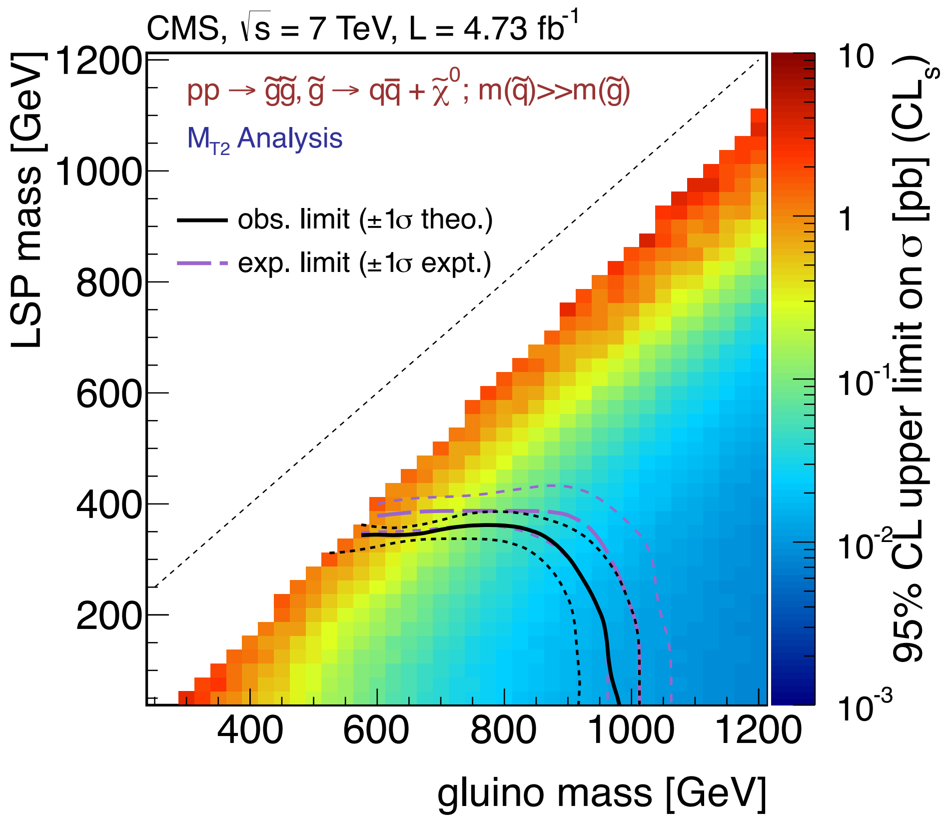
Photons $\longrightarrow$



Interpreting results

- The analyses are also interpreted in simplified models.
  - Models are reduced to one SUSY decay chain only.





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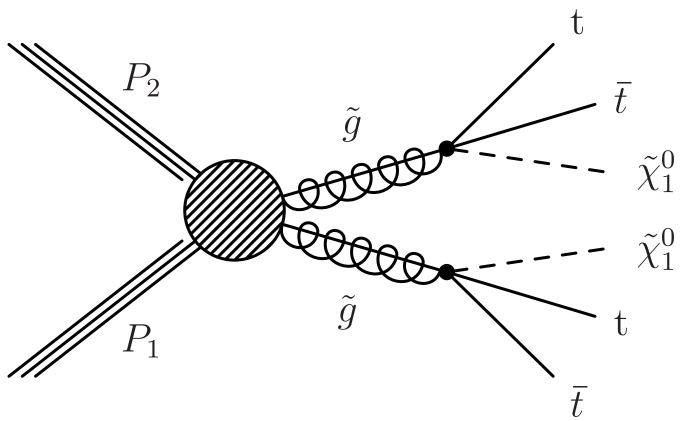

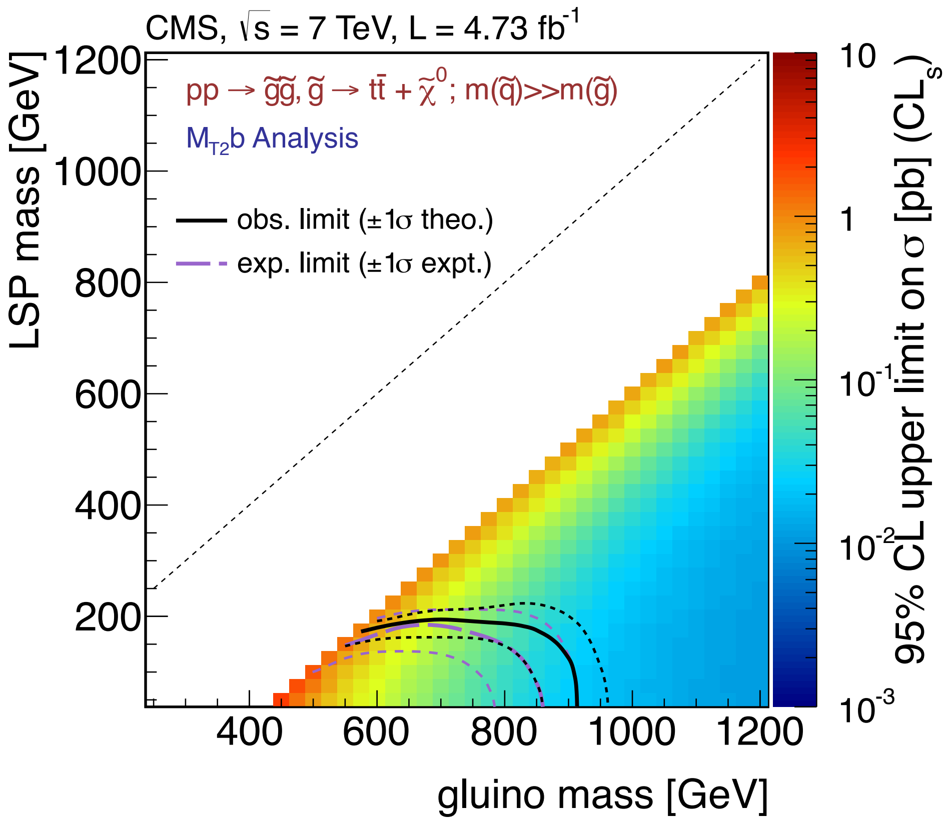

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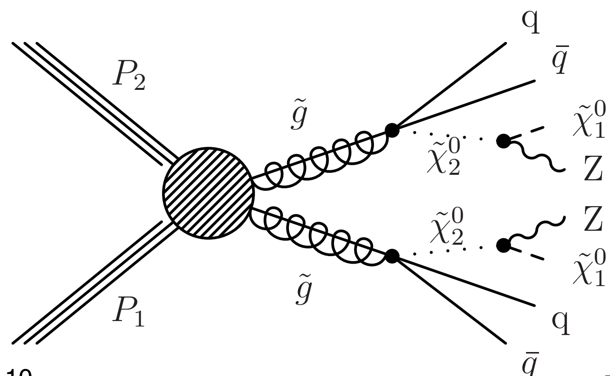
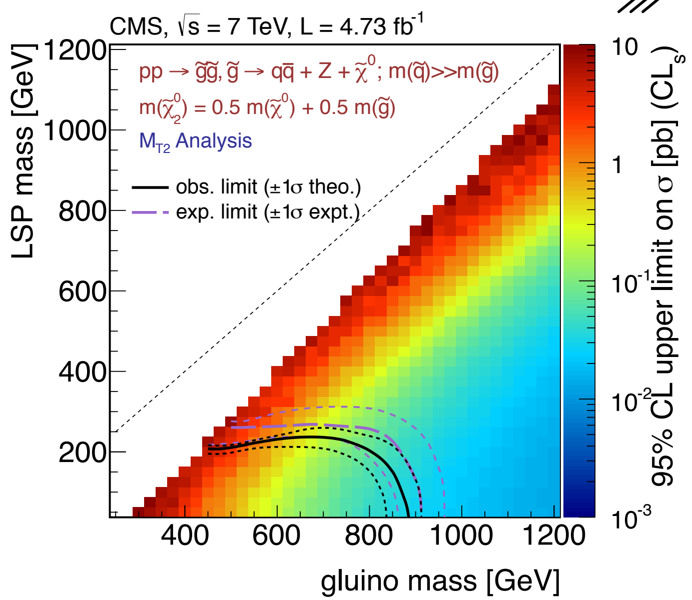
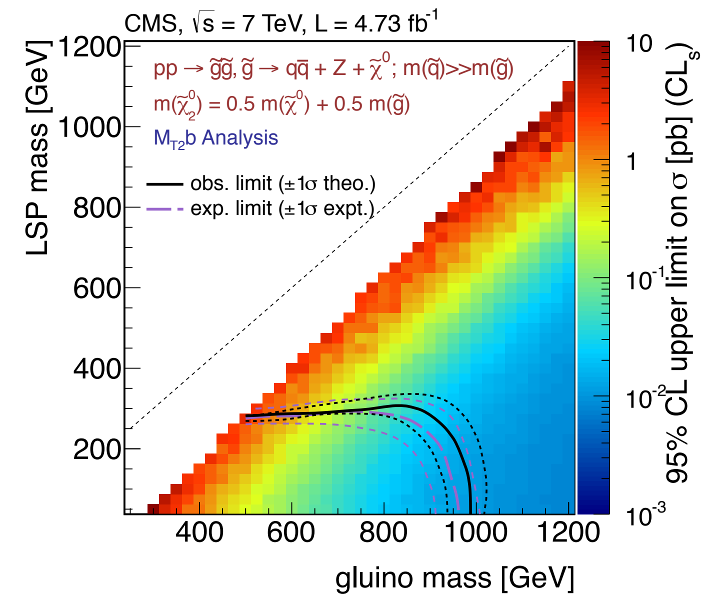
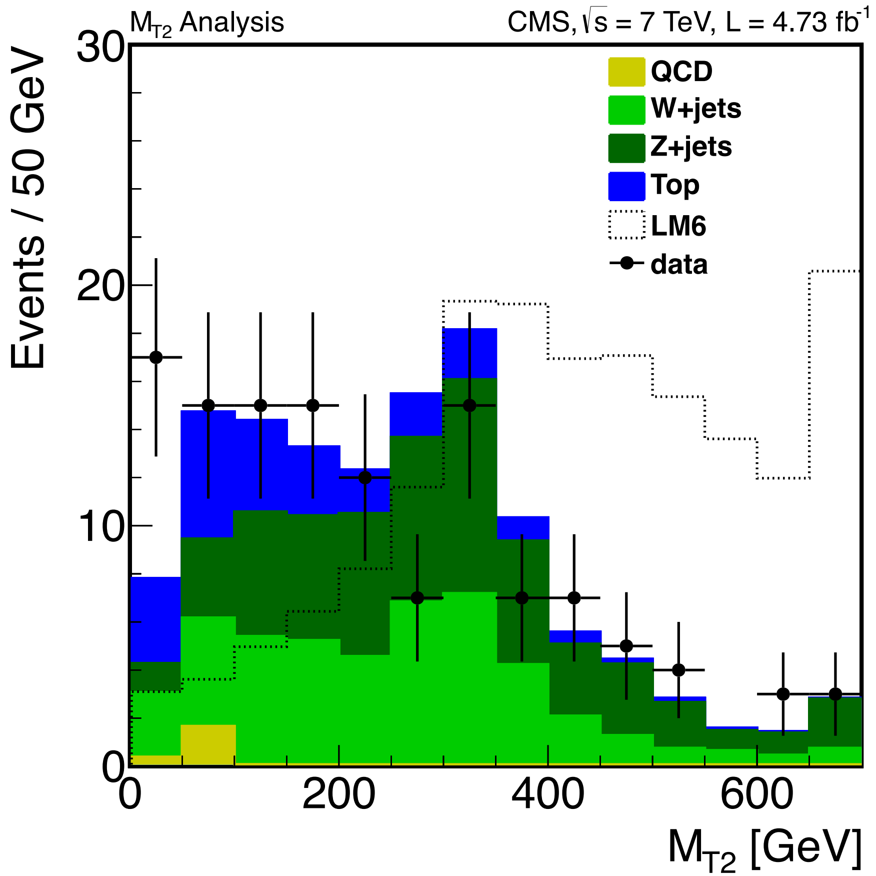




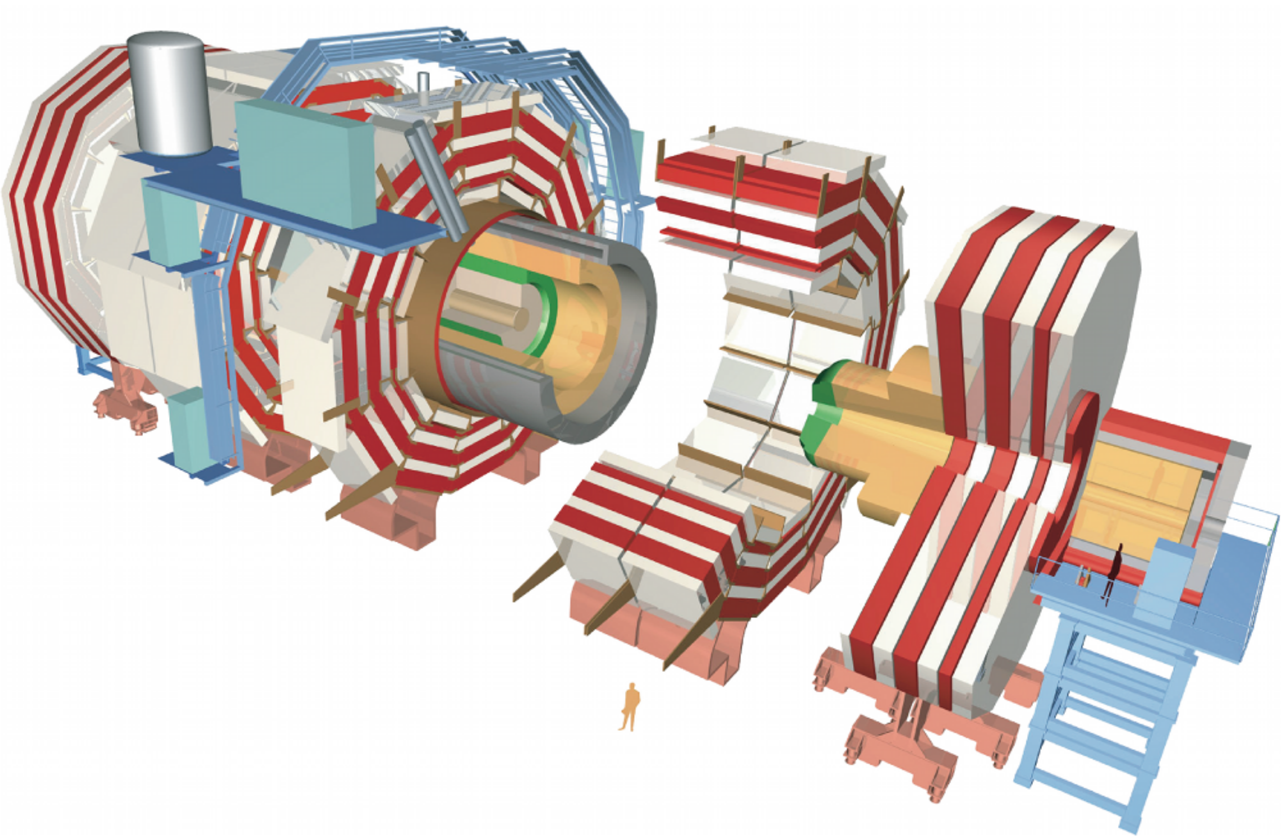


Advantages of M_{T2} over E_T^{miss}

- Taking $E_T^{miss} > 300$ GeV:

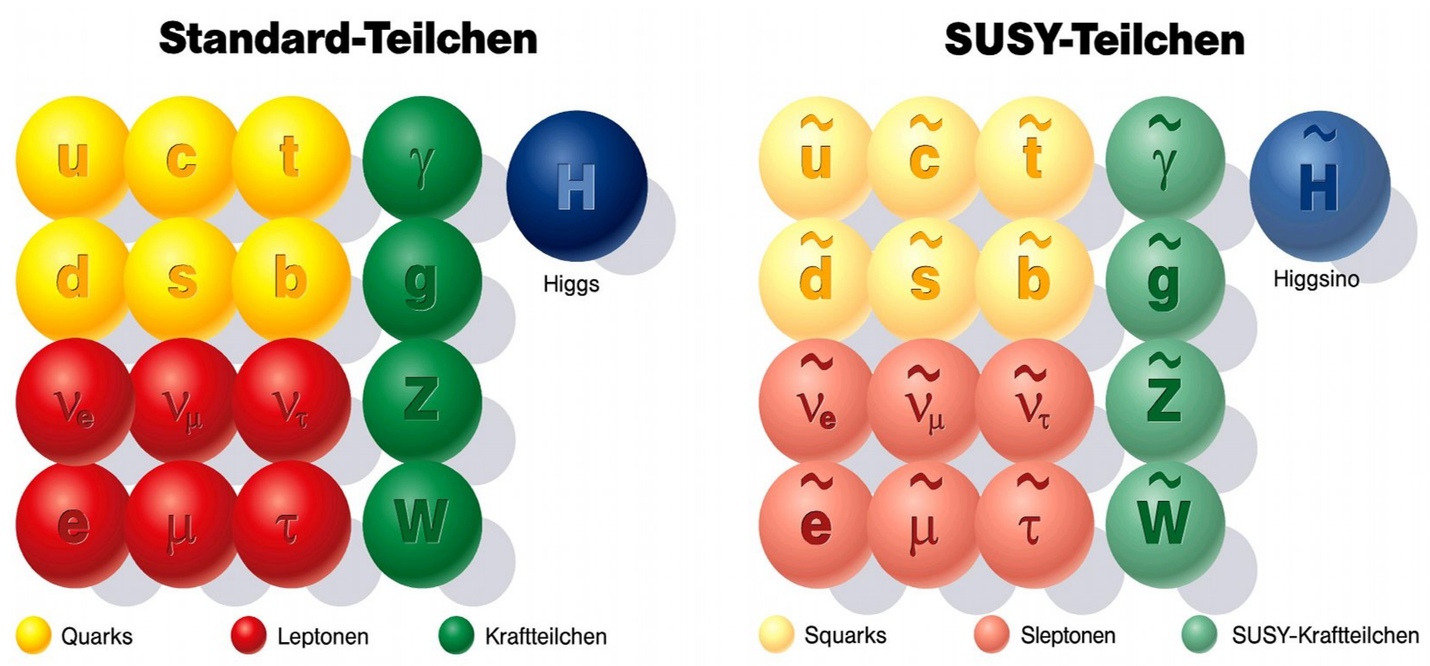


The CMS detector



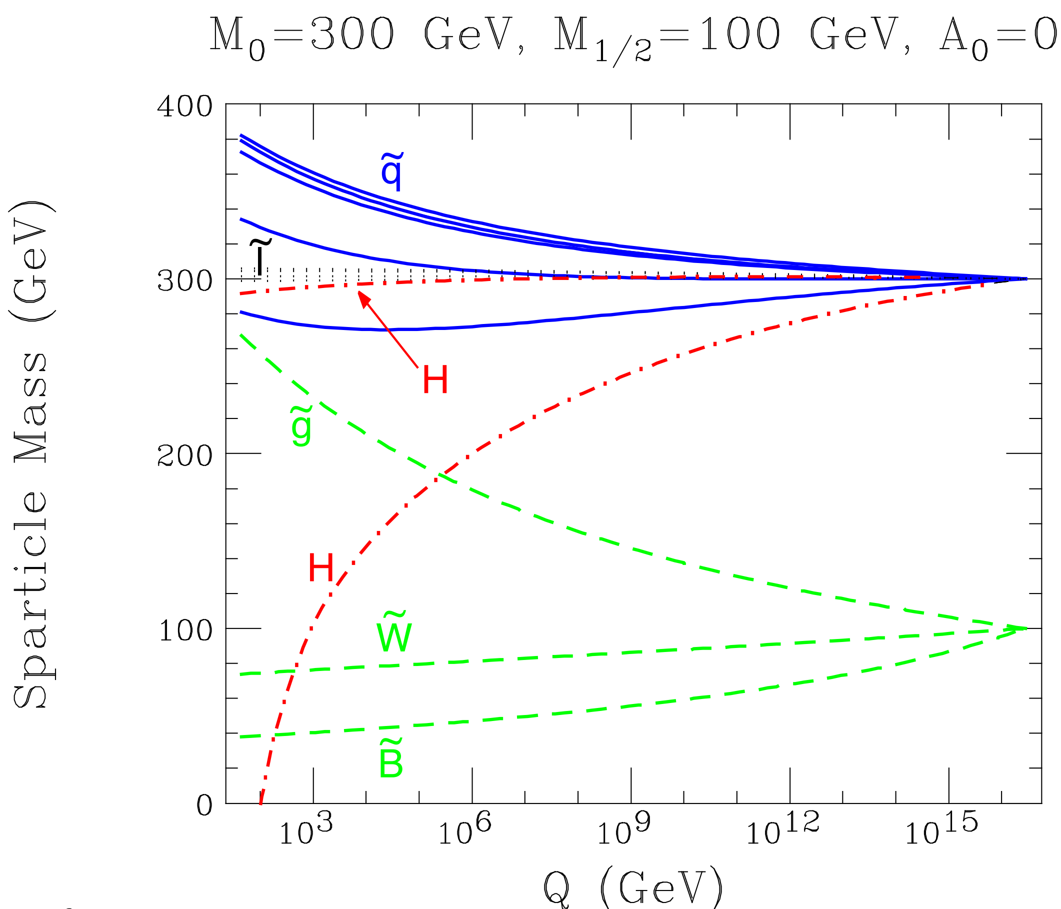
JINST 03 (2008) S08004

SUSY spectrum



Running of sparticle masses

- Running of sparticle masses in mSugra/cMSSM due to renormalization group equation.



Unification of scalar masses

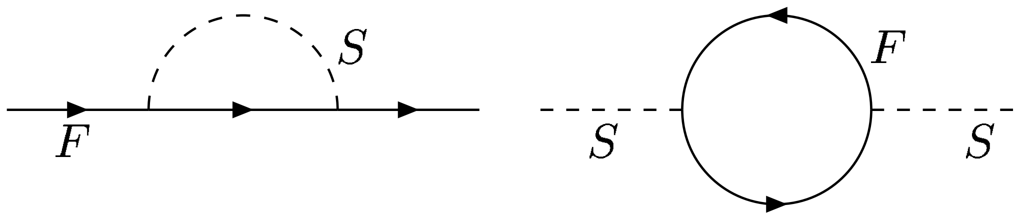
Unification of gaugino masses

J.A.Bagger: arXiv: hep/-ph/9508392

Solving hierarchy problem

- Fermion masses have only mild divergences due to loops
- Scalar masses (e.g. Higgs mass) have quadratic divergences due to loops.

$$\mathcal{L}_1 = \bar{\psi}(i\partial\!\!\!/ - m_F)\psi + \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 - \frac{\lambda_F}{2}\bar{\psi}\psi S$$



$$\delta m_F = -\frac{3\lambda_F^2 m_F}{64\pi^2}\log\frac{\Lambda^2}{m_F^2} + \cdots$$

$$\delta m_S^2 = -\frac{\lambda_F^2}{8\pi^2}\left[\Lambda^2 - m_F^2\log\frac{\Lambda^2}{m_F^2}\right] + \cdots$$

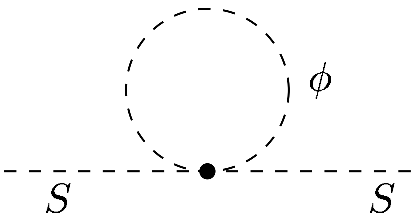
Taken from lecture of M.Spira

Solving hierarchy problem

- Due to new sparticles a secondary loop diagrams are added.
- These cancel the quadratic divergences if masses of sparticle and SM particle are not too different.

$$\mathcal{L}_2 = |\partial_\mu \phi_1|^2 + |\partial_\mu \phi_2|^2 + \frac{\lambda_S}{2} S^2 (|\phi_1|^2 + |\phi_2|^2)$$

$$[\psi \leftrightarrow \phi_1, \phi_2] \qquad -m_\phi^2 (|\phi_1|^2 + |\phi_2|^2)$$



$$\delta m'^2_S = + \frac{\lambda_S^2}{8\pi^2} \left[\Lambda^2 - m_\phi^2 \log \frac{\Lambda^2}{m_\phi^2} \right] + \cdots$$

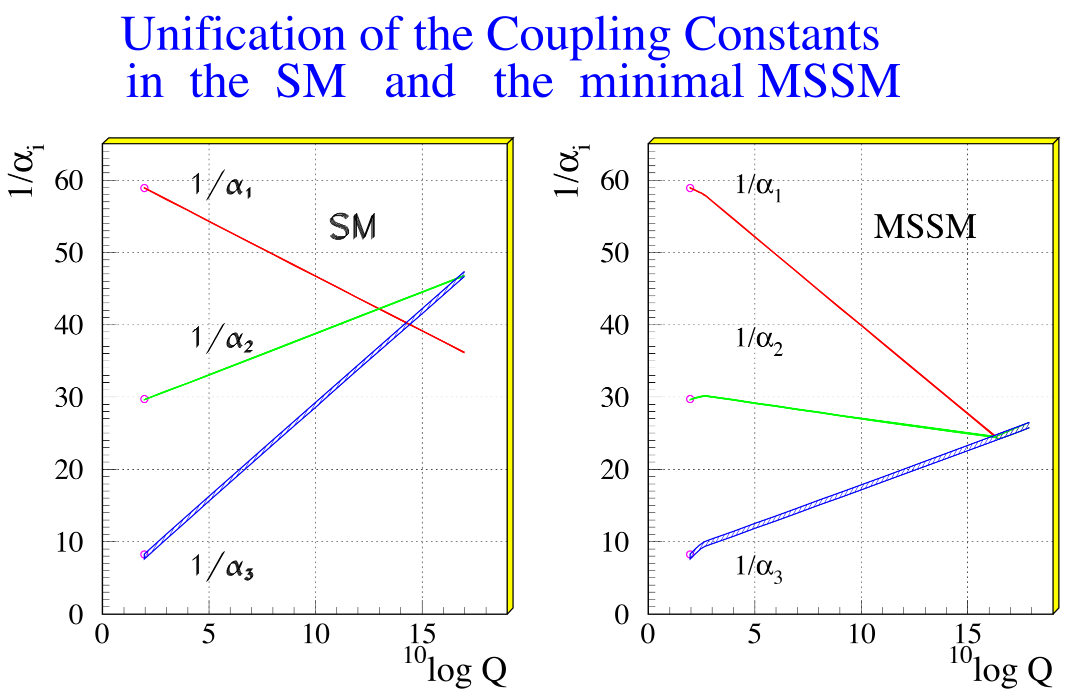
($\pm$ = Pauli–Prinzip)

SUSY:

$$\left.\begin{array}{l} \text{FG: 2 ferm.} \leftrightarrow \text{2 bos.} \\ \lambda_F = \lambda_S \end{array}\right\} \delta m_S^2 \sim \frac{\lambda_S^2}{8\pi^2} (m_F^2 - m_\phi^2) \log \Lambda^2$$

Taken from lecture of M.Spira

Unification of forces



U. Amaldi, W. de Boer, H. Fürstenau, PL B260(1991)

$\alpha_1, \alpha_2, \alpha_3$ **coupling constants of electromagnetic –, weak–, and strong interactions**

$1/\alpha_i \propto \log Q^2$ **due to radiative corrections (LO)**

B-Tagging

- B-Tagging is based on reconstruction of secondary vertices.