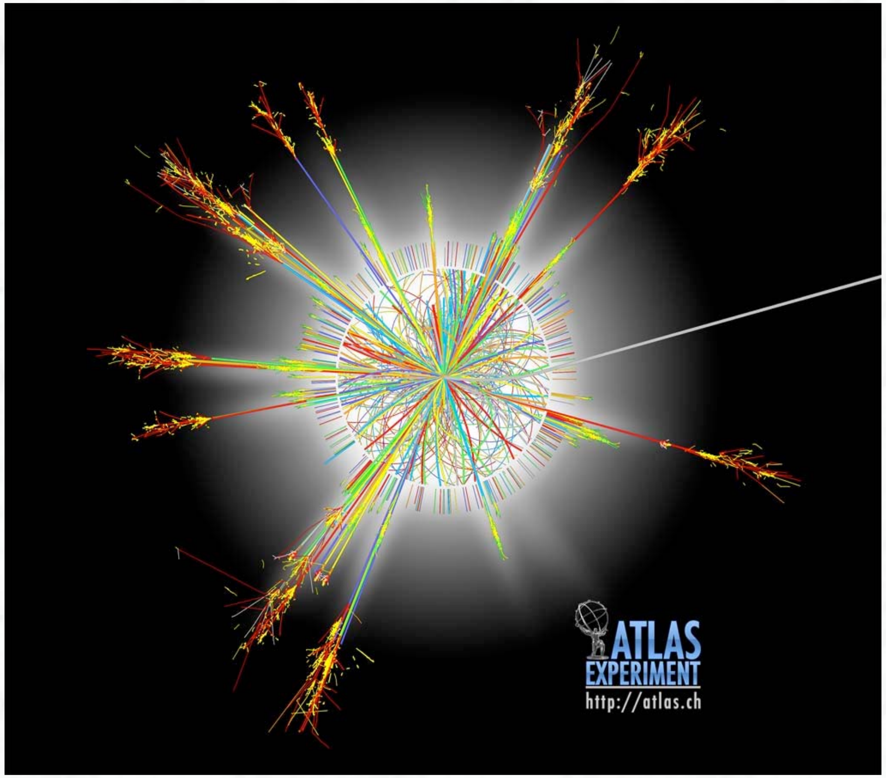
Searches for Physics Beyond the Standard Model at the LHC



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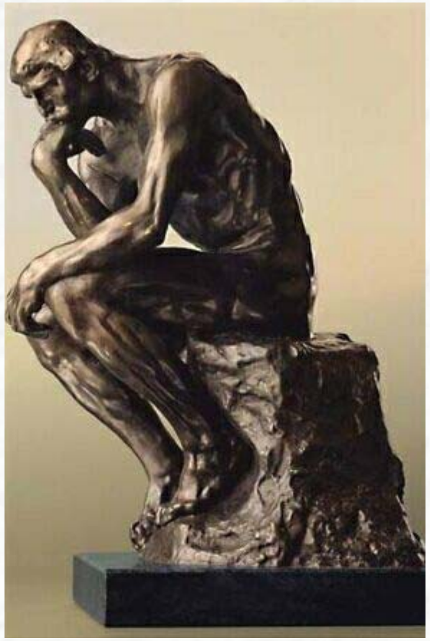
Outline of the lectures:

1. Introduction
2. Brief summary of detector performance and Standard Model processes relevant for searches
3. The search for supersymmetry
4. Search for other new particles (new gauge bosons, leptoquarks, …)
5. Search for signals from Extra Dimensions

Disclaimer: I will try to highlight important results on searches for new physics with early LHC data. The coverage is not complete, i.e. not all results available will be presented; Results from both general purpose experiments, ATLAS and CMS, are shown, but there might still be a bias towards the experiment I am working on. This bias is not linked to the scientific quality of the results.

Why Physics Beyond the Standard Model



Why Physics Beyond the Standard Model ?

1. Gravity is not yet incorporated in the Standard Model

2. Dark Matter not accomodated

3. Many open questions in the Standard Model
   - Hierarchy problem: m_W (100 GeV) $\rightarrow$ m_{Planck} (10^{19} GeV)
   - Unification of couplings
   - Flavour / family problem
   - …..

All this calls for a ***more fundamental theory*** of which
the Standard Model is a low energy approximation $\rightarrow$ **New Physics**

Candidate theories: Supersymmetry
Extra Dimensions
Technicolor
…….

Many extensions predict new physics at the TeV scale !!

Strong motivation for LHC, mass reach ~ 3 TeV

Theoretical models
for physics Beyond the
Standard Model

The role of the LHC

1. Explore the TeV mass scale

- What is the origin of the electroweak symmetry breaking ?

- The search for “low energy” supersymmetry
  Can a link between SUSY and dark matter be established?

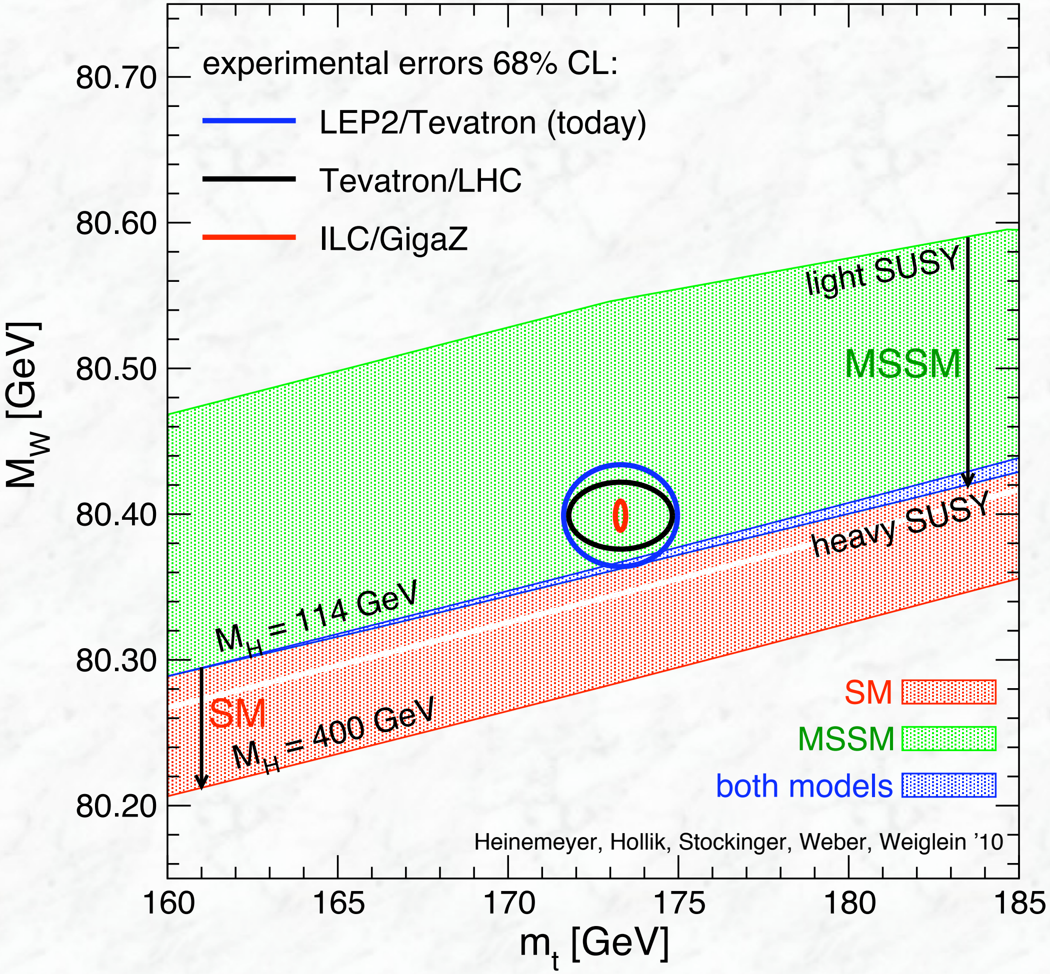
- Other scenarios beyond the Standard Model
- …….

Look for the “expected”, but we need to be open for surprises
→ perform as many searches (inclusive, exclusive…) for as many final states as possible

2. Precise tests of the Standard Model

- There is much sensitivity to physics beyond the Standard Model in the precision area

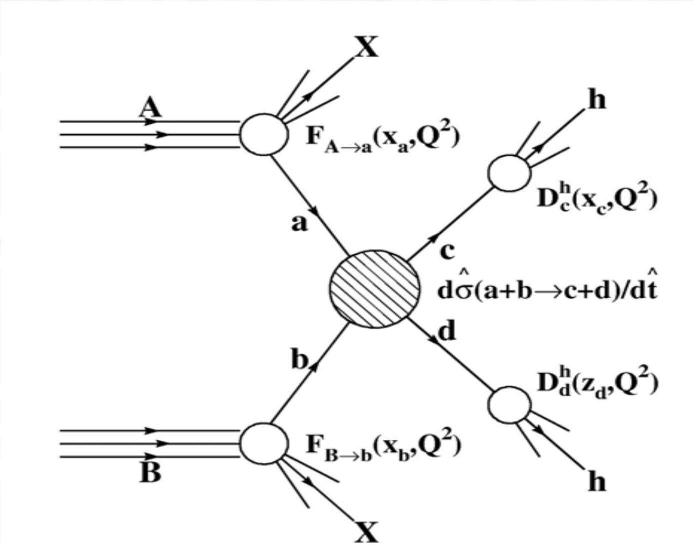
- Many Standard Model measurements can be used to test and to tune the detector performance



Predictions for future precision (including LHC), compared to the Standard Model and its Minimal Supersymmetric Extension (MSSM)

Ultimate test of the Standard Model: compare direct prediction of Higgs mass with direct observation

Calculation of cross sections



$$\sigma = \sum_{a,b} \int dx_a \, dx_b \, f_a(x_a, Q^2) \, f_b(x_b, Q^2) \, \hat{\sigma}_{ab}(x_a, x_b)$$

Sum over initial partonic states a,b

$\hat{\sigma}_{ab}$ $\equiv$ hard scattering cross section

f_i (x, Q^2) $\equiv$ parton density function

… + higher order QCD corrections (perturbation theory)
meanwhile available for many signal and background processes !

which for some processes turn out to be large
(e.g. Higgs production via gg fusion)

usually introduced as K-factors: $K_{[n]} = \sigma_{[n]} / \sigma_{[LO]}$

a few examples: Drell-Yan production of W/Z: K_{NLO} ~ 1.2
Higgs production via gg fusion: K_{NLO} ~ 1.8

Luminosity

The rate of events produced for a given physics process is given by:

$$\boxed{N = L \cdot \sigma}$$

L = Luminosity
σ = cross section

dimensions: $s^{-1} = cm^{-2}\, s^{-1} \cdot cm^2$

Luminosity depends on the machine:
important parameters: number of protons stored, beam focus at interaction region,….

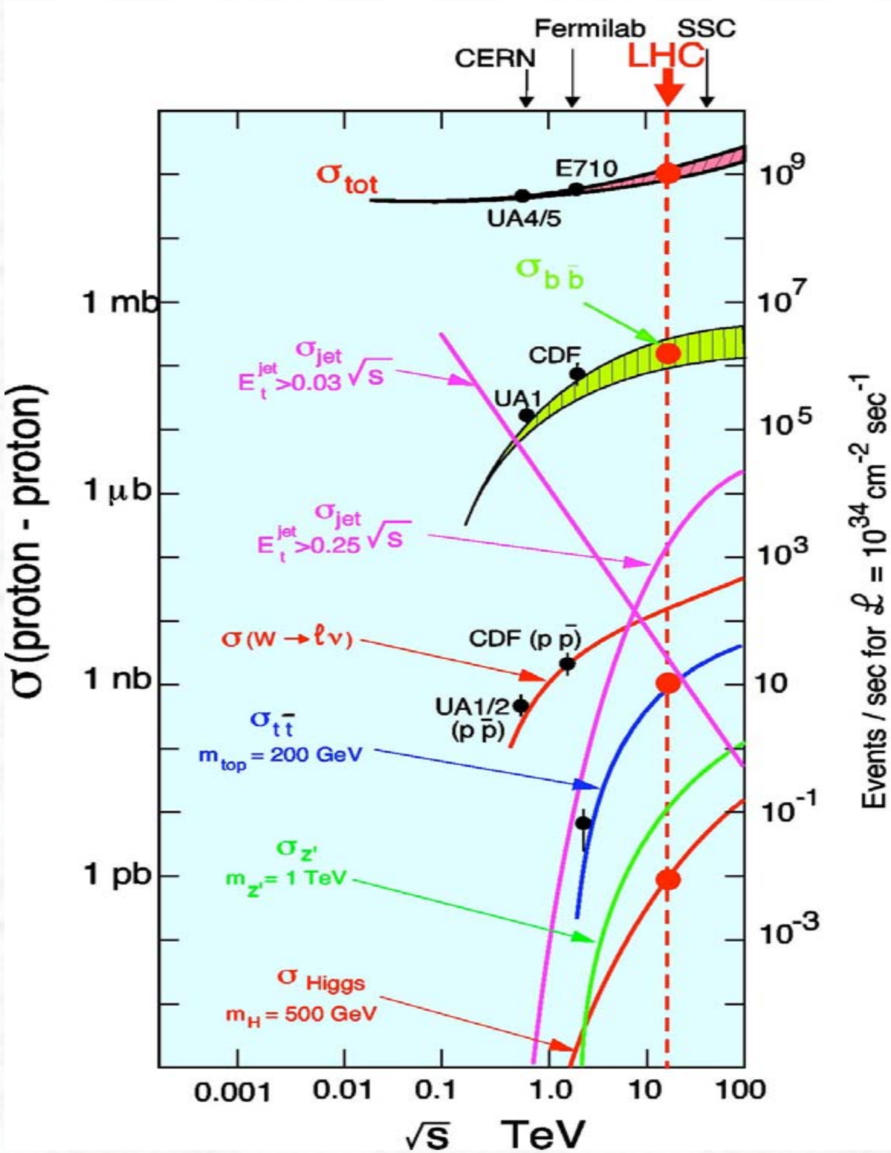
In order to achieve acceptable production rates for the interesting physics processes, the luminosity must be high !

$L = 2 \cdot 10^{32}\ cm^{-2}\, s^{-1}$ design value for Tevatron Run II
$L = 10^{33}\ cm^{-2}\, s^{-1}$ planned for the initial phase of the LHC
$L = 10^{34}\ cm^{-2}\, s^{-1}$ LHC design luminosity, very large !!
(1000 x larger than LEP-2, 50 x Tevatron Run II design)

One experimental year has ~ 10^7 s $\rightarrow$

Integrated luminosity at the LHC: 10 fb^{-1} per year for $L = 10^{33}\ cm^{-2}\, s^{-1}$
100 fb^{-1} per year for $L = 10^{34}\ cm^{-2}\, s^{-1}$

Cross Sections and Production Rates



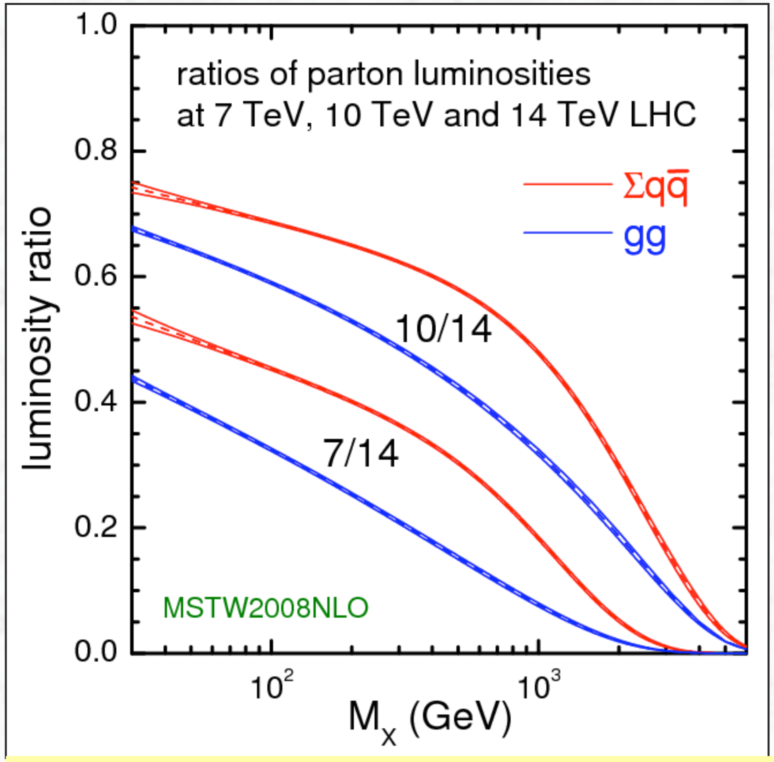
Rates for L = 10^{34} cm^{-2} s^{-1}: (LHC)

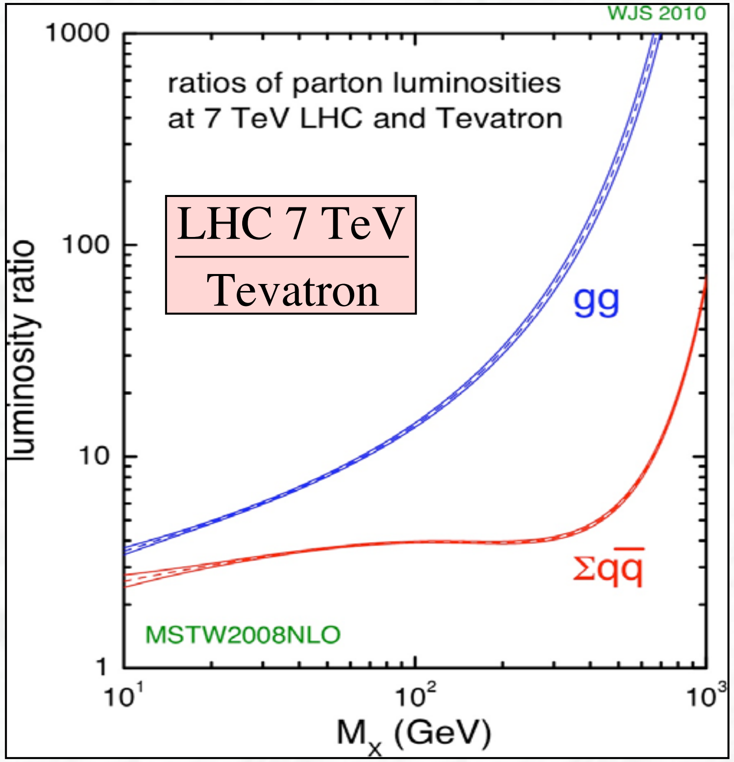
• Inelastic proton-proton reactions:	10^9 / s
• bb pairs • tt pairs	5 10^6 / s 8 / s
• W → e ν • Z → e e	150 / s 15 / s
• **Higgs (150 GeV)** • **Gluino, Squarks (1 TeV)**	**0.2 / s** **0.03 / s**

LHC is a factory for:
top-quarks, b-quarks, W, Z, …,Higgs, …

Impact of reduced beam energy

- Ratio of parton luminosities for 7/14 and 10/14 TeV …





J.Stirling
http://projects.hepforge.org/mstwpdf/plots/plots.html

ttbar:
7/14 = 0.2

W' (1.5 TeV):
7/14 = 0.1

W' (1 TeV):
7(pp) / 2(ppbar) ~ 60

...but still large factor compared to the Tevatron (√s =1.96 TeV)

Detector requirements from physics

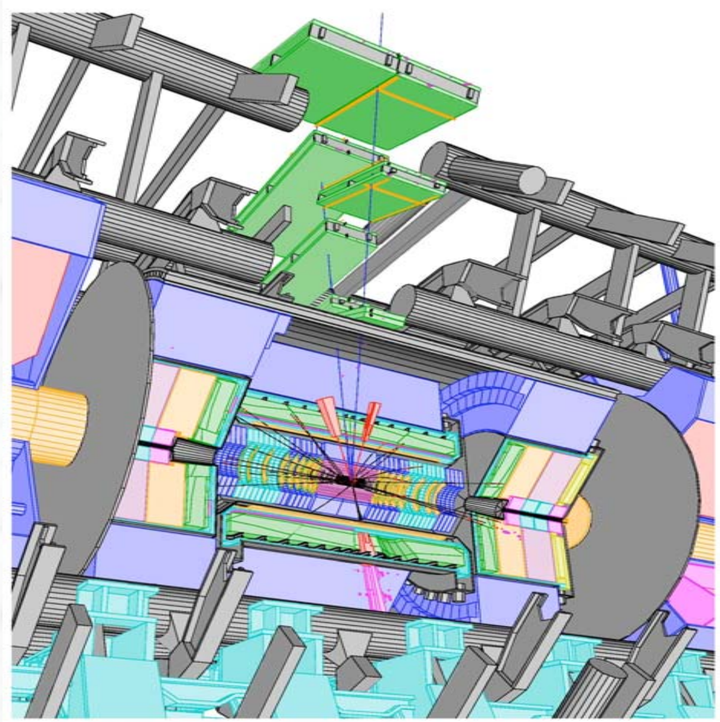
- Good measurement of leptons and photons over a large range of transverse momentum p_T

- Good measurement of missing transverse energy (E_T^{miss})

  and

  energy measurements in the forward regions
  $\Rightarrow$ calorimeter coverage down to $\eta \sim 5$

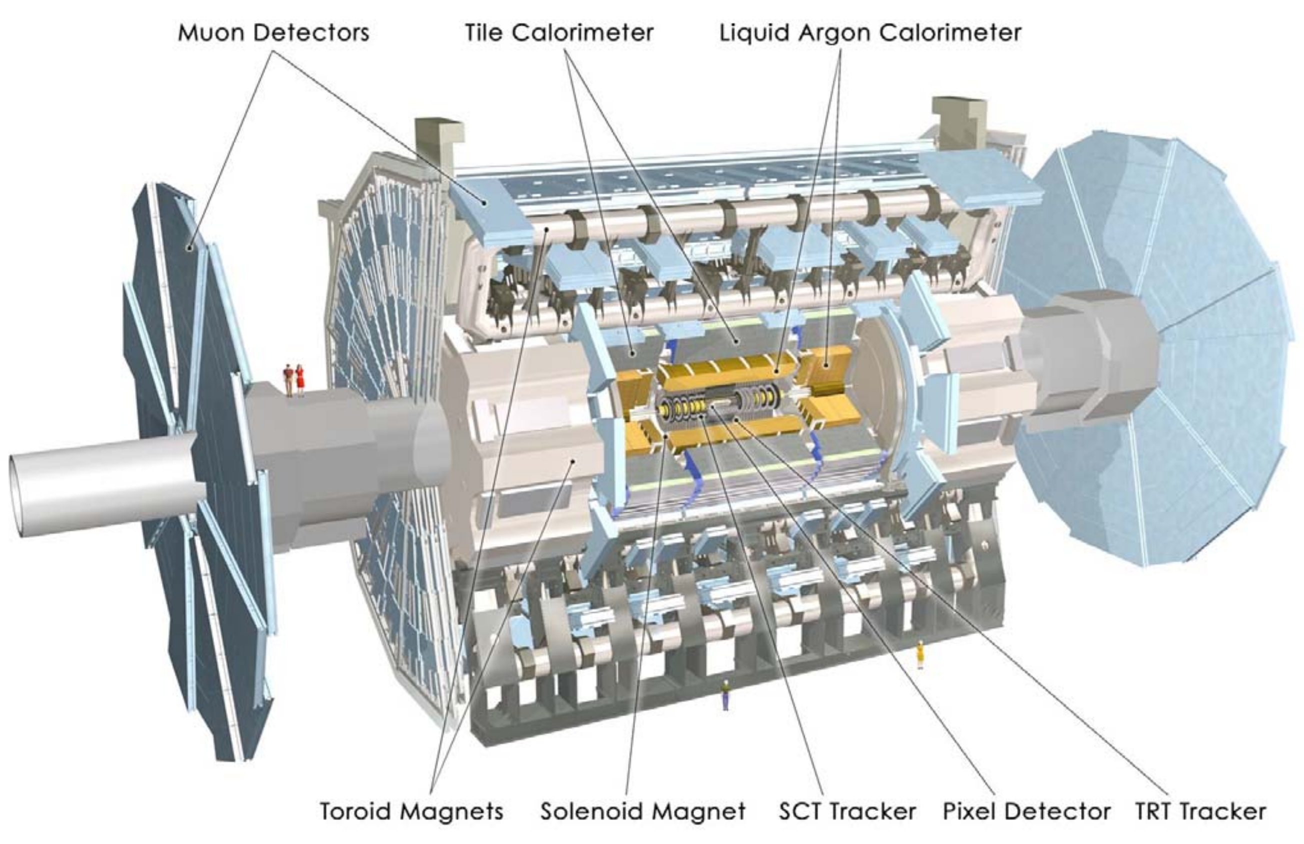
- Efficient b-tagging and τ identification (silicon strip and pixel detectors)



What is relevant for Searches for New Physics ?

Answer: everything !!!

The ATLAS experiment



- Solenoidal magnetic field (2T) in the central region (momentum measurement)

  High resolution silicon detectors:
  - 6 Mio. channels (80 μm x 12 cm)
  - 100 Mio. channels (50 μm x 400 μm)

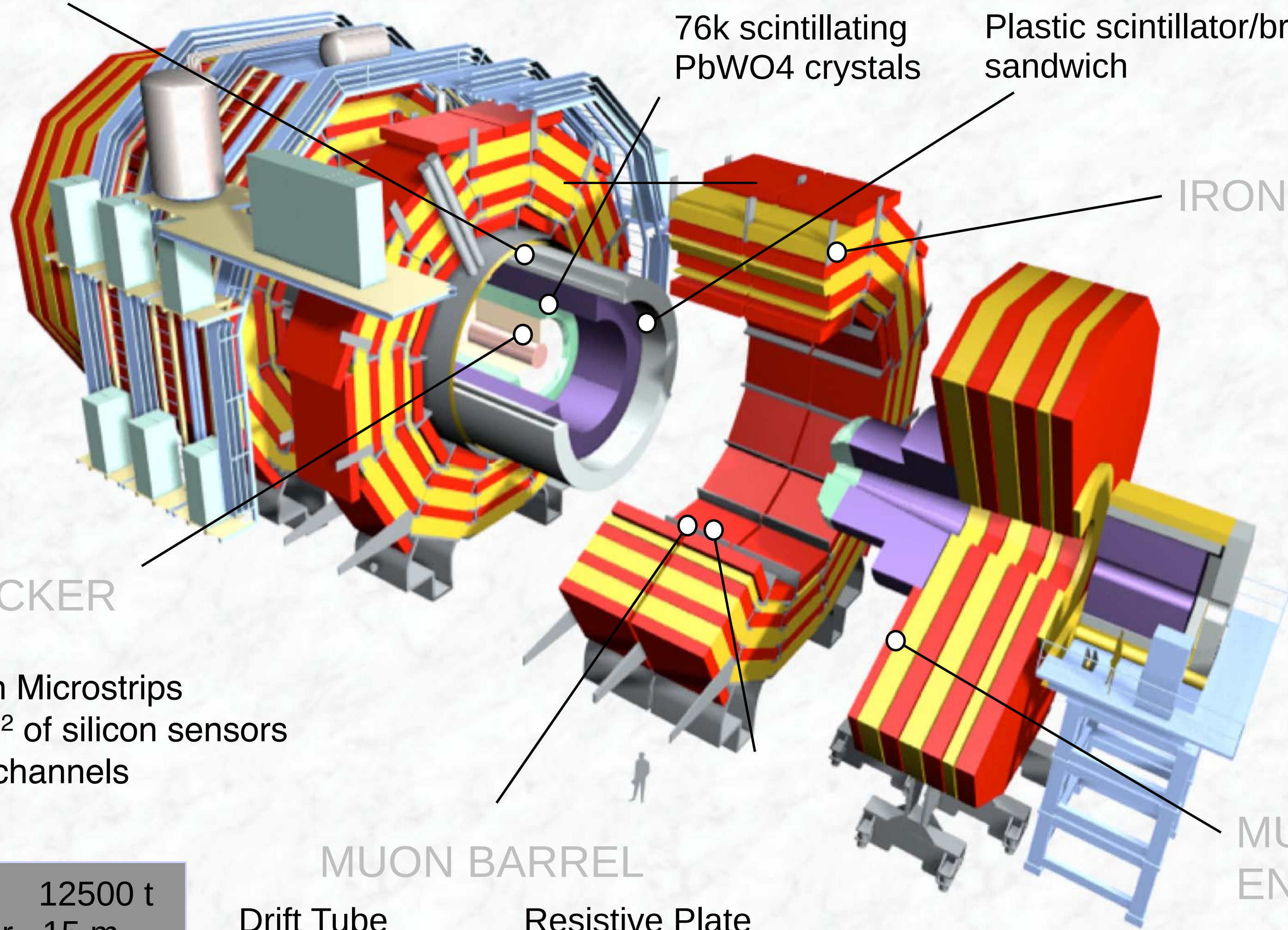
  space resolution: ~ 15 μm

- Energy measurement down to 1º to the beam line

- Independent muon spectrometer (supercond. toroid system)

Diameter	25 m
Barrel toroid length	26 m
End-cap end-wall chamber span	46 m
Overall weight	7000 Tons

CMS



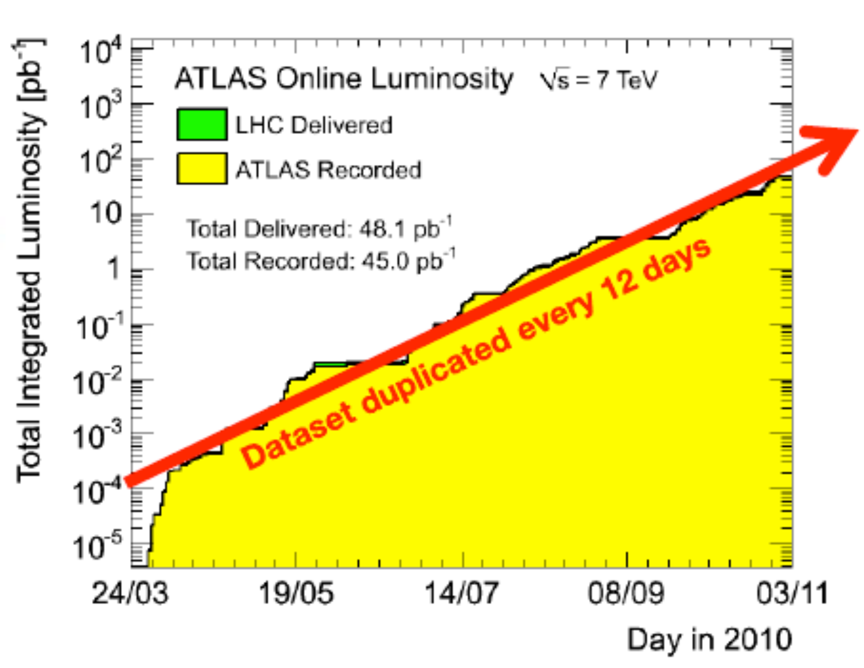
Total weight	12500 t
Overall diameter	15 m
Overall length	21.6 m

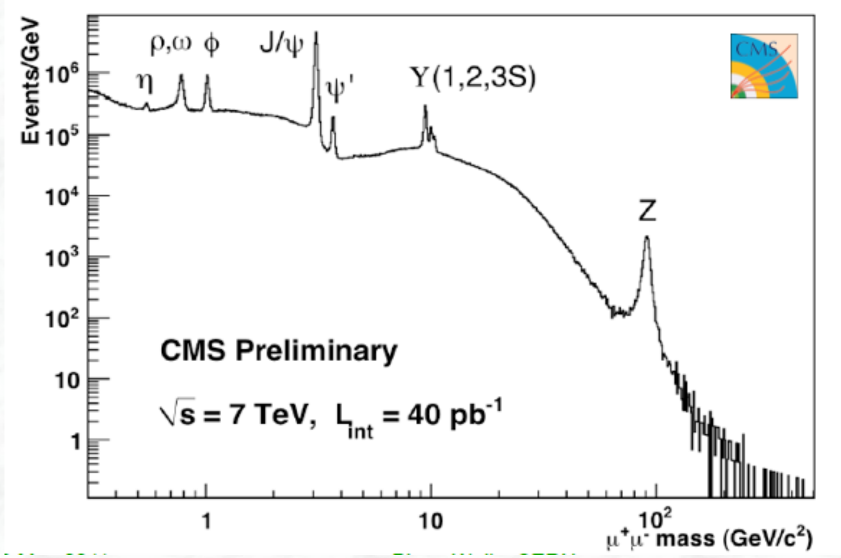
Collected data in 2010:

~40 pb^{-1} recorded
~36 pb^{-1} used in analysis
(good quality)

Both experiments have a very high data taking efficiency !

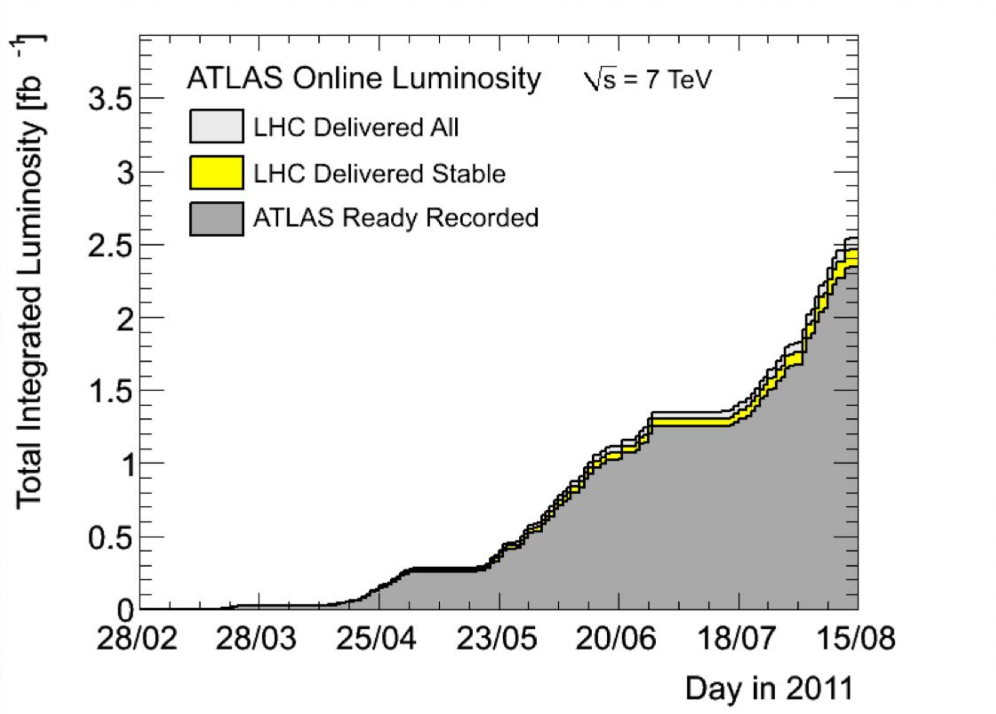
Well known resonances appeared "online"



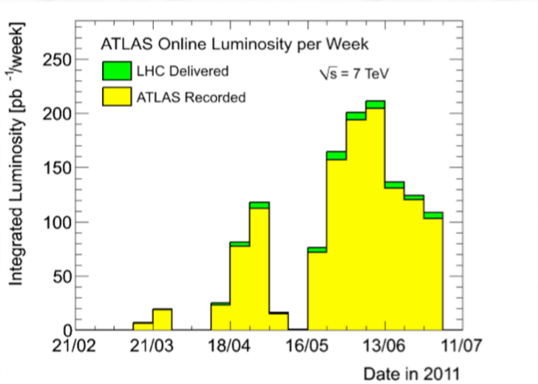


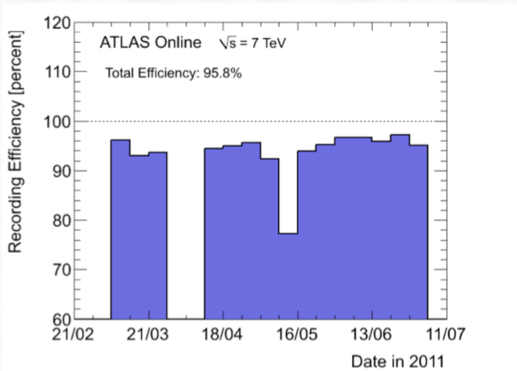
Data taking in 2011

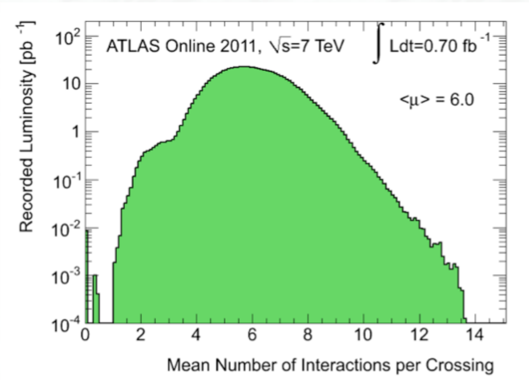
Original goal to collect 1 fb^{-1} already surpassed in June 2011



- World record on instantaneous luminosity on 22. April 2011:
  $4.67\ 10^{32}\ cm^{-2}\ s^{-1}$
  (Tevatron record: $4.02\ 10^{32}\ cm^{-2}\ s^{-1}$)
- 1 fb^{-1} line passed in June 2011
- Collect per day as much luminosity as in 2010
- Data taking efficiency is high
- Pile-up is high
  (high intensity bunches)







It is important to establish the Standard Model reference processes before complex searches begin:

- Test of the theory itself
Deviations → evidence for Physics beyond the Standard Model (?)

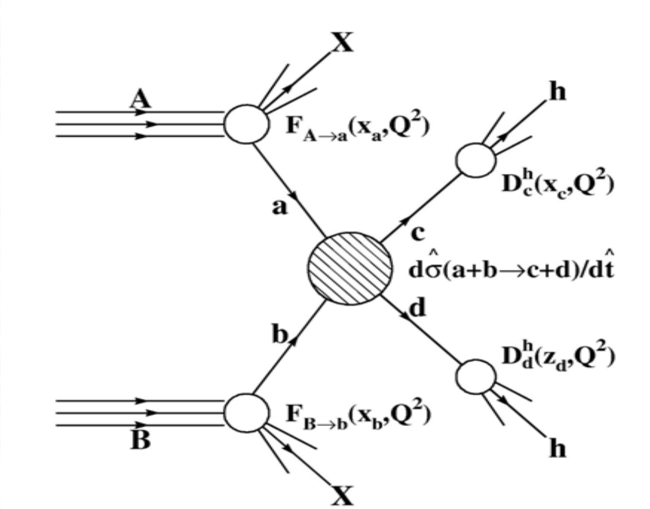
- Important to understand the detector performance
  → understand the so called "Fake" or "instrumental" background, in particular for leptons (e,μ) and E_T^{miss}

- Standard Model processes are important background processes for many searches for Physics Beyond the Standard Model
  "Physics Background"

  Typical selections require: leptons, jets, E_T^{miss} , ….

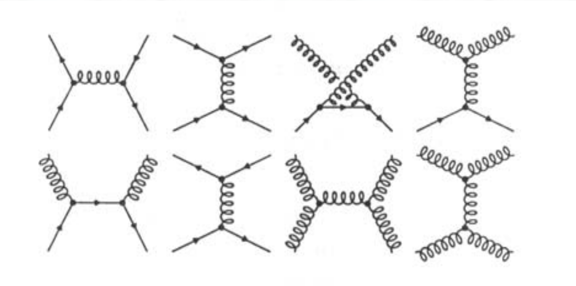
  → W/Z + jets and tt productions are omnipresent !

QCD processes at hadron colliders

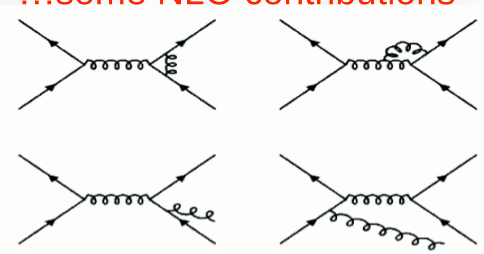


- Hard scattering processes are dominated by QCD jet production
- Originating from qq, qg and gg scattering
- Cross sections can be calculated in QCD (perturbation theory)

Leading order



…some NLO contributions

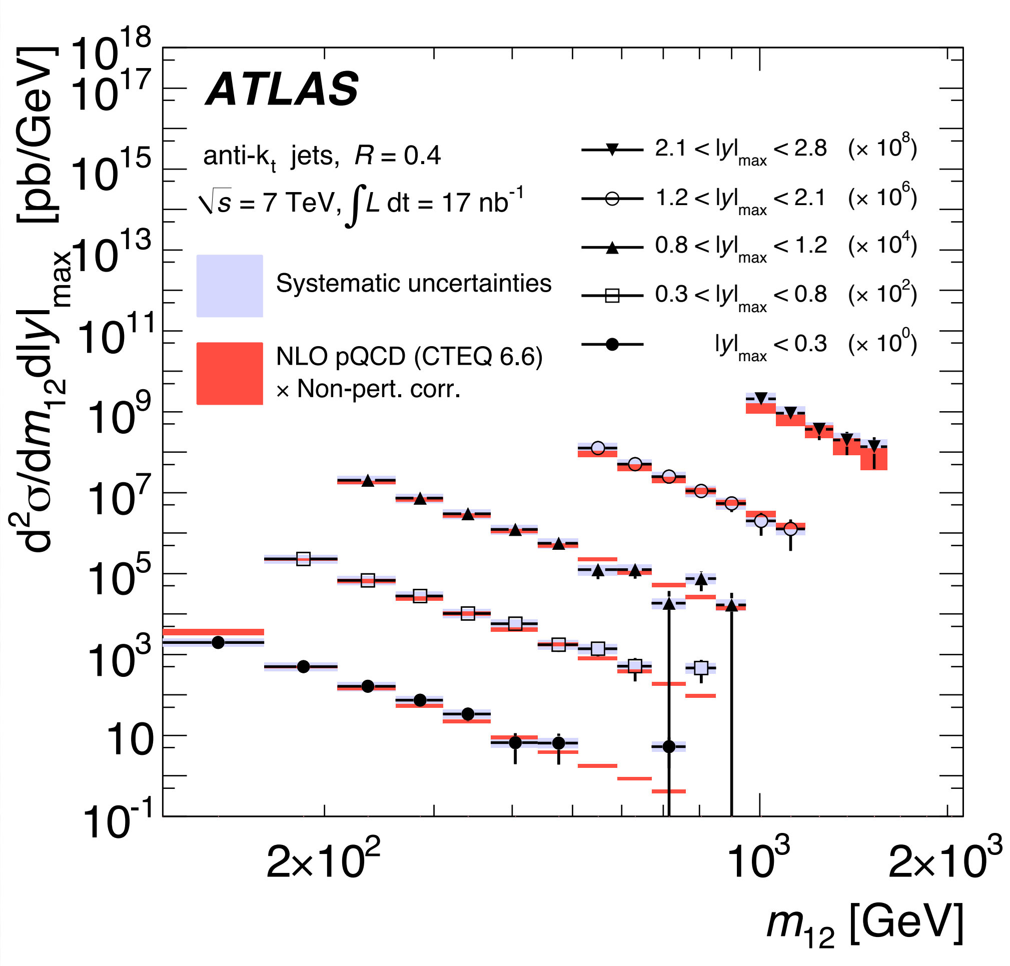


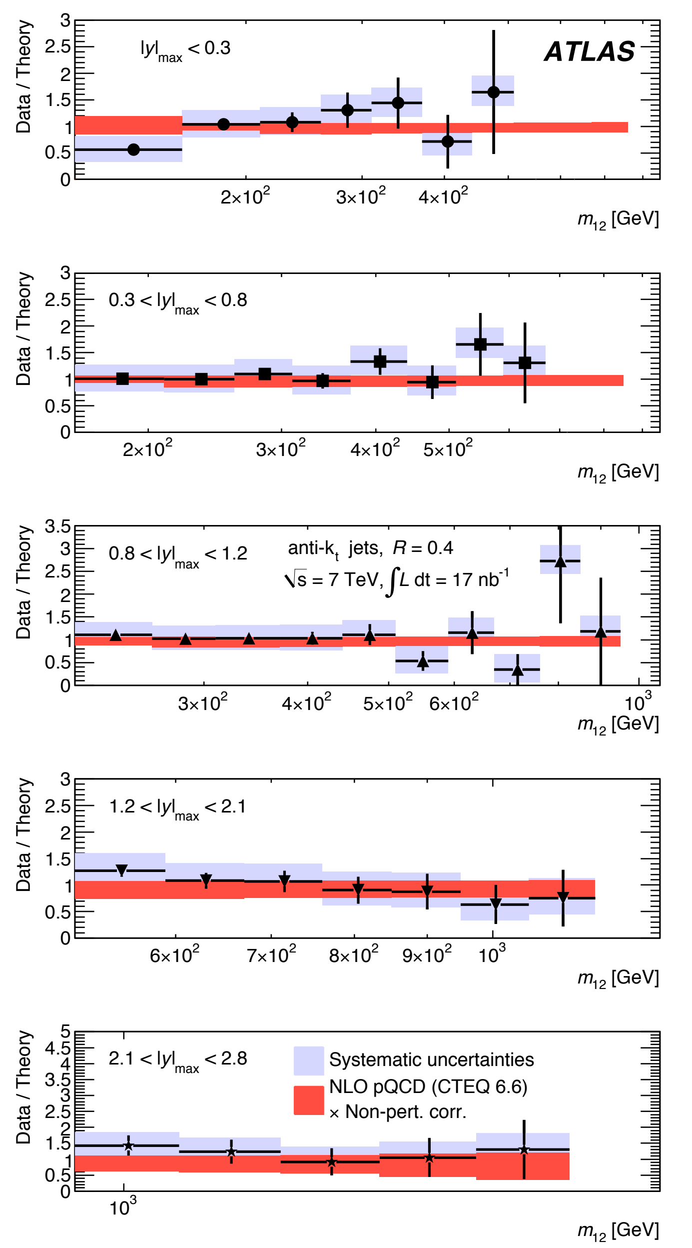
Comparison between experimental data and theoretical predictions constitutes an important test of the theory.

Deviations?

→ Problem in the experiment ?
Problem in the theory (QCD) ?
New Physics, e.g. quark substructure ?

Invariant di-jet mass spectra, ratio data/theory:





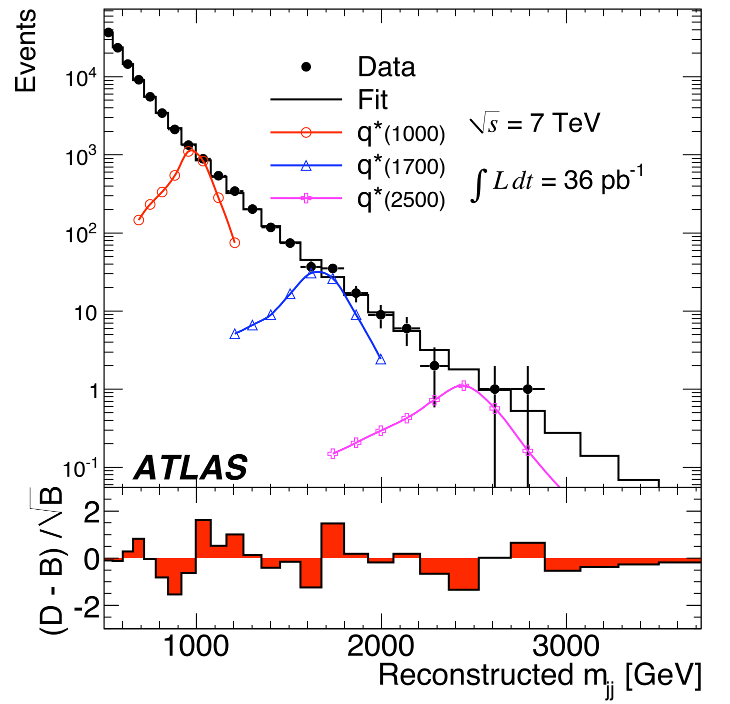
Important for: - Test of QCD
- Search for new resonances decaying into two jets

In addition to QCD test: Sensitivity to New Physics

- Di-jet mass spectrum provides large sensitivity to new physics

  e.g. Resonances decaying into qq, excited quarks q*, ….

- Search for resonant structures in the di-jet invariant mass spectrum



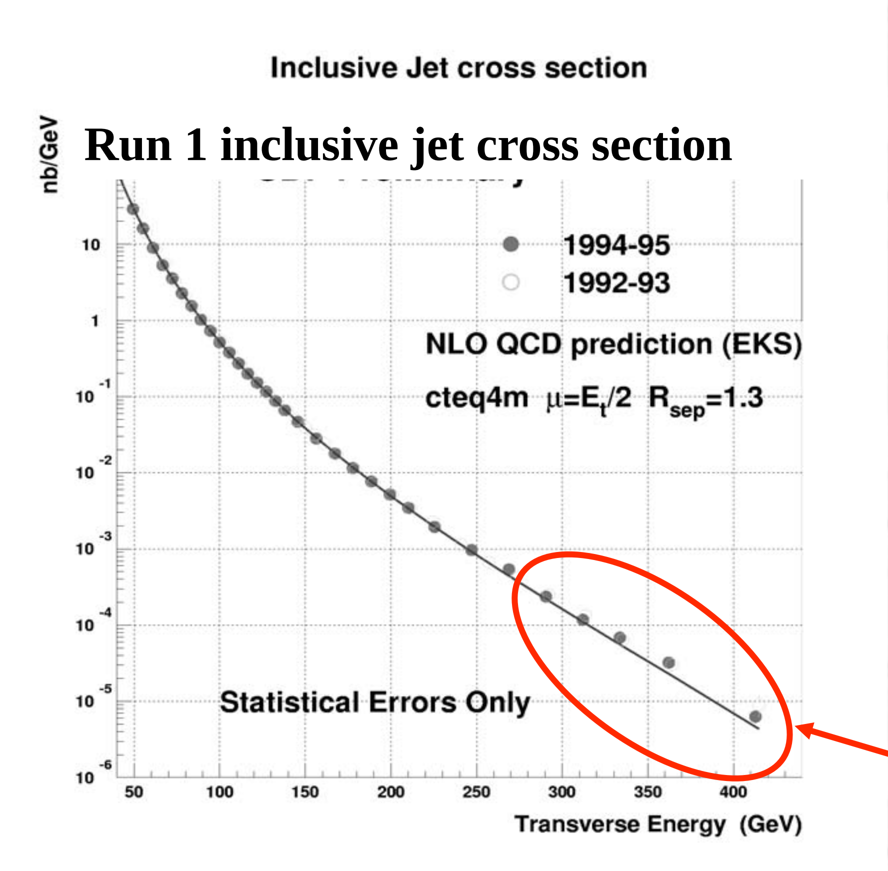
CDF (Tevatron), $L = 1.13\ fb^{-1}$: $0.26 < m_{q*} < 0.87$ TeV

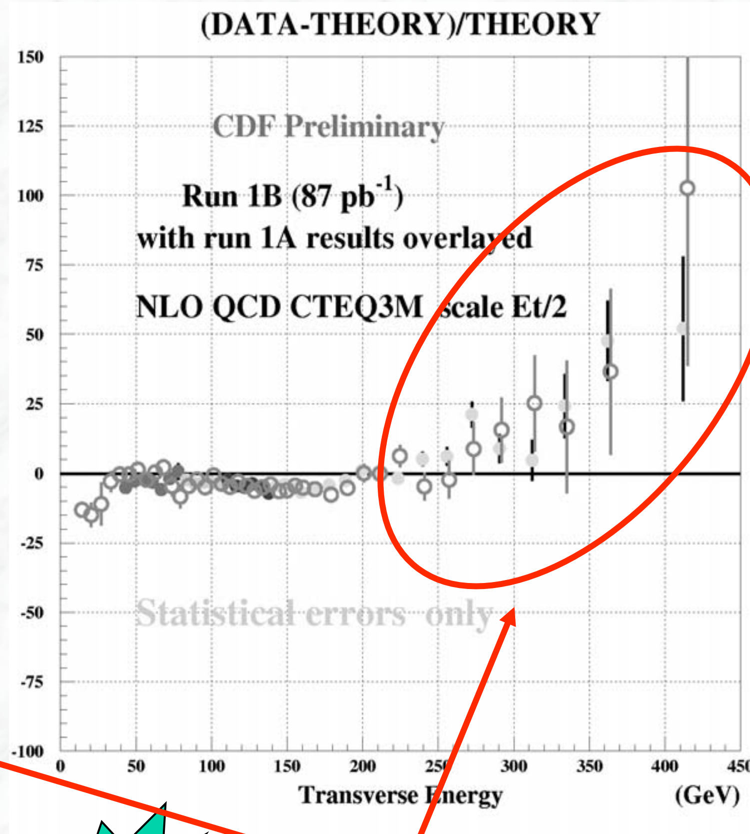
ATLAS (LHC), $L = 0.000315\ fb^{-1}$ exclude (95% C.L) q* mass interval
$0.30 < m_{q*} < 1.26$ TeV

$L = 0.036\ fb^{-1}$: $0.60 < m_{q*} < 2.64$ TeV

Reminder: CDF Inclusive Jet Cross-section in Run I

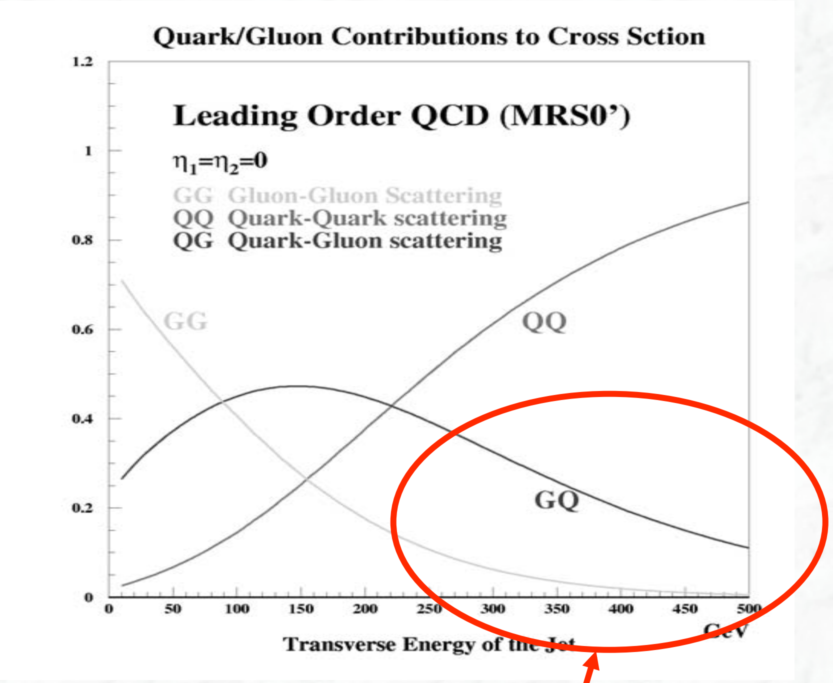
Vital to understand QCD in order to perform precision/search physics





Consistent over 7 orders of magnitude **BUT** **deviation at high Et**

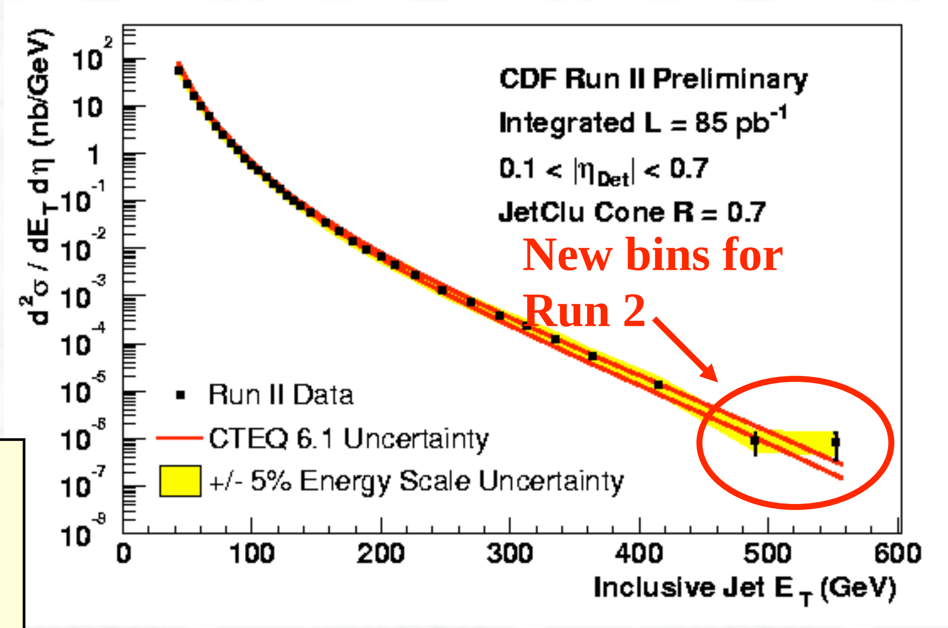
Possible Standard Model explanation



Run 2 - more high Et jets:

Test QCD at high Et

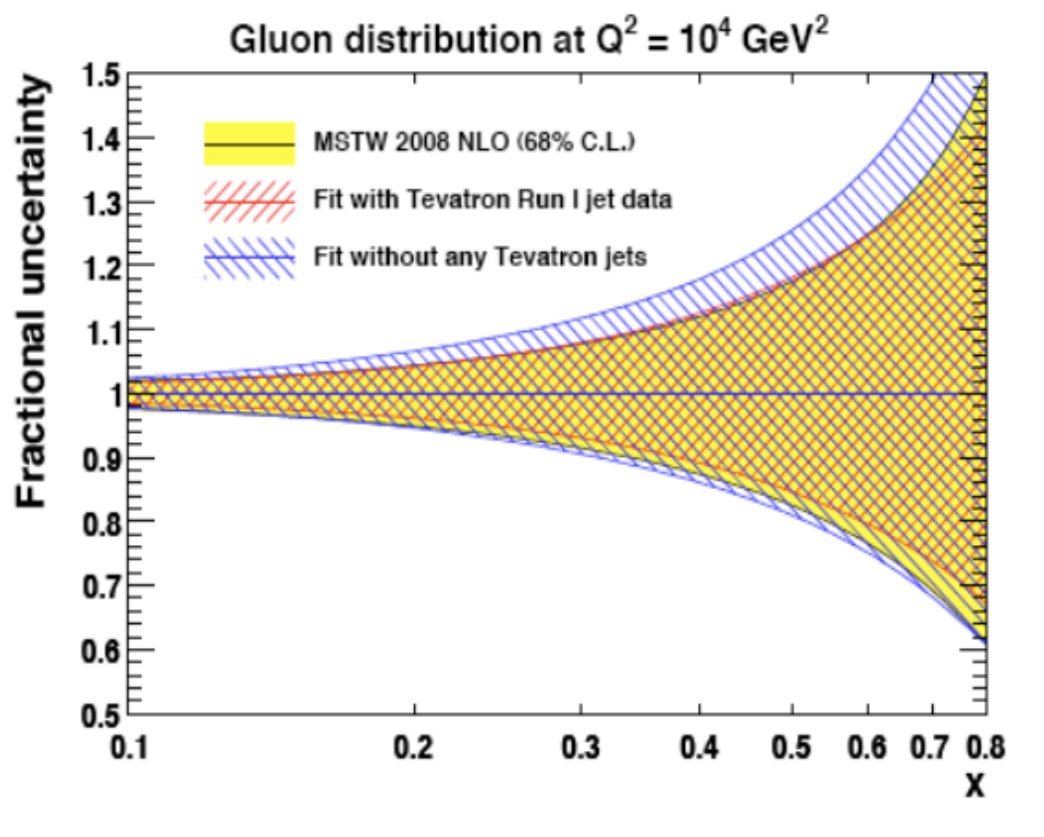
Discriminate between new physics and gluon PDF



Important gluon-gluon and gluon-quark contributions at high Et
Gluon PDF @ high x not well known.

Tevatron jet data are included in recent pdf fits:

- Reduced pdf uncertainty
  (already included and used in recent cross-section calculations at the Tevatron and at the LHC)



It is expected that LHC data will be added as well very soon → further constraints

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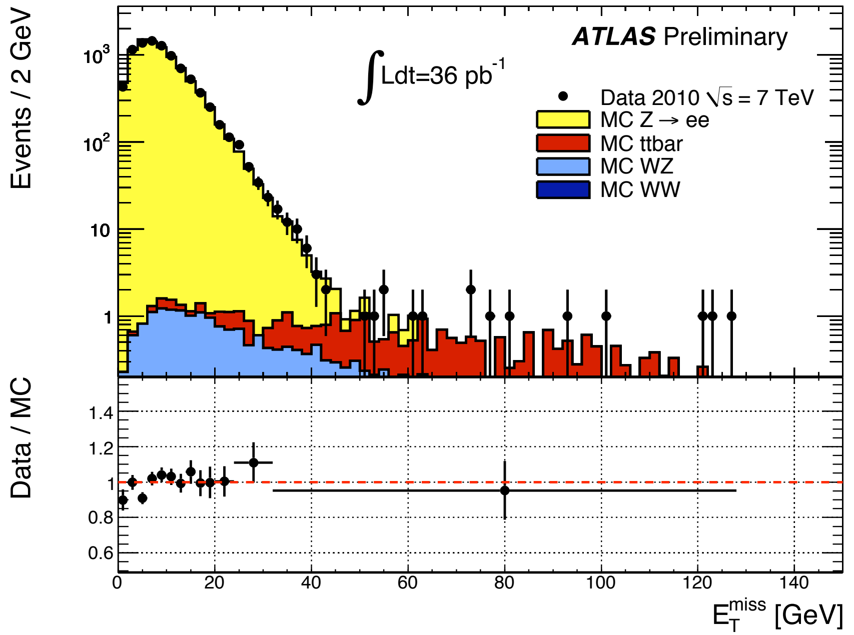
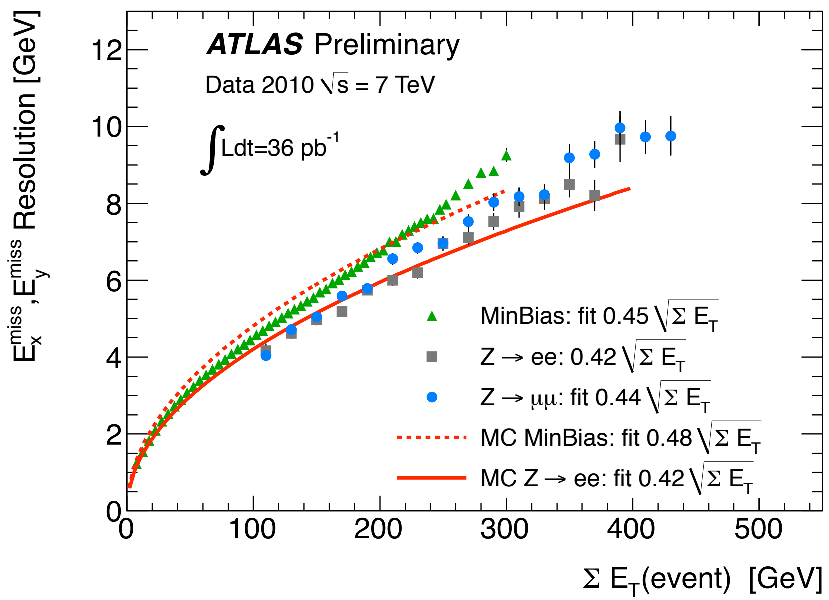
How well can the missing transverse energy be measured ?

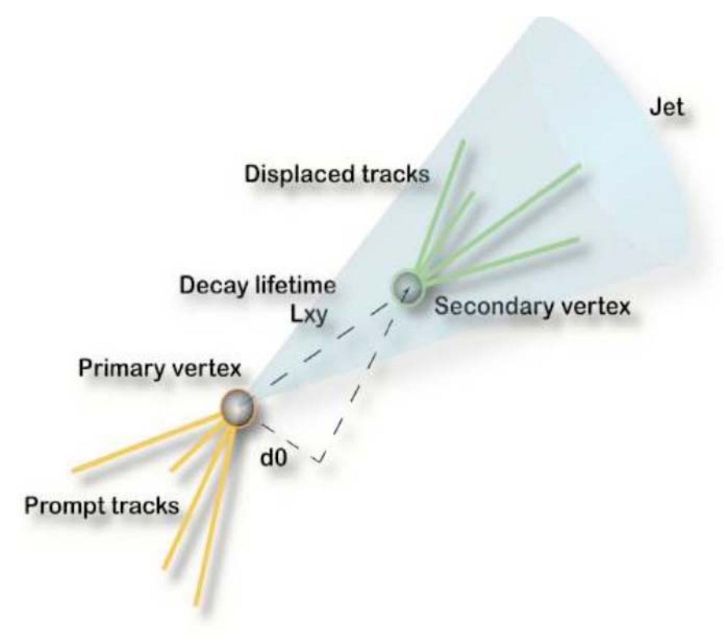




Distribution of E_T^{miss} as measured in a data sample of Z → ee events. The expectation from Monte Carlo simulation is superimposed (histogram) and normalized to data, after each Monte Carlo sample is weighted with its corresponding cross-section. The ratio of the data distribution and the Monte Carlo distribution is shown below the plot.

Resolution of E_x^{miss} and E_y^{miss} as a function of the total transverse energy in the event calculated by summing the p_T of muons and the total calorimeter energy. The resolution in Z→ee and Z→μμ events is compared with the resolution in minimum bias for data taken at √s = 7 TeV. The fit to the resolution in Monte Carlo minimum bias and Z→ee events are superposed.

How well can b-quarks be tagged ?



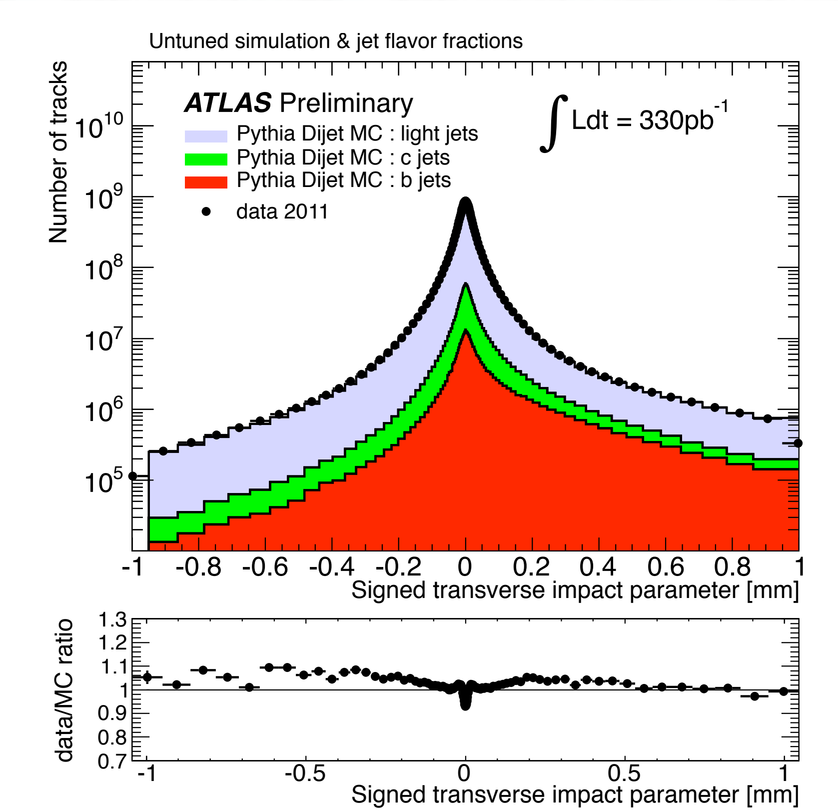
- b quarks fragment into B hadrons (mesons and baryons)
- B mesons have a lifetime of ~1.5 ps

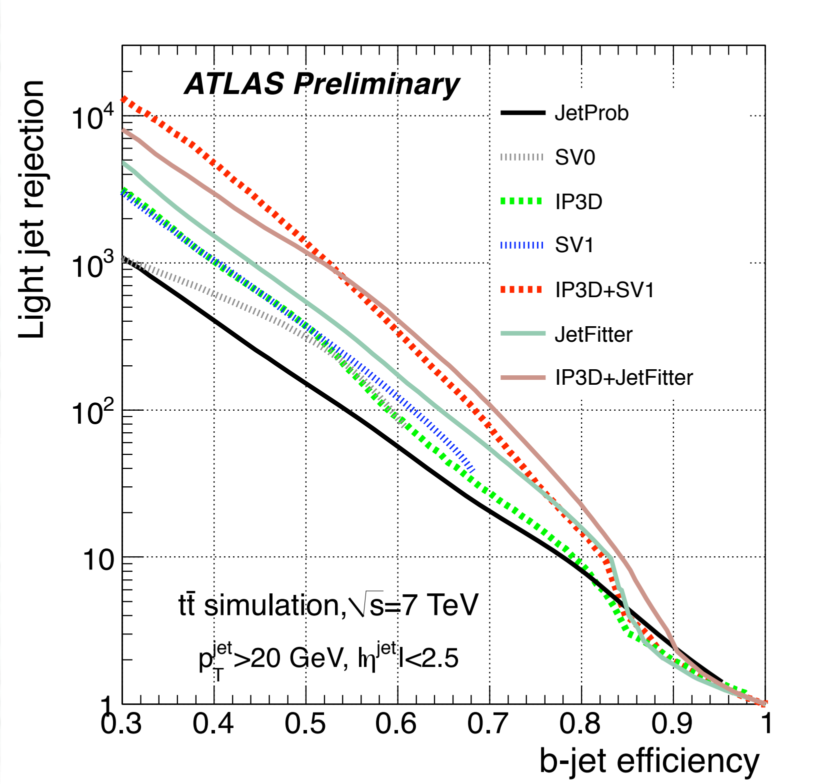
  They fly in the detector about 2-3 mm before they decay

  → reconstruction of a secondary vertex possible
  (requires high granularity silicon pixel and strip detectors close to the interaction point)

  → tracks from B meson decays have a large impact parameter w.r.t. the primary vertex

ATLAS results on b-tagging performance:





Distribution of the signed transverse impact parameter with respect to primary vertex for tracks of b-tagging quality associated to jets, for experimental data (solid black points) and for simulated data (filled histograms for the various flavors). The ratio data/simulation is shown at the bottom of the plot.

Light-jet rejection as a function of the b-jet tagging efficiency for the early tagging algorithms (JetProb and SV0) and for the high performance algorithms, based on simulated top-antitop events.

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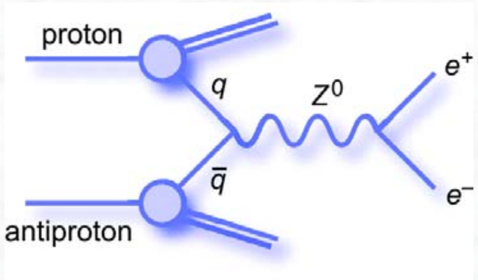
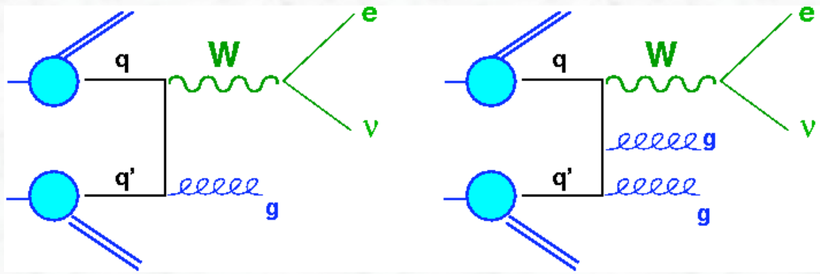
QCD aspects in W/Z (+ jet) production

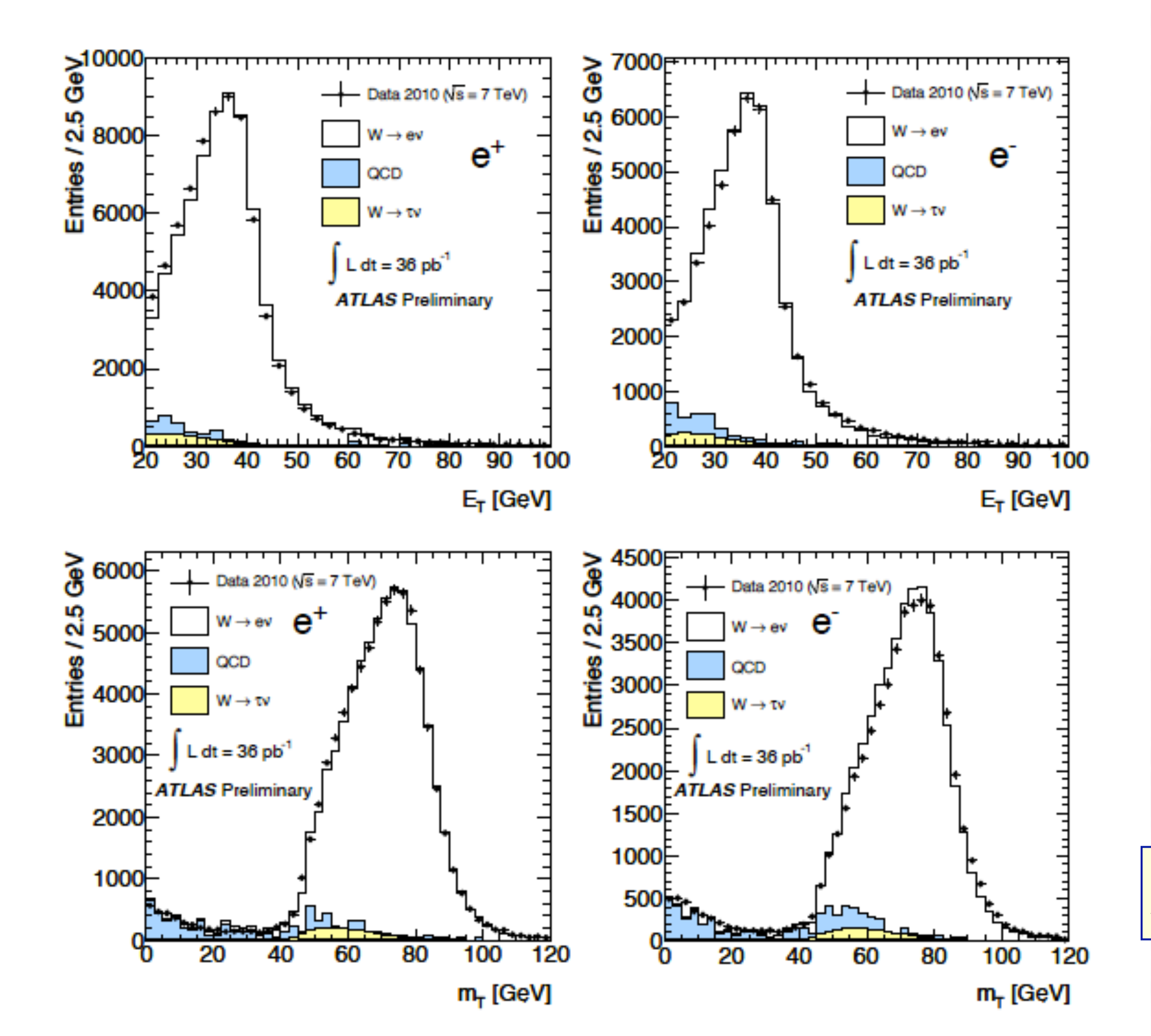


QCD at work



- Important test of NNLO Drell-Yan QCD prediction for the total cross section
- Test of perturbative QCD in high p_T region (jet multiplicities, p_T spectra,….)
- Tuning and „calibration“ of Monte Carlos for background predictions in searches at the LHC

W cross sections in ATLAS, charge separated



Full ATLAS data set from 2010

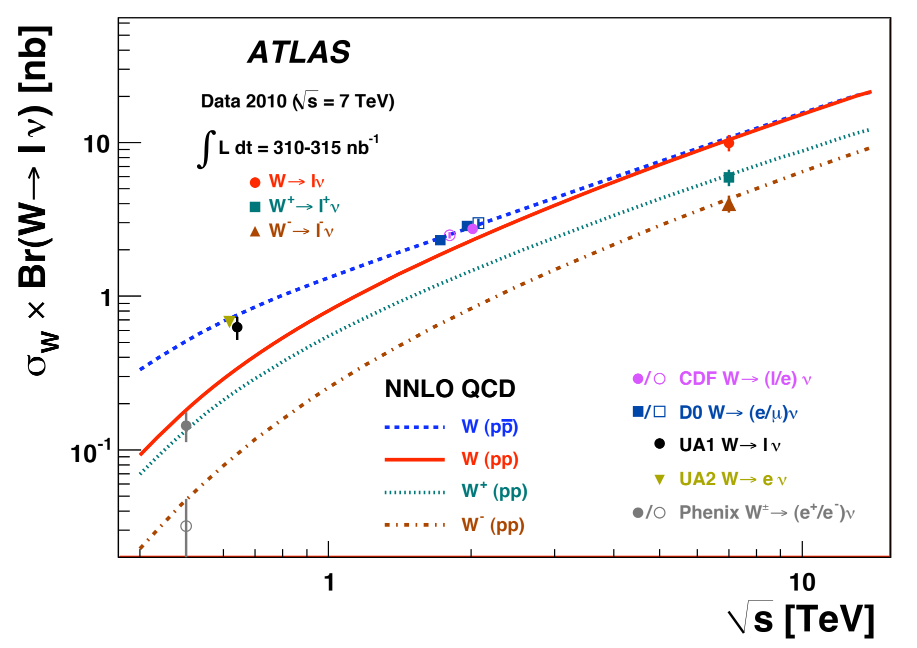
L = 36 pb^{-1}

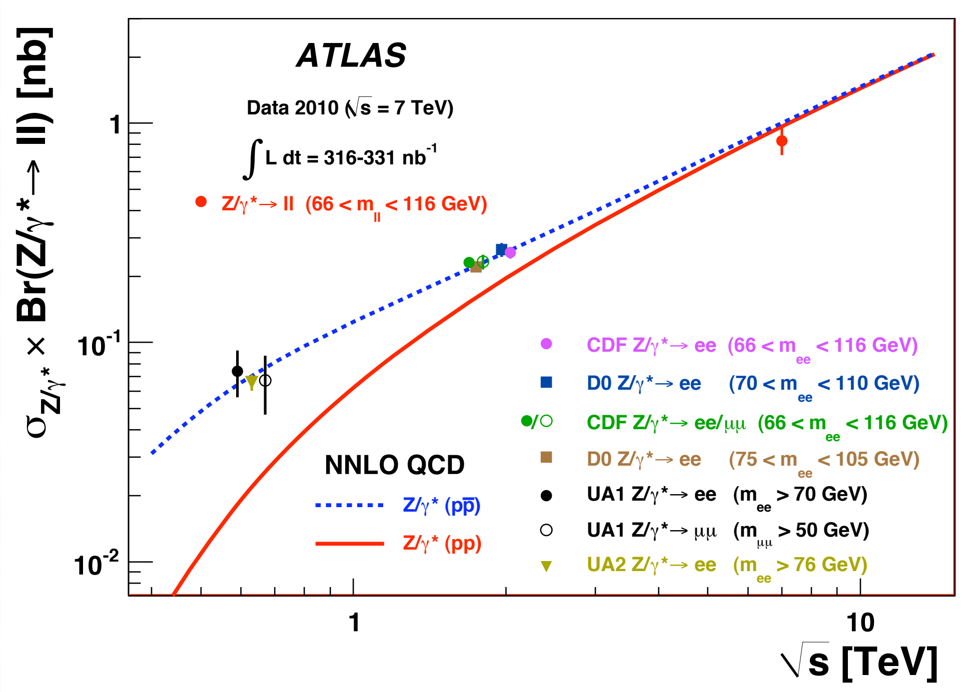
transverse mass:

$$m_T = \sqrt{2 p_T^e E_T^{miss} (1 - \cos \Delta\phi(e, p_T^{miss}))}$$

Distribution of transverse energy (top) and transverse mass m_T (bottom) of the electron in the selected W to electron candidate events after all cuts for positive (left) and negative (right) charge. The simulated distributions are normalised to the data.

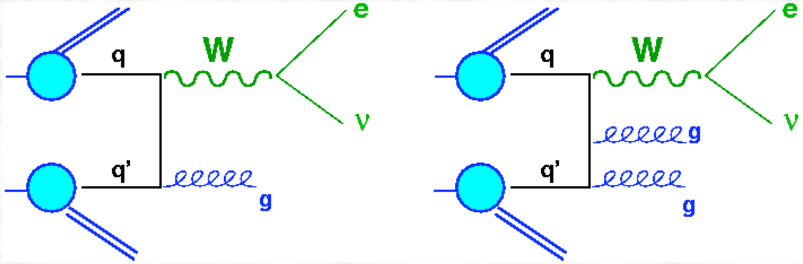
W and Z production cross sections at hadron colliders





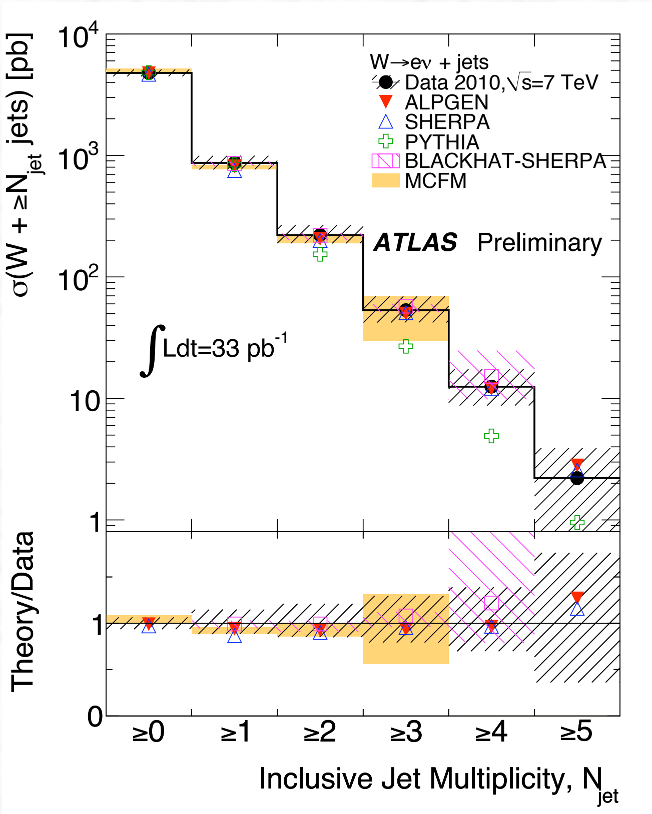
Theoretical NNLO predictions in very good agreement with the experimental measurements (for pp, ppbar and as a function of energy)

QCD Test in W/Z + jet production

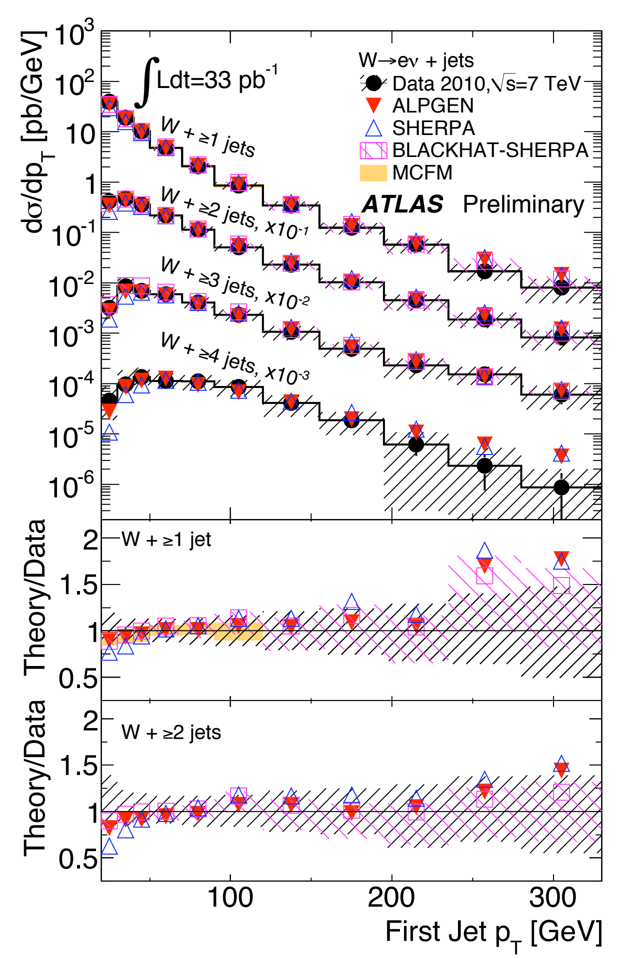


- LO predictions fail to describe the data;
- Jet multiplicities and p_T spectra in agreement with NLO predictions within errors; NLO central value ~10% low

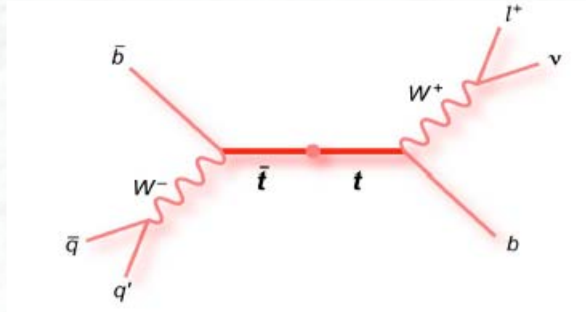
Jet multiplicities in W+jet production



p_T spectrum of leading jet



Top Quark Decays



BR ($t \to Wb$) ~ 100%

Dilepton channel:

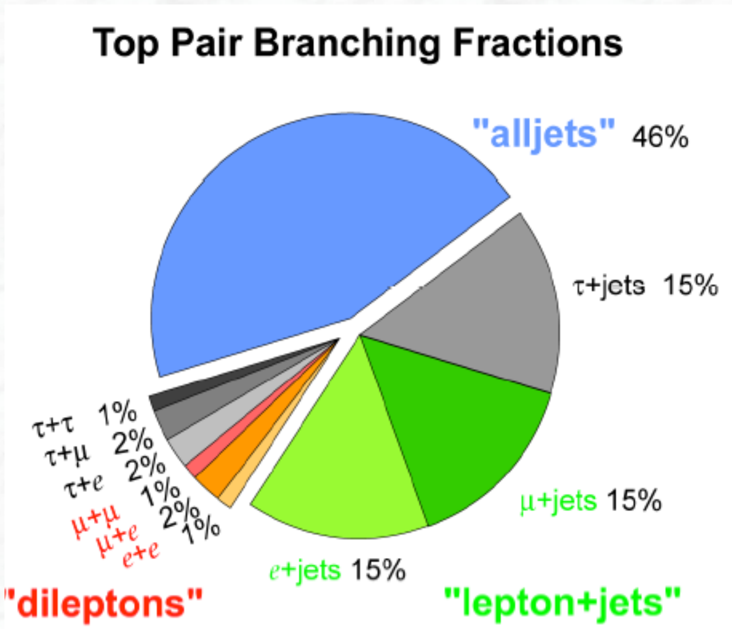
Both W's decay via $W \to \ell\nu$ (ℓ=e or μ; 4%)

Lepton + jet channel:

One W decays via $W \to \ell\nu$ (ℓ=e or μ; 30%)

Full hadronic channel:

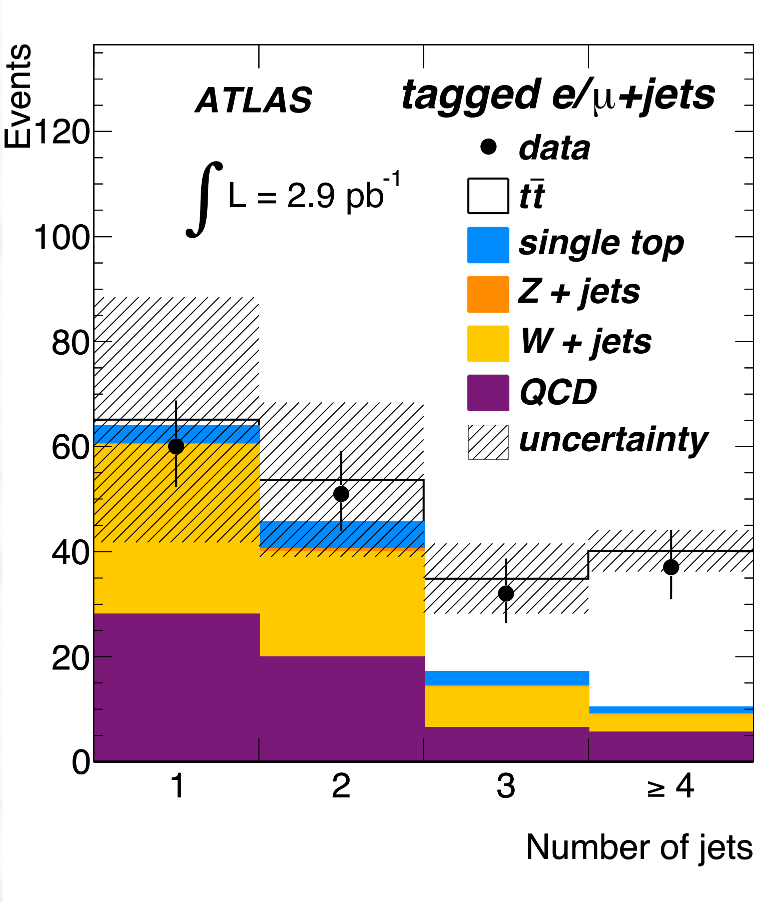
Both W's decay via $W \to qq$ (46%)



<u>Important experimental signatures</u>: : - Lepton(s)

- Missing transverse momentum
- b-jet(s)

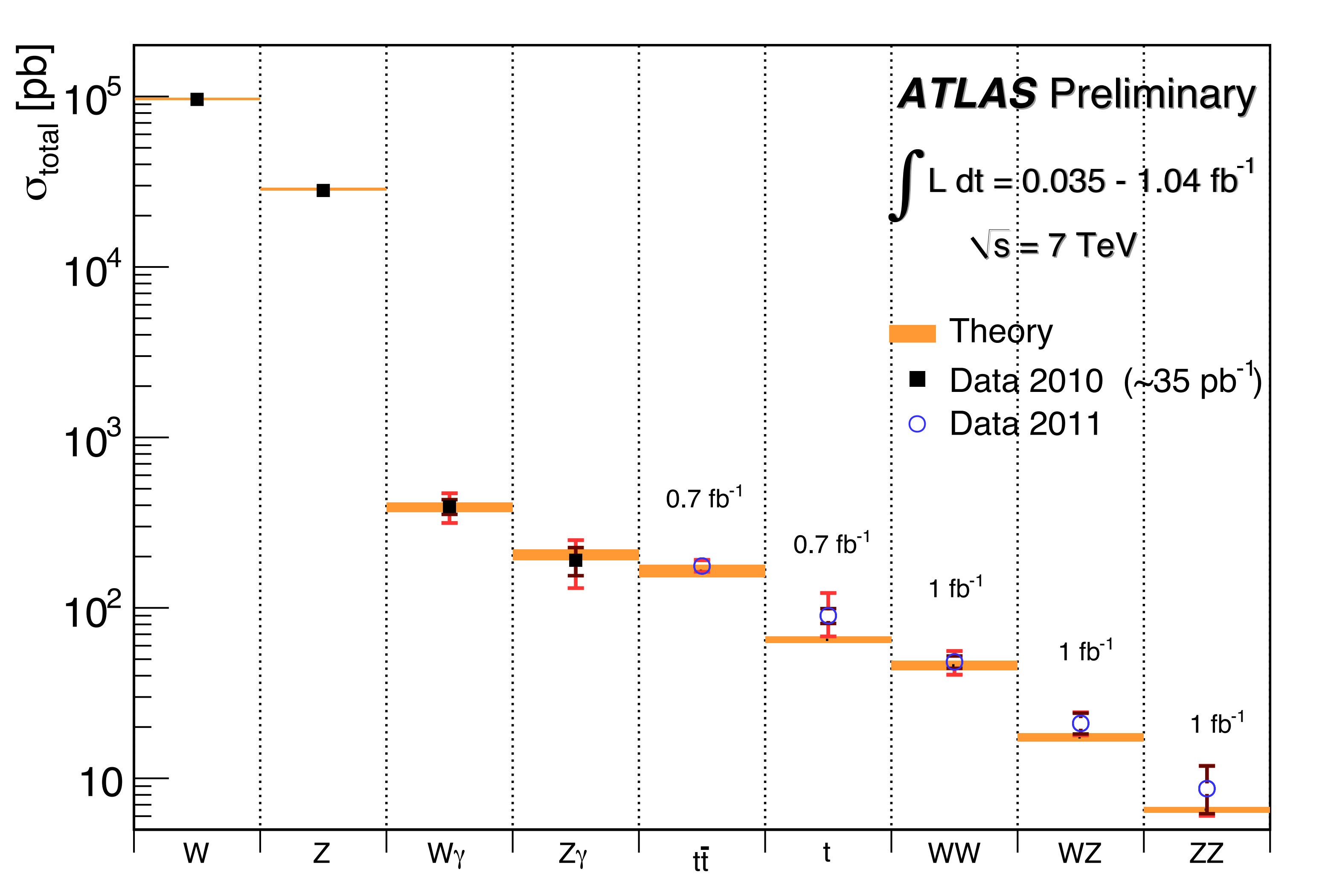
First results on top production from the LHC



Event Selection:

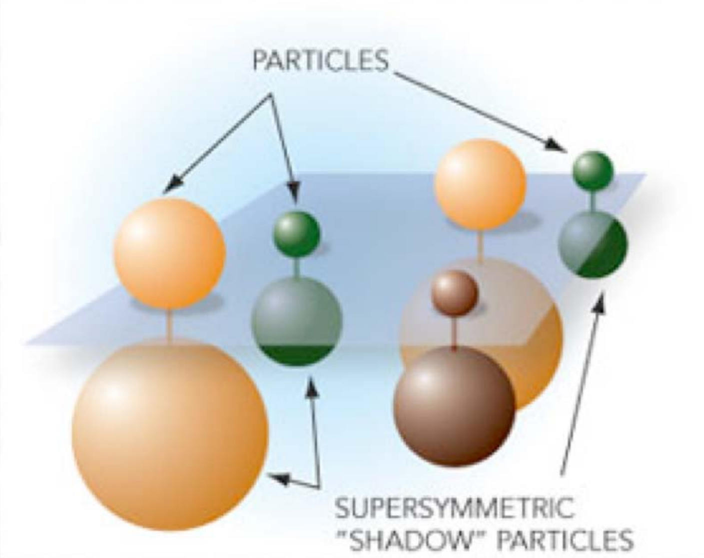
- Lepton trigger
- One identified lepton (e,μ) with p_T > 20 GeV
- Missing transverse energy: E_T^{miss} > 35 GeV (significant rejection against QCD events)
- Transverse mass: M_T (l,ν) > 25 GeV (lepton from W decay in event)
- One or more jets with p_T > 25 GeV and η < 2.5

Summary of Standard model cross section measurements by ATLAS



Searches for Physics Beyond the Standard Model at the LHC

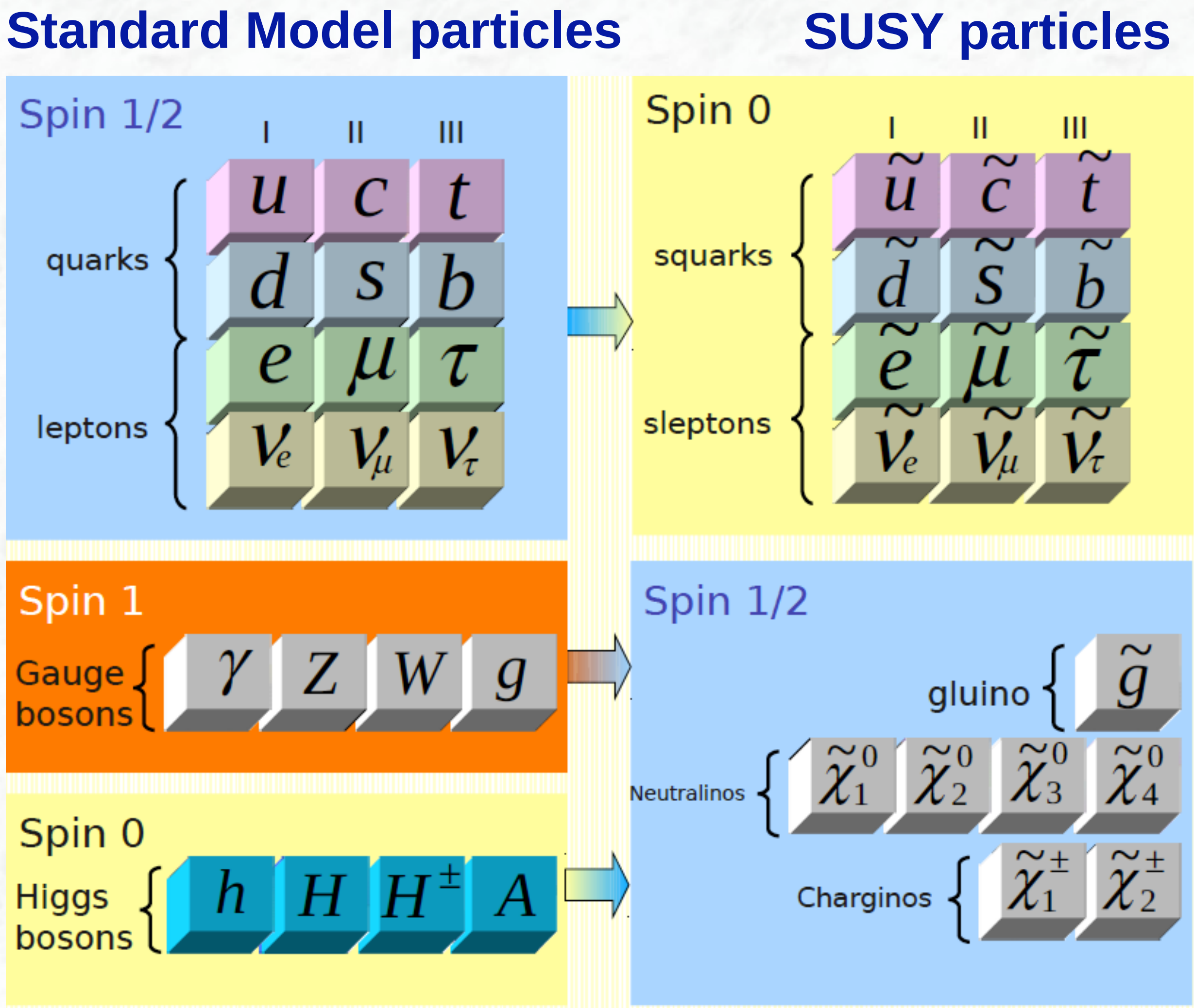
-Part 2: Search for Supersymmetry-



For theoretical background: see lecture by Gian Giudice

Supersymmetry

Extends the Standard Model by predicting a new symmetry
Spin ½ matter particles (fermions) ⇔ Spin 1 force carriers (bosons)

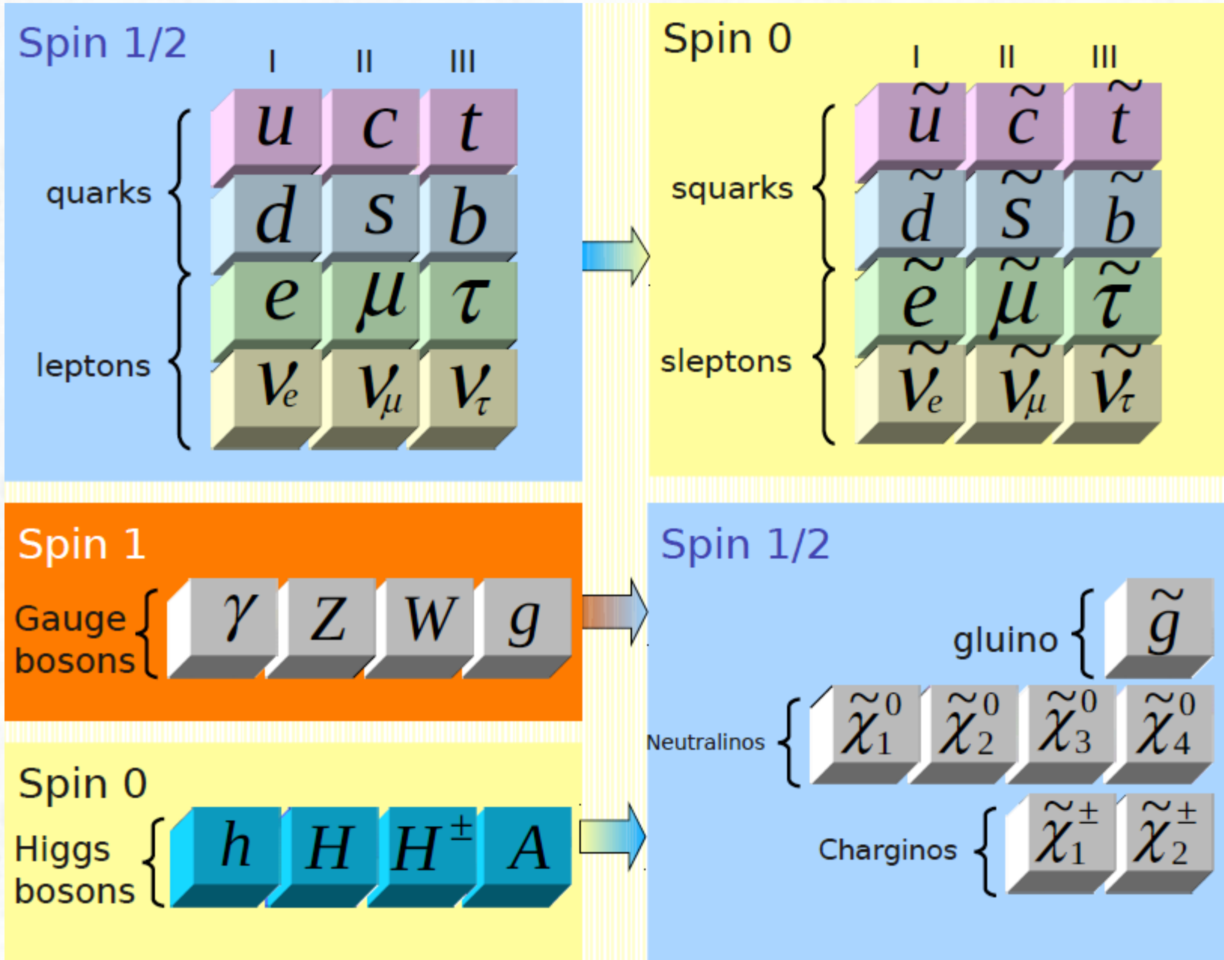


Supersymmetry

Standard Model particles and supersymmetry partners can be distinguished by a discrete quantum number: R parity $R = (-1)^{3B+L+2S}$ = +1 SM particles

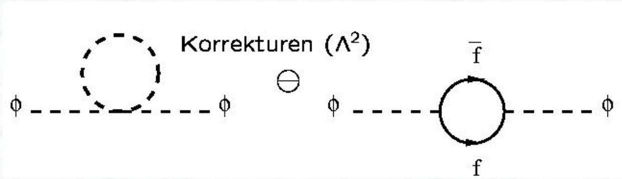
- 1 SUSY particles

Standard Model particles **SUSY particles**



Why do we like SUSY so much?

1. Quadratically divergent quantum corrections to the Higgs boson mass are avoided



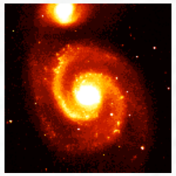
$$\Delta m_H = f(m_B^2 - m_f^2)$$

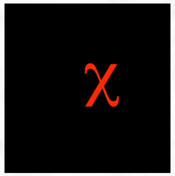
→ $m_{SUSY} \sim 1$ TeV

(Hierarchy or naturalness problem)

2. Unification of coupling constants of the three interactions seems possible

3. SUSY provides a candidate for dark matter

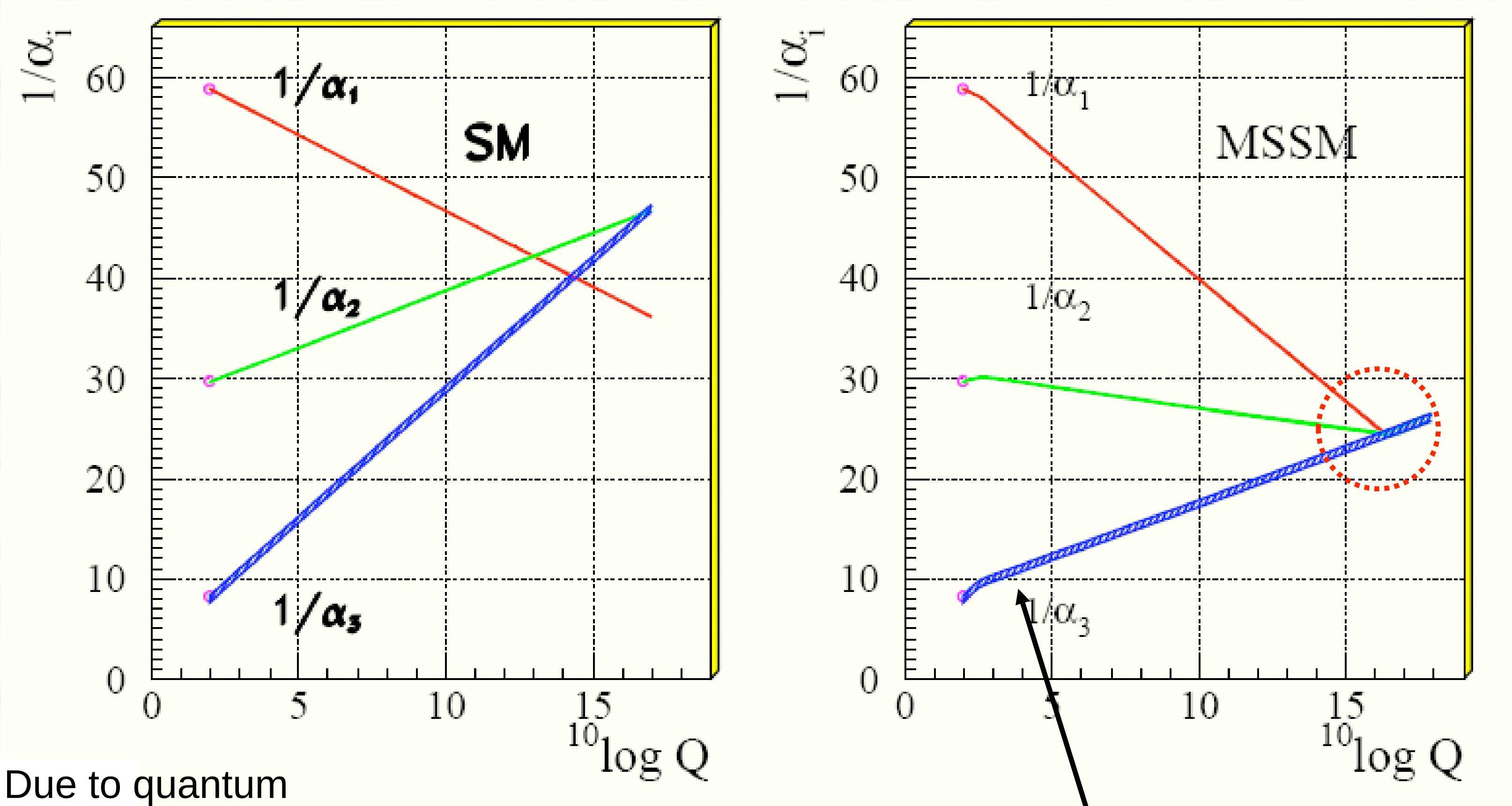




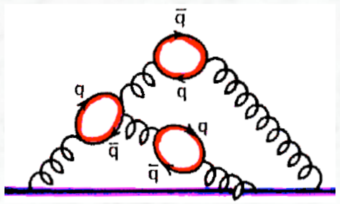
The lightest SUSY particle (LSP)

4. A SUSY extension is a small perturbation, consistent with the electroweak precision data

The unification of the couplings of the three interactions seems possible in a SUSY model



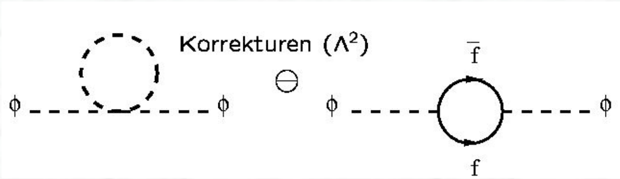
Due to quantum corrections, e.g.



slope is changed due to contributions from SUSY particles

Why do we like SUSY so much?

1. Quadratically divergent quantum corrections to the Higgs boson mass are avoided



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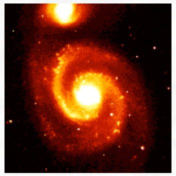

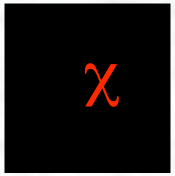

The lightest SUSY particle (LSP)

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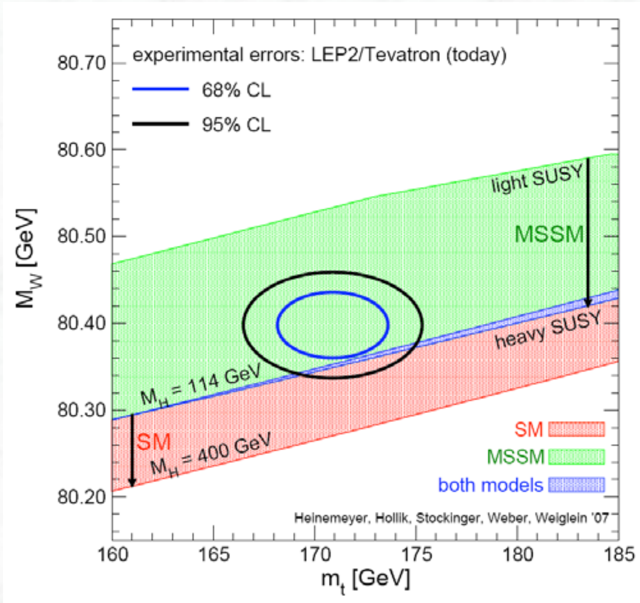


	Particle	Sparticle (corresp. SUSY particle)	
Spin-1/2	quarks (L&R) leptons (L&R) neutrinos (L)	squarks (L&R) sleptons (L&R) sneutrinos (L)	Spin-0
Spin-1	B, W^0 → γ, Z^0 $W^\pm$ gluon	Bino Wino^0 $\text{Wino}^\pm$ gluino	Spin-1/2
Spin-0	**Higgs** $\begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix}$ $\begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix}$	**Higgsinos** $\begin{pmatrix} \tilde{H}_1^1 \\ \tilde{H}_1^2 \end{pmatrix}$ $\begin{pmatrix} \tilde{H}_2^1 \\ \tilde{H}_2^2 \end{pmatrix}$	Spin-1/2

Extended Higgs sector: 2 complex Higgs doublets

→ Degrees of freedom: 8 – 3 = 5 Higgs bosons: $h^0, H^0, A^0, H^\pm$

	Particle	Sparticle (corresp. SUSY particle)	
Spin-1/2	quarks (L&R) leptons (L&R) neutrinos (L)	squarks (L&R) sleptons (L&R) sneutrinos (L)	Spin-0
Spin-1	B, W^0 } { γ, Z^0 $W^{\pm}$ gluon	Bino Wino^0 $\text{Wino}^{\pm}$ gluino	Spin-1/2
Spin-0	**Higgs** $\begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix}$ $\begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix}$	**Higgsinos** $\begin{pmatrix} \tilde{H}_1^1 \\ \tilde{H}_1^2 \end{pmatrix}$ $\begin{pmatrix} \tilde{H}_2^1 \\ \tilde{H}_2^2 \end{pmatrix}$	Spin-1/2

After Mixing

- 4 neutralinos
- 2 charginos

Extended Higgs sector: 2 complex Higgs doublets

→ Degrees of freedom: 8 – 3 = 5 Higgs bosons: h^0, H^0, A^0, $H^{\pm}$

Names		spin 0	spin 1/2	$SU(3)_C,\ SU(2)_L,\ U(1)_Y$
squarks, quarks	Q	$(\widetilde{u}_L\ \ \widetilde{d}_L)$	$(u_L\ \ d_L)$	$(\,\mathbf{3},\ \mathbf{2}\,,\ \frac{1}{6})$
($\times 3$ families)	$\overline{u}$	$\widetilde{u}^*_R$	$u^\dagger_R$	$(\,\overline{\mathbf{3}},\ \mathbf{1},\ -\frac{2}{3})$
	$\overline{d}$	$\widetilde{d}^*_R$	$d^\dagger_R$	$(\,\overline{\mathbf{3}},\ \mathbf{1},\ \frac{1}{3})$
sleptons, leptons	L	$(\widetilde{\nu}\ \widetilde{e}_L)$	$(\nu\ \ e_L)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ -\frac{1}{2})$
($\times 3$ families)	$\overline{e}$	$\widetilde{e}^*_R$	$e^\dagger_R$	$(\,\mathbf{1},\ \mathbf{1},\ 1)$
Higgs, higgsinos	H_u	$(H_u^+\ \ H_u^0)$	$(\widetilde{H}_u^+\ \ \widetilde{H}_u^0)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ +\frac{1}{2})$
	H_d	$(H_d^0\ \ H_d^-)$	$(\widetilde{H}_d^0\ \ \widetilde{H}_d^-)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ -\frac{1}{2})$

Chiral supermultiplets in the Minimal Supersymmetric Standard Model. The spin-0 fields are complex scalars, and the spin-1/2 fields are left-handed two-component Weyl fermions.

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

Gauge supermultiplets in the Minimal Supersymmetric Standard Model.

R parity

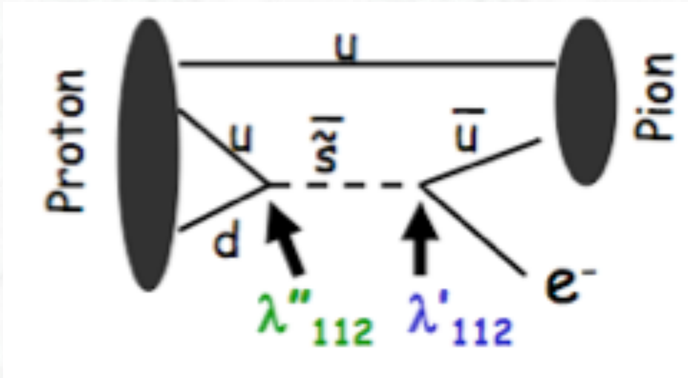
- New terms in the Lagrangian:

$$W_{RPV} = \frac{1}{2}\left(\lambda_{ijk} LLE + \underbrace{\lambda'_{ijk} LQD}_{\text{L-violating}} + \underbrace{\lambda''_{ijk} UDD}_{\text{B-violating}}\right) + \mu LH$$

- Contains L- and B-violating terms

- Problem: these couplings lead to proton decay,
  with high rates compared to present experimental limits
  (τ_p > ~ 10^{33} years)

  → strong limits on product of couplings



Protect theory by introducing a multiplicative quantum number R

Experimental consequences of R-parity conservation:

- SUSY particles are produced in pairs
- Lightest Supersymmetric Particle (LSP) is stable.

LSP is only weakly interacting:
LSP $\equiv \chi^0_1$ (lightest neutralino, in many models)

$\rightarrow$ LSP behaves like a ν $\rightarrow$ it escapes detection

$\rightarrow$ E_T^{miss} (typical SUSY signature)

SUSY breaking: → Gian Giudice

- Supersymmetry cannot be an exact symmetry, since we have not seen SUSY particles with masses equal to the Standard Model particles

- It is expected that supersymmetry is broken spontaneously

- The mechanism of SUSY breaking is not known

  Our ignorance is parametrized by introducing extra terms that break SUSY explicitly (so called soft SUSY breaking terms*) into the Lagrangian and consider it as an “effective” Lagrangian

- → about 105 parameters are introduced:
  masses, couplings, mixing angles…..

*) only such terms are allowed that guarantee that no new quadratically divergent radiative corrections appear

If one assumes universality for all masses and couplings at the GUT scale, the following five parameters suffice to characterize the so called mSUGRA/cMSSM
(constrained Minimal Supersymmetric Standard Model)

<u>Five parameters:</u>

m_0, $m_{1/2}$	particle masses at the GUT scale
A_0	common coupling term
$\tan\beta$	ratio of vacuum expectation value of the two Higgs doublets
μ	Higgs mass term

Sparticle Masses and Mixing

(i) Sfermions:

- Each flavour of charged lepton or quark has both left- and right handed components, $f_{L,R}$ and these have separate spin-0 boson superpartners $f'_{LR.}$
- The superpartners can mix, and the mass matrix in the MSSM is given by:

$$M^2_{\tilde{f}} \equiv \begin{pmatrix} m^2_{\tilde{f}_{LL}} & m^2_{\tilde{f}_{LR}} \\ m^2_{\tilde{f}_{LR}} & m^2_{\tilde{f}_{RR}} \end{pmatrix}$$

where the off-diagonal mixing terms take the general form (with m_f being the corresponding fermion mass).

$$m^2_{\tilde{f}_{L,R}} = m_f \left(A_f + \mu^{\tan\beta}_{\cot\beta} \right) \quad \text{for} \quad f =^{e,\mu,\tau,d,s,b}_{u,c,t}$$

- Since mixing effects are proportional to the SM fermion masses, they are in particular important for third generation sfermions. They are as well enhanced for large tan β.
- Diagonalization of this mass matrix leads to the physical SUSY particle masses. Mixing might split the two states in mass, usually referred to as the lighter f'_1 and the heavier state f'_2.

Sparticle Masses and Mixing

(ii) Charginos:

- Charginos are the supersymmetric partners of the $W^{\pm}$ and charged Higgs bosons $H^{\pm}$.

  Their masses are determined via the parameters: $M_{2,}$ μ and tan β, via the mass mixing matrix M_C:

$$-\frac{1}{2}\,(\tilde{W}^-,\tilde{H}^-)\;\; M_C\;\; \begin{pmatrix}\tilde{W}^+\\ \tilde{H}^+\end{pmatrix}\;\; +\;\; \text{herm.conj.}$$

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

where M_2 is the unmixed SU(2) gaugino mass and μ is the Higgs mass parameter.

Sparticle Masses and Mixing

(ii) Neutralinos:

- Masses of neutralinos, the supersymmetric partners of the neutral fields

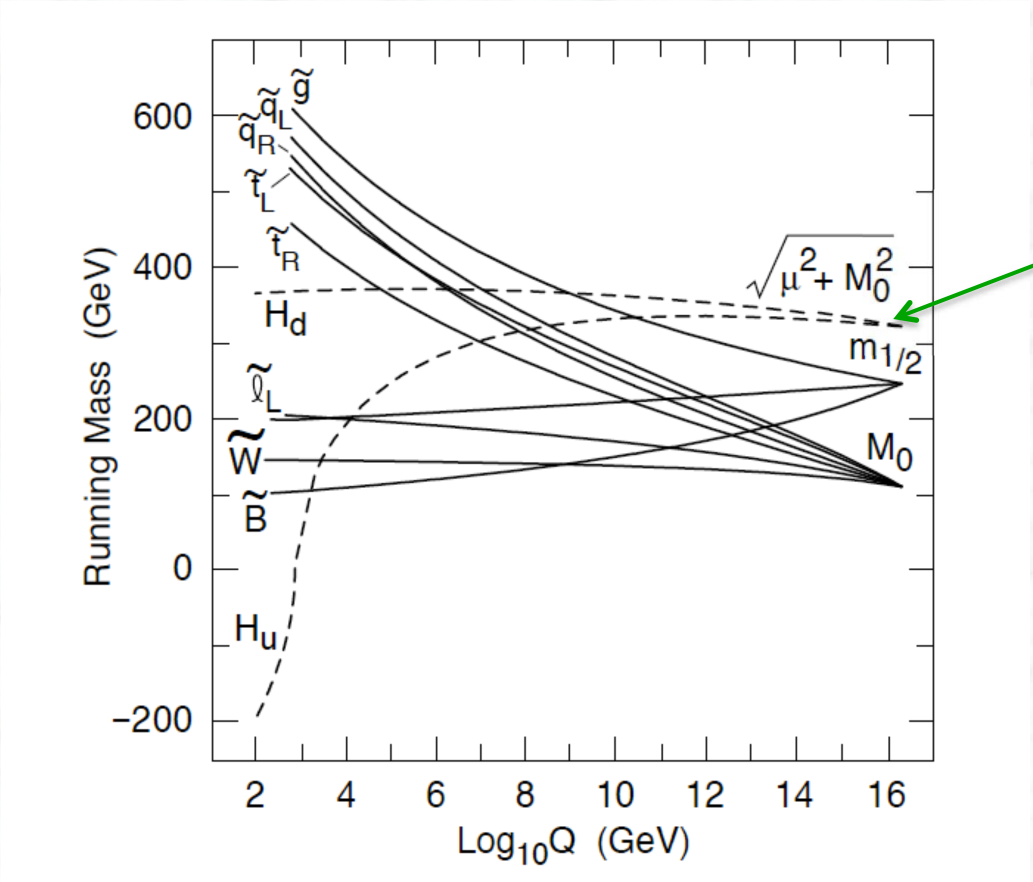
$(\tilde{W}^3, \tilde{B}, \tilde{H}_2^0, \tilde{H}_1^0)$

are given by the following mixing matrix:

$$m_N = \begin{pmatrix} M_2 & 0 & \frac{-g_2 v_2}{\sqrt{2}} & \frac{g_2 v_1}{\sqrt{2}} \\ 0 & M_1 & \frac{g' v_2}{\sqrt{2}} & \frac{-g' v_1}{\sqrt{2}} \\ \frac{-g_2 v_2}{\sqrt{2}} & \frac{g' v_2}{\sqrt{2}} & 0 & \mu \\ \frac{g_2 v_1}{\sqrt{2}} & \frac{-g' v_1}{\sqrt{2}} & \mu & 0 \end{pmatrix}$$

where M_1, M_2 is the unmixed U(1), SU(2) gaugino mass, μ is the Higgs mass parameter, and g_2 and g' are the gauge couplings of the SU(2) / U(1) group.

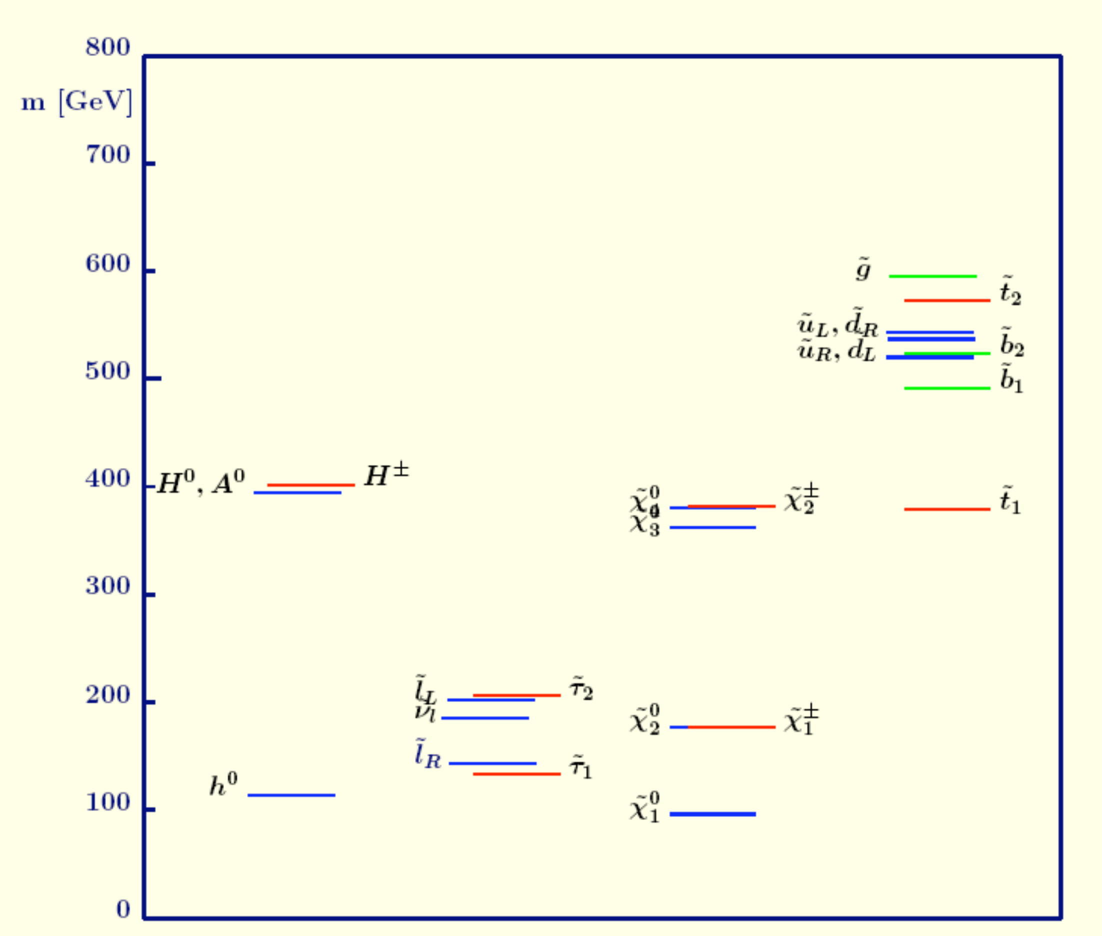
The energy dependence of the SUSY particle masses can be calculated (renormalization group equations)



In this example a separate Higgs mass term is used at the GUT scale

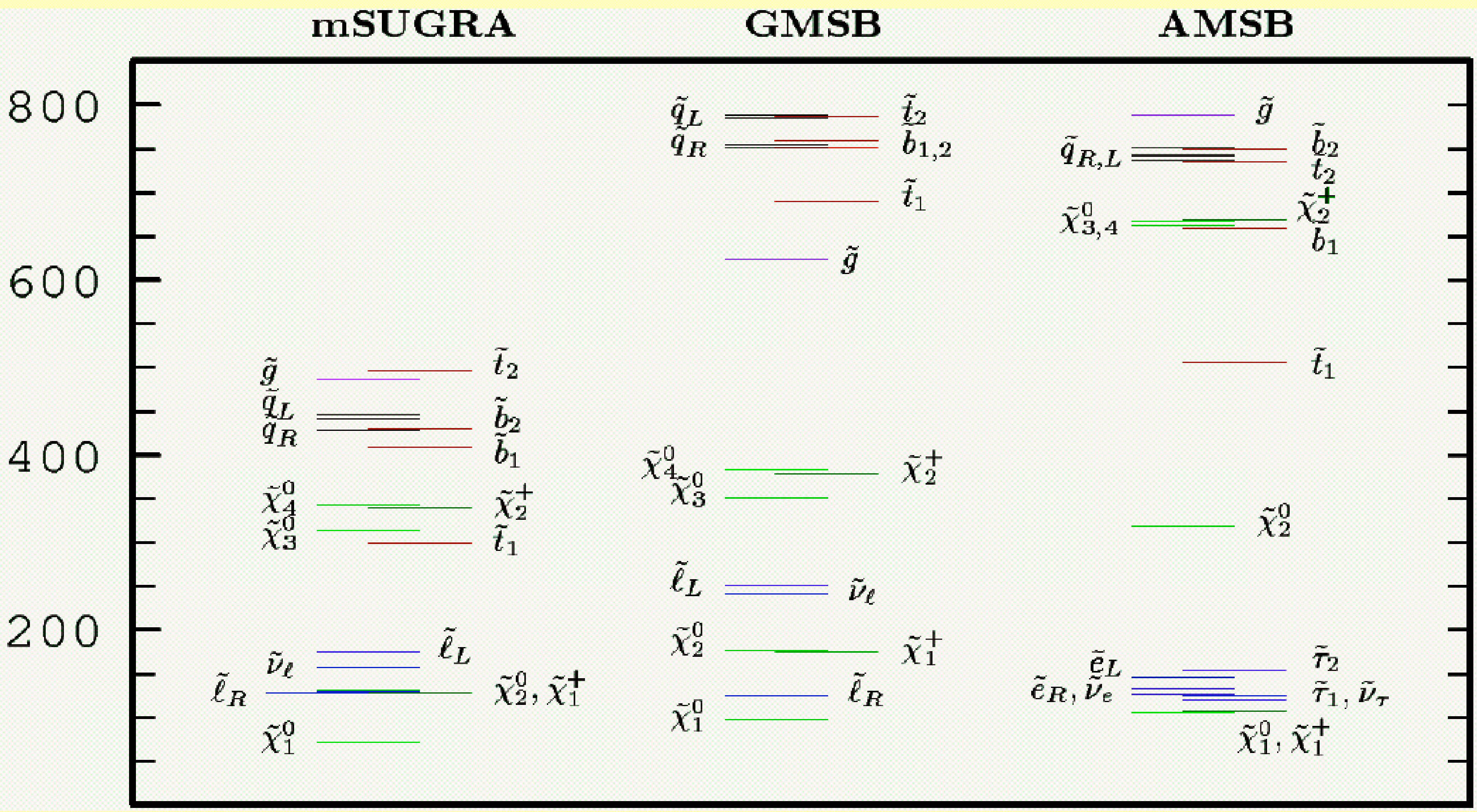
- In such models, squarks and/or gluinos are the heaviest sparticles
- Stops might be the lightest squarks
- Mixing effects (see later) can lead to mass splitting between t_L and t_R
- Sleptons / charginos / neutralinos are lightest sparticles

Example for a calculated mass spectrum at the electroweak scale:



- In many models, the lightest neutralino is the lightest SUSY particle (LSP)
- Lightest Higgs boson (h^0) might also be light, split from heavier Higgs particles
- Production of SUSY particles at the LHC is dominated by coloured squarks and gluinos

SUSY mass spectra for different SUSY breaking models:



mSUGRA: minimal SUperGRAvity model (gravity responsible for SUSY breaking)
GMSB: Gauge mediated SUSY Breaking (breaking via gauge interactions)
AMSB: Anomaly mediated SUSY Breaking

Link to the Dark Matter in the Universe ?

Parameters of the SUSY model $\Rightarrow$ predictions for the relic density of dark matter

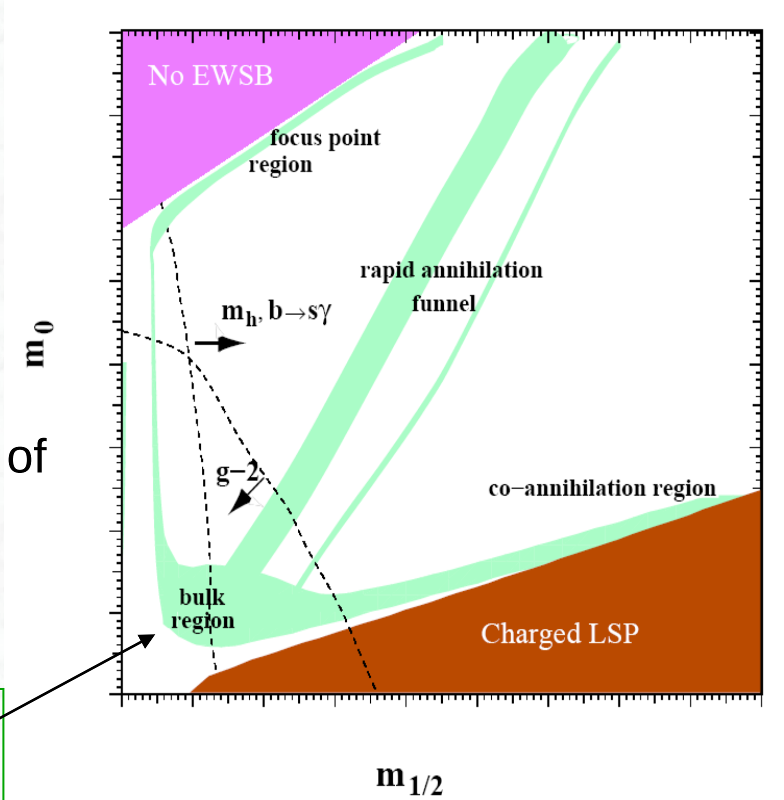
$$\rho_\chi \sim m_\chi n_\chi , \quad n_\chi \sim \frac{1}{\sigma_{ann}(\chi\chi \to \ldots)}$$

Interpretation in a simplified model

cMSSM
(constrained Minimal Supersymmetric
Standard Model)

Five parameters:

m_0, $m_{1/2}$ particle masses at the GUT scale
A_0 common coupling term
tan β ratio of vacuum expectation value of the two Higgs doublets
μ (sign μ) Higgs mass term



regions of parameter space which are consistent with the measured relic density of dark matter (WMAP,…..)

Summary of pre-LHC limits on SUSY masses

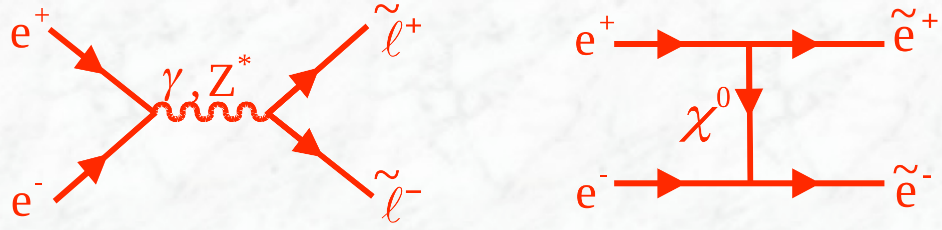
The Search for

SUSY at LEP and at the Tevatron

Direct searches for sleptons at LEP

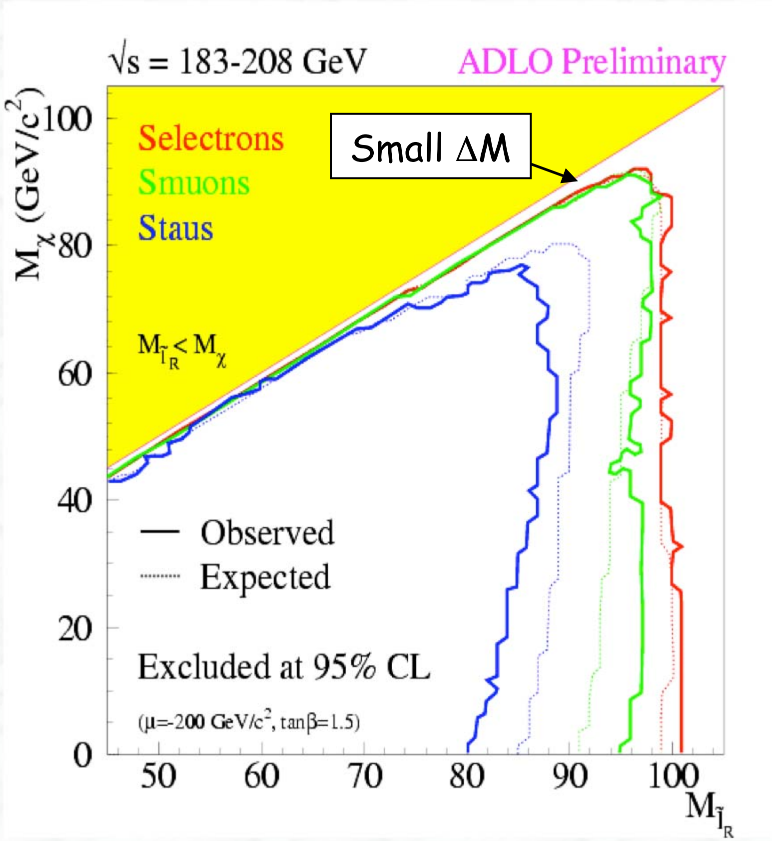
- Clear domain of LEP are
  Slepton & Chargino/Neutralino
  searches (e^+e^-, E_{cm}~ 200 GeV)

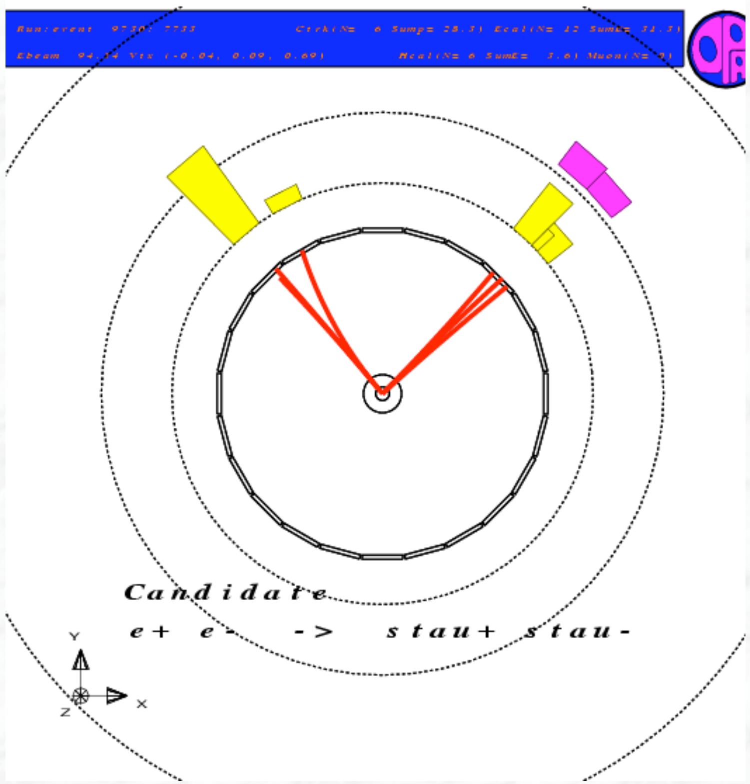
→ Excluded up to masses of
  80 … 100 GeV (~ $E_{cm}/2$)



$\tilde{\ell} \to \ell\, \chi^0_1$ **(2 leptons + missing E)**

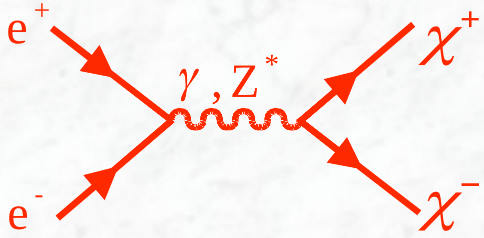
OPAL stau event candidate





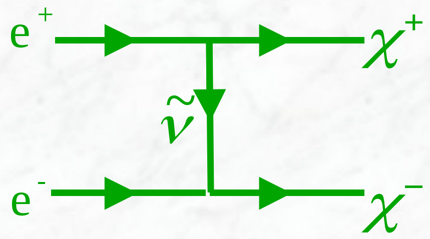
Direct searches for charginos at LEP

Large m_0 ($\tilde{\ell}$ are heavy)



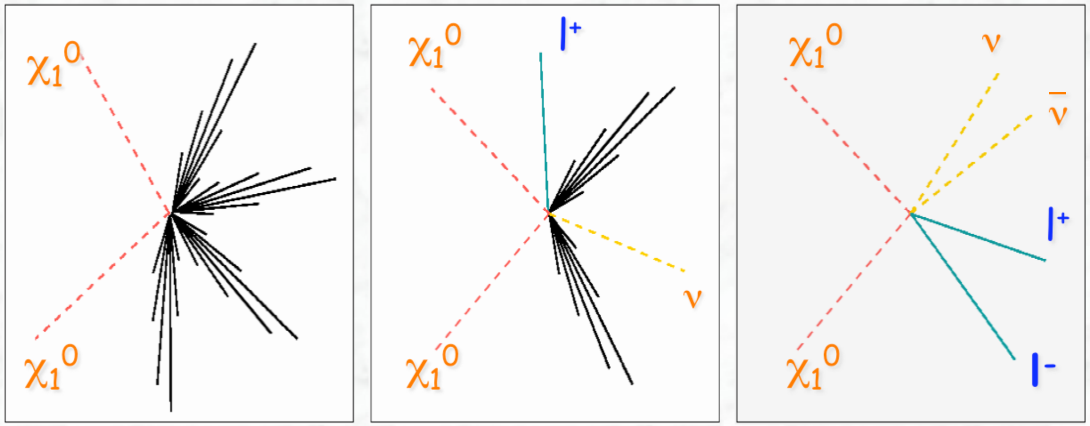
$$\chi^+\chi^- \rightarrow W^*\chi^0{}_1 W^*\chi^0{}_1$$

Small m_0 ($\tilde{\ell}$ are light)



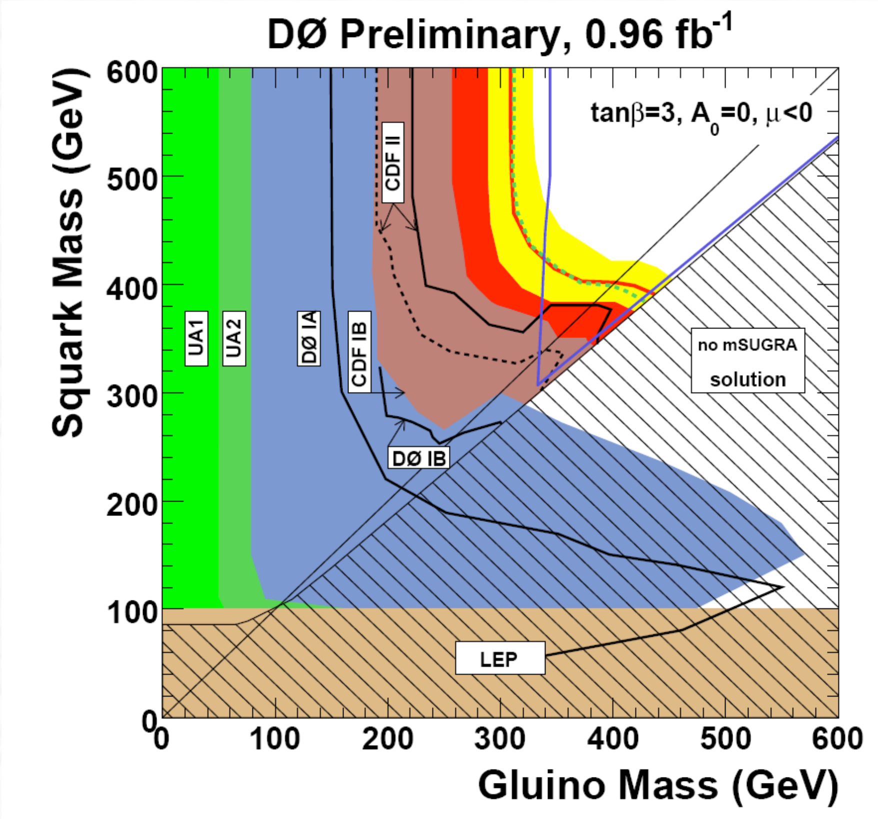
$$\chi^+\chi^- \rightarrow \ell^+\tilde{\nu}\,\ell^-\tilde{\nu} \rightarrow \ell^+\nu\chi^0{}_1\,\ell^-\nu\chi^0{}_1$$

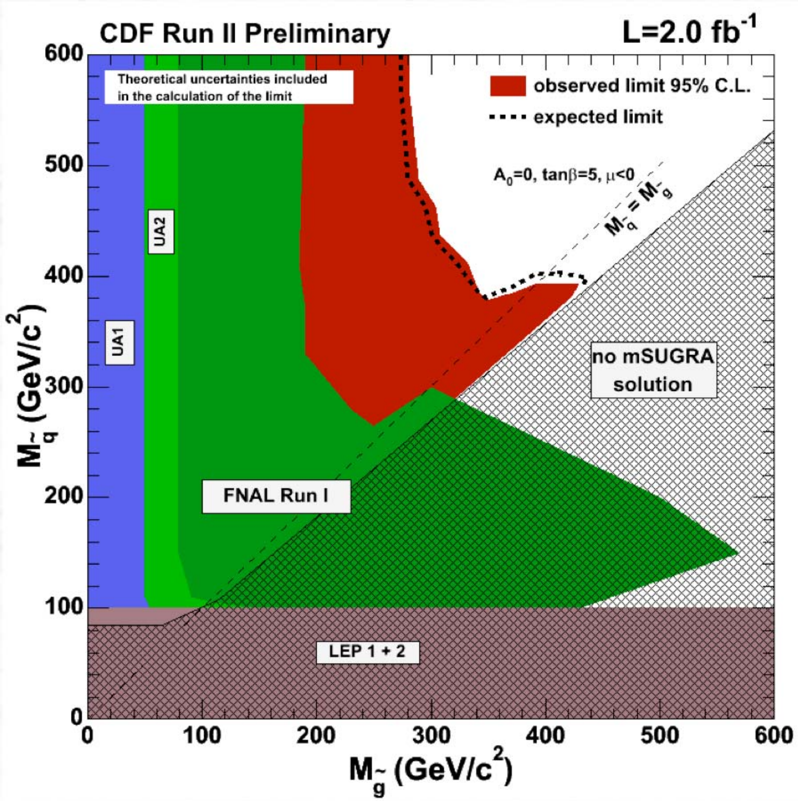
WW → qqqq　　WW → lνqq　　WW → lν lν



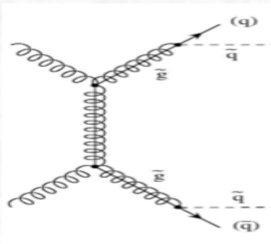
Main SM backgrounds (WW, ZZ production) suppressed by requiring large missing mass or missing energy in the event.

Excluded regions in the m(squark) vs. m(gluino) plane





Exclusion limits
(incl. systematic uncertainties)*:
m(gluino) > 290 GeV/c^2
m(squark) > 375 GeV/c^2

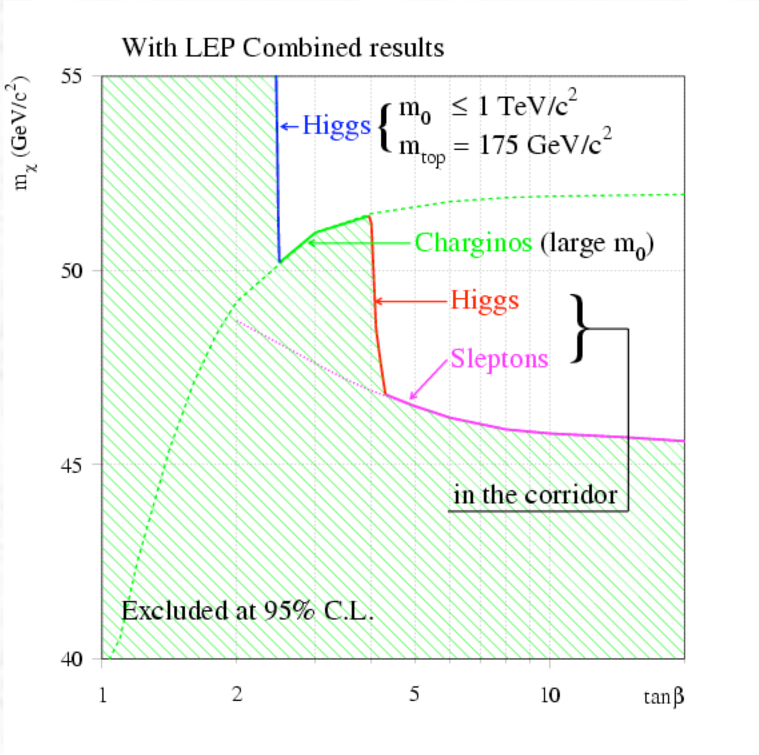


Production via strong interaction

)* uncertainties from structure functions, change of renormalization and factorization scale μ by a factor of 2, NLO calculation, default choice: μ = m(gluino), m(squark) or ½(m(gluino)+m(squark)) for gg, qq, qg production

Summary of pre-LHC **SUSY mass limits** from colliders

m (sleptons, charginos)	>	90-103 GeV	LEP II
m (squarks, gluinos)	>	~ 350 GeV	Tevatron
m (LSP, lightest neutralino)	>	~ 45 GeV	LEP II



LEP-II limit on the mass of the Lightest SUSY particle

assumption:
lightest neutralino = LSP