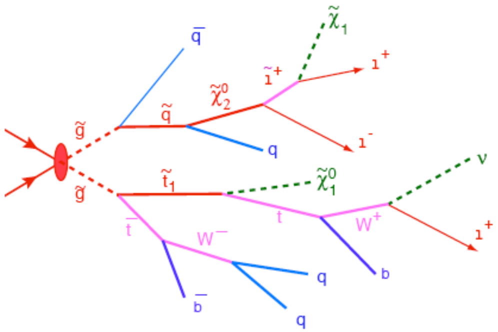
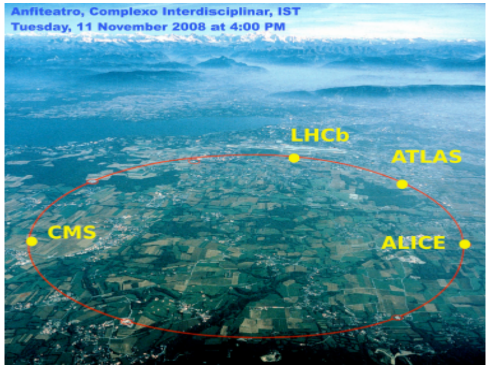
Search for SUSY at the LHC in 2010



Oliver Buchmüller
Imperial College London



- *Why is SUSY so attractive?*
- *Early "SUSY" searches at the LHC*
- *Making sense out of what we will see*

Cracow-Warsaw Workshop on LHC 15/01/2010

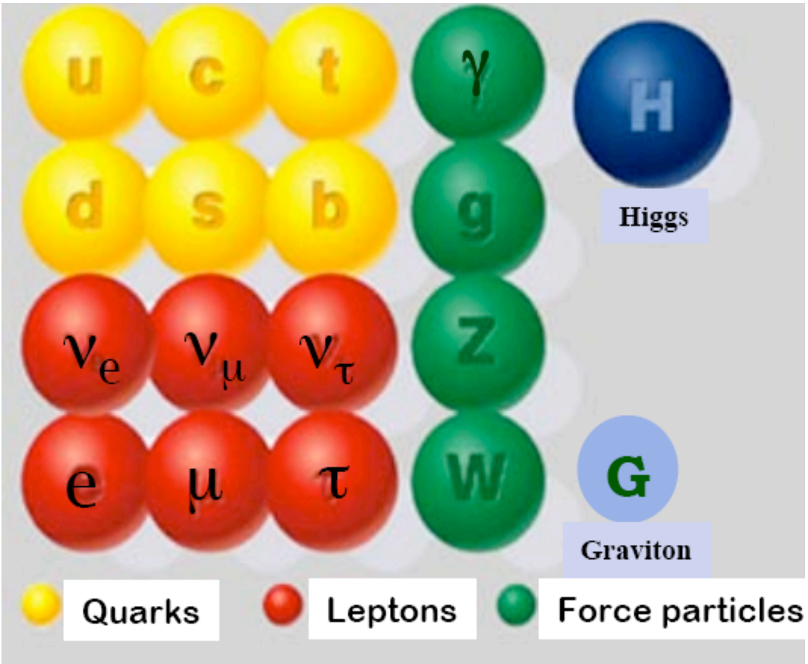
Imperial College London

Why is SUSY so attractive?

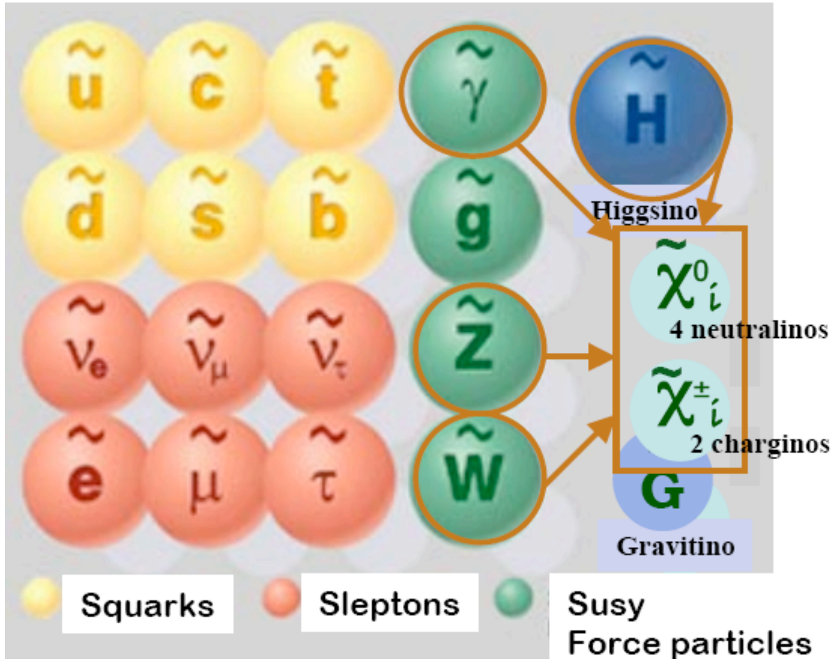
Supersymmetry

Extension of the Standard Model: Introduce a new symmetry
Spin ½ matter particles (fermions) ⇔ Spin 1 force carriers (bosons)

Standard Model particles



SUSY particles



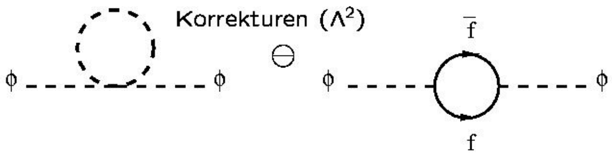
New Quantum number: R-parity: $R_p = (-1)^{B+L+2s}$ *= +1 SM particles*
- 1 SUSY particles

<u>R-parity conservation</u>:
- *SUSY particles are produced in pairs*
- *The lightest SUSY particle (LSP) is stable*

R-Parity – oft also called Matter Parity

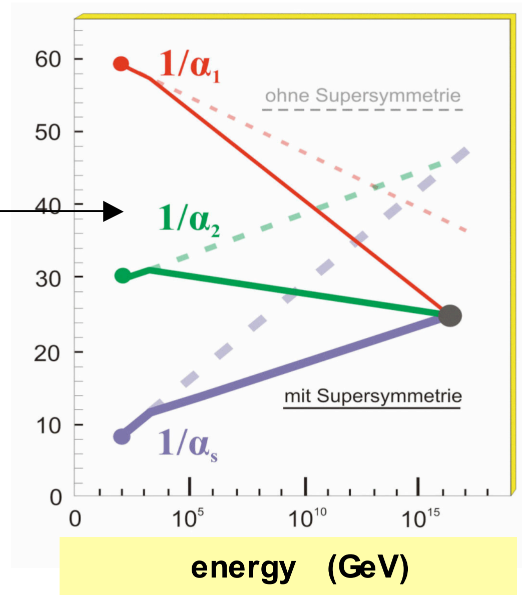
Why is SUSY so Attractive?

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

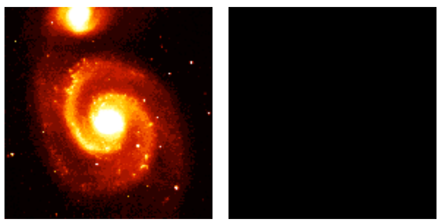


$\Delta m_H = f(m_B^2 - m_f^2)$ → m_{SUSY} ~ 1 TeV

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



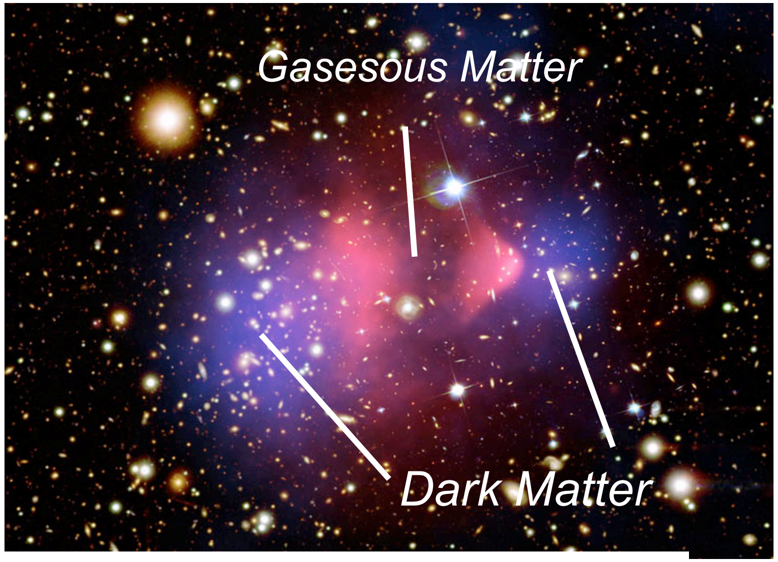
3. SUSY provides a candidate for dark matter,

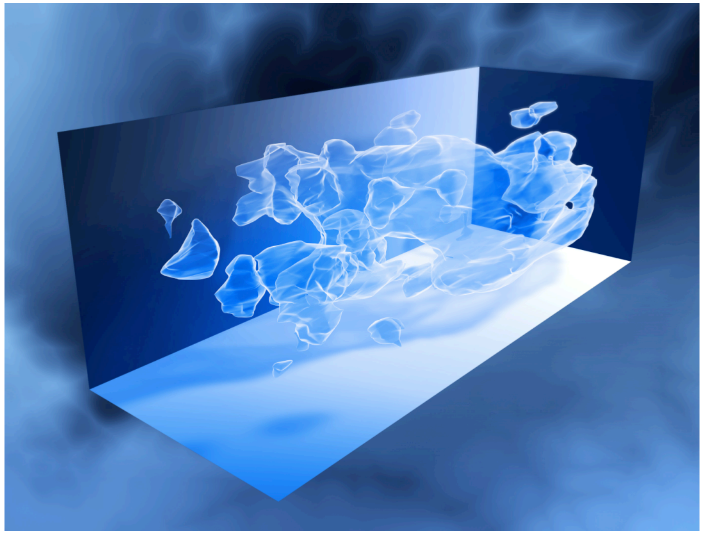


The lightest SUSY particle (LSP)

4. A SUSY extension of the SM is a small perturbation, consistent with all available precision data.

The Dark Side of the Universe: Illustrating Dark Matter





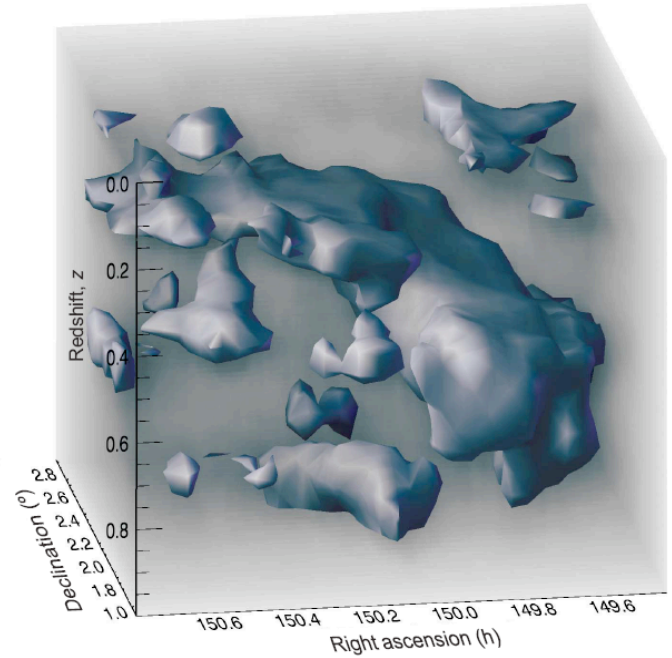
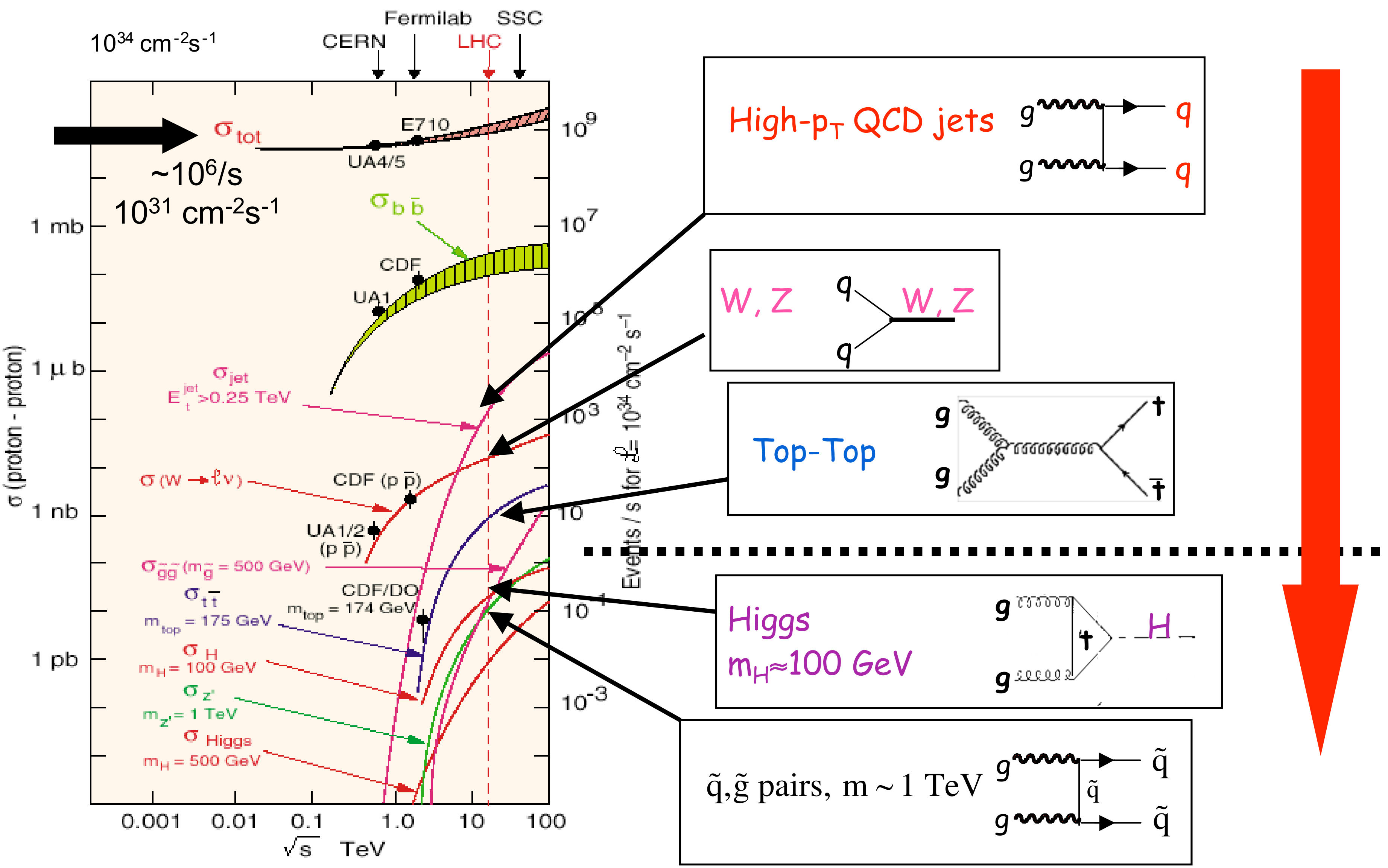


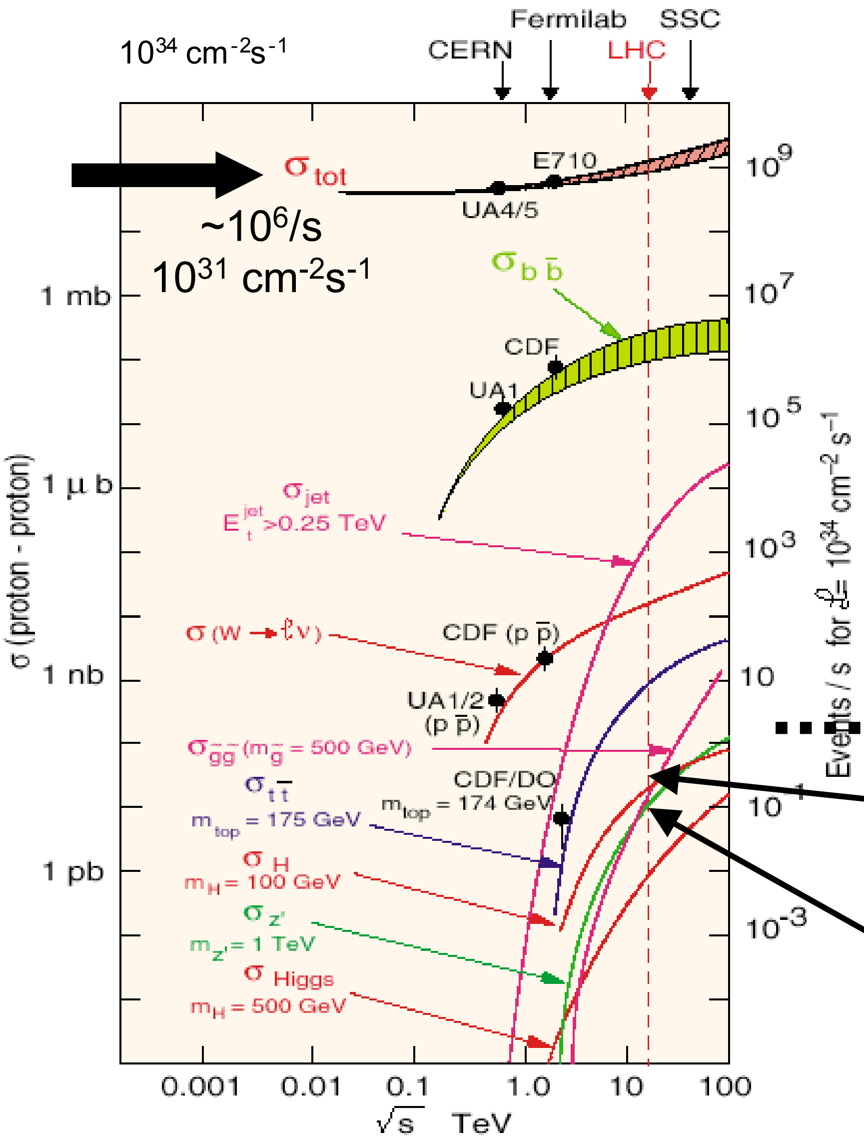
Figure 5 | **Three-dimensional reconstruction of the dark matter distribution.**

The Challenge

Background and Signal



Background and Signal

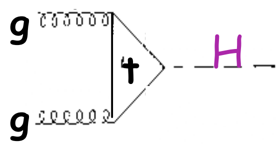


Searching for these events is like looking for a needle in a (very) big haystack:

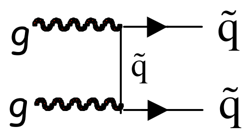
σ_{tot}	$\approx$ 100mb
Jets w. E_T>100 GeV	$\approx$ 1μb
ttar	$\approx$ 800pb

In order to find the "needle", we need to understand these processes very well (don't forget, additional hard jets only cost α_s/π ~0.1)

Higgs
m_H≈100 GeV

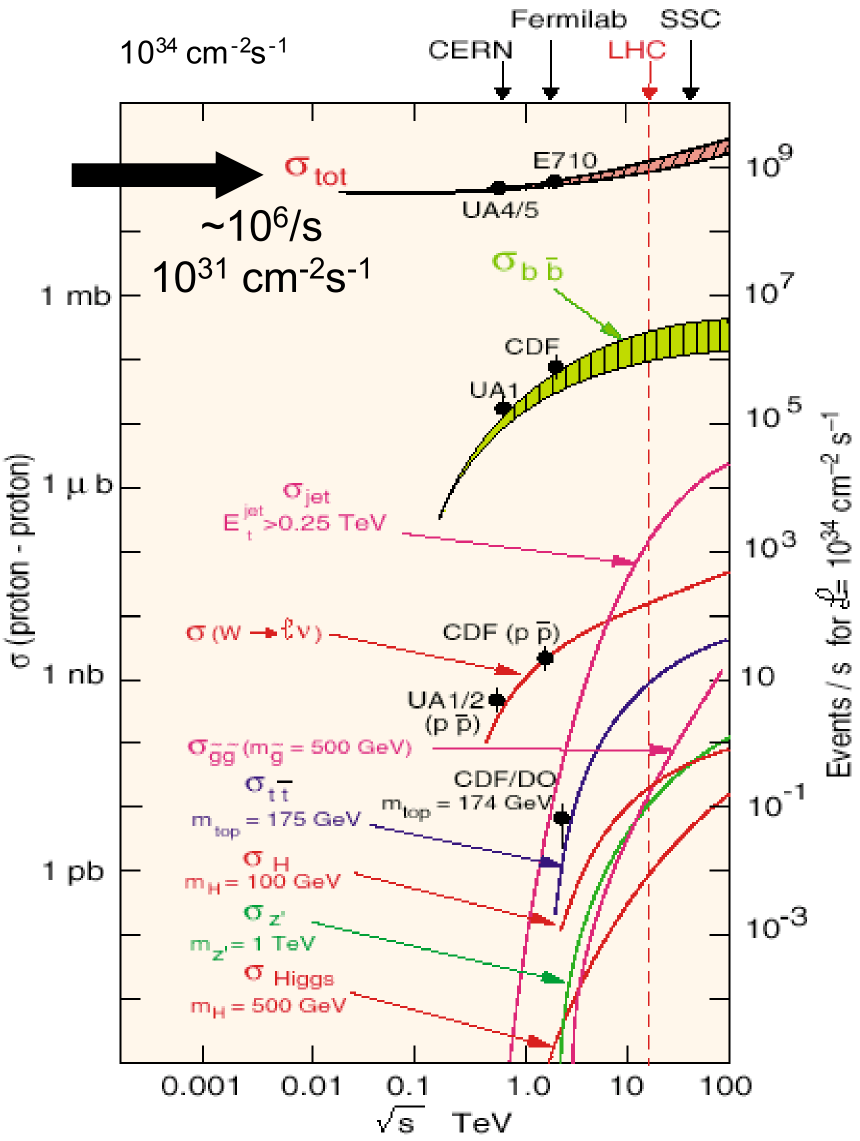


$\tilde{q},\tilde{g}$ pairs, m ~ 1 TeV



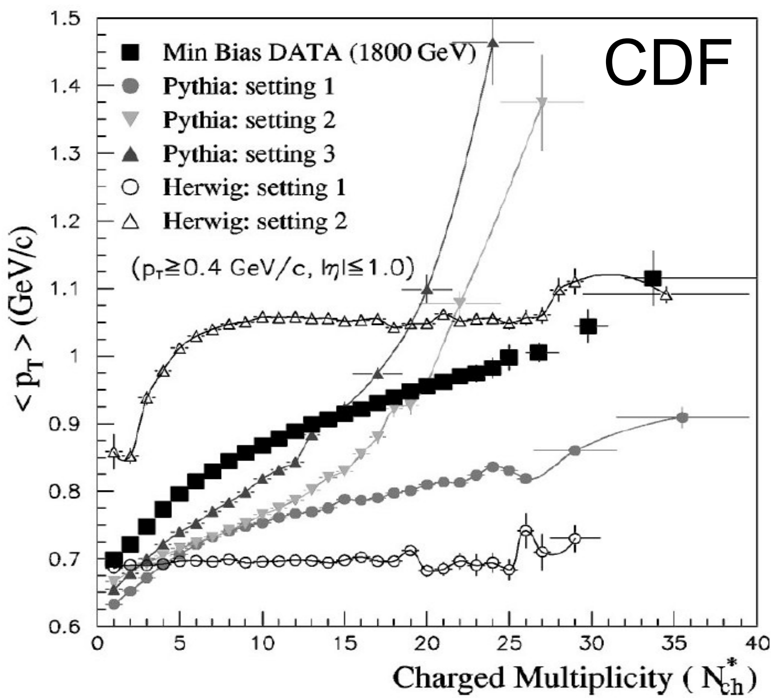
Building the Foundation for (SUSY) Searches

First Phase



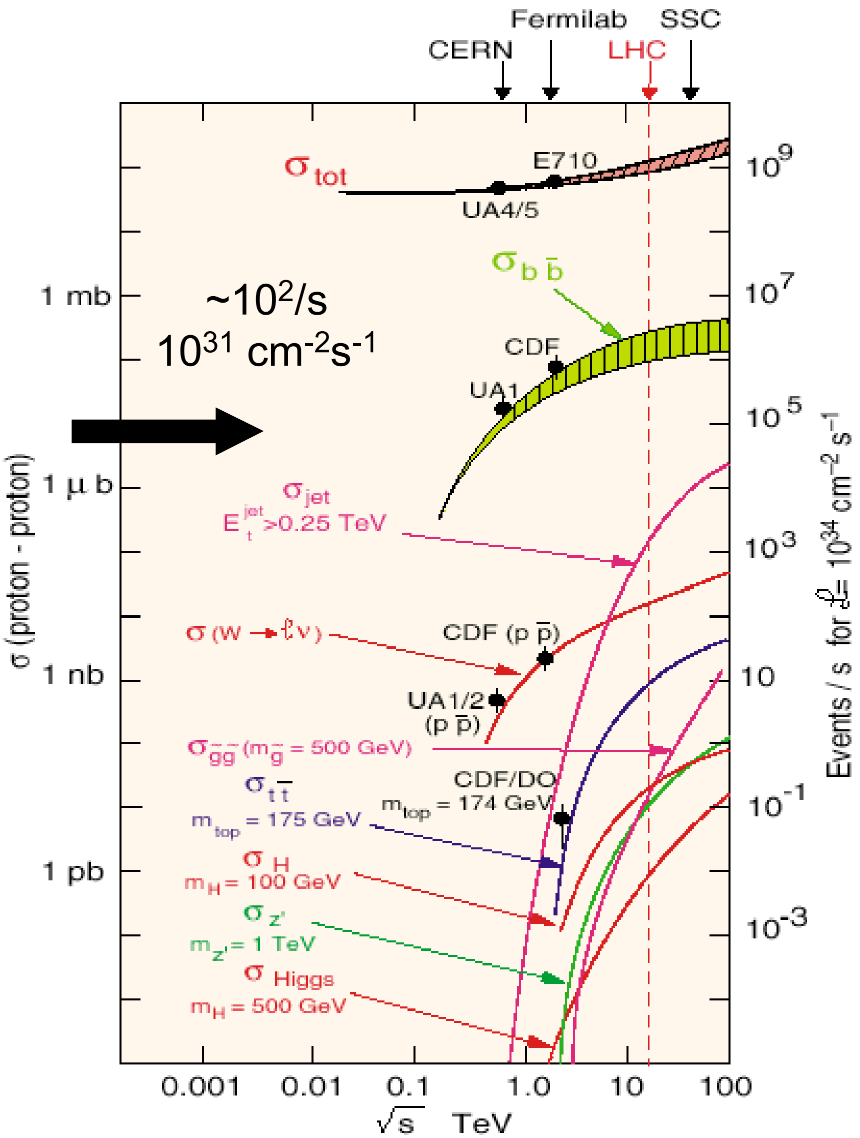
"Why":Measure
Charged Particle Density

- W,Z, ttbar cross sections known to ~3 to 10%
- Large uncertainties in minimum bias **$dN_{ch}/d\eta$** known to only ~50% (or worse)



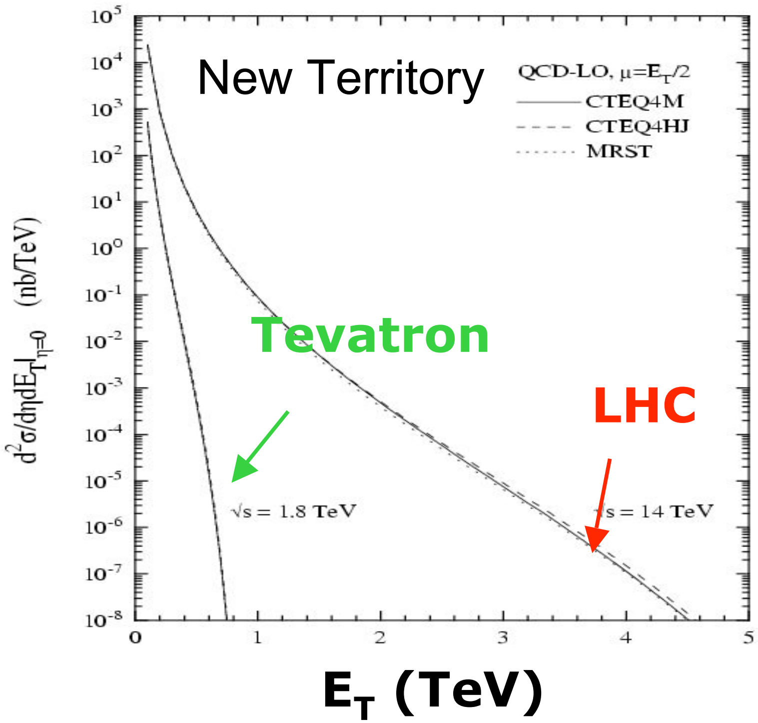
Precise knowledge of $dN_{ch}/d\eta$ very important for *MC tuning, understanding underlying event*, pile-up etc.

Second Phase

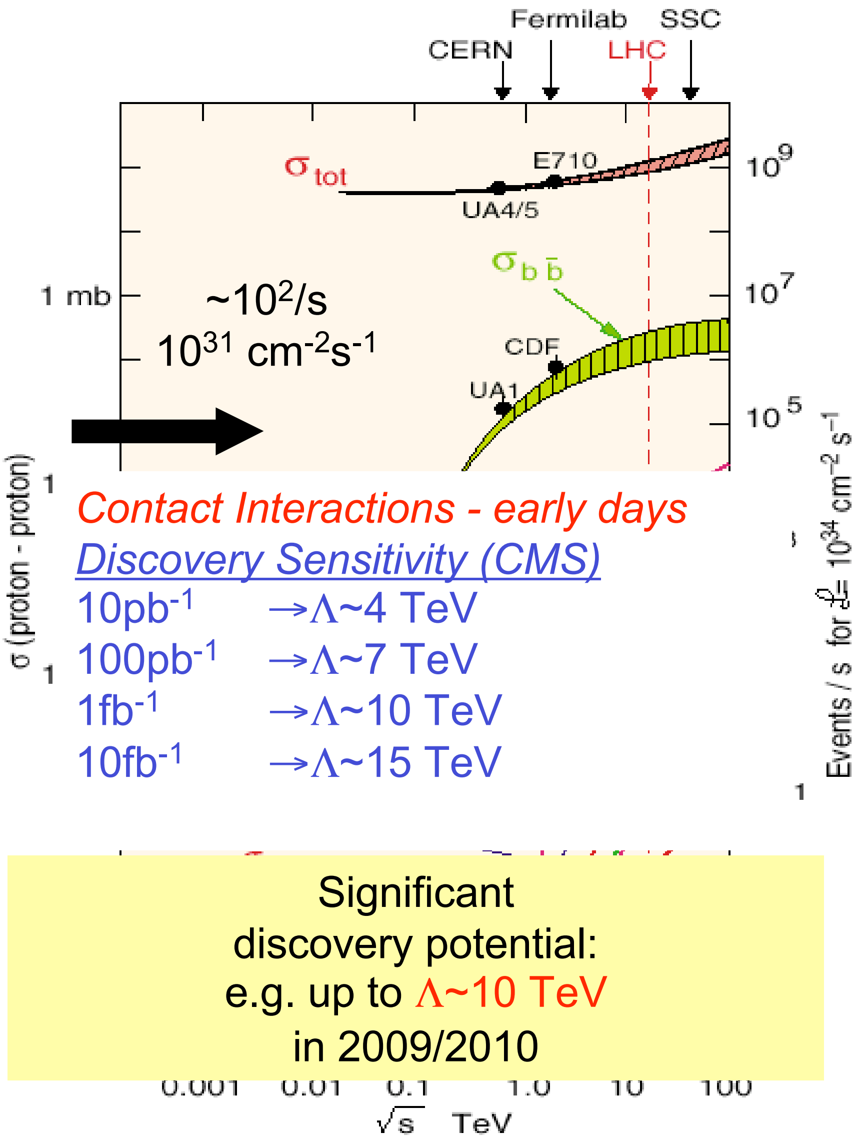


Measure Jet Cross Section

- E_T^{Jet} > 500 GeV after a few weeks at $10^{31}cm^{-2}s^{-1}$
- Going fast beyond the reach of the Tevatron
- Early sensitivity to compositeness requires understanding of the jet energy scale, PDF's, …



Second Phase



Contact Interactions - early days

Discovery Sensitivity (CMS)

$10 pb^{-1}$ →Λ~4 TeV

$100 pb^{-1}$ →Λ~7 TeV

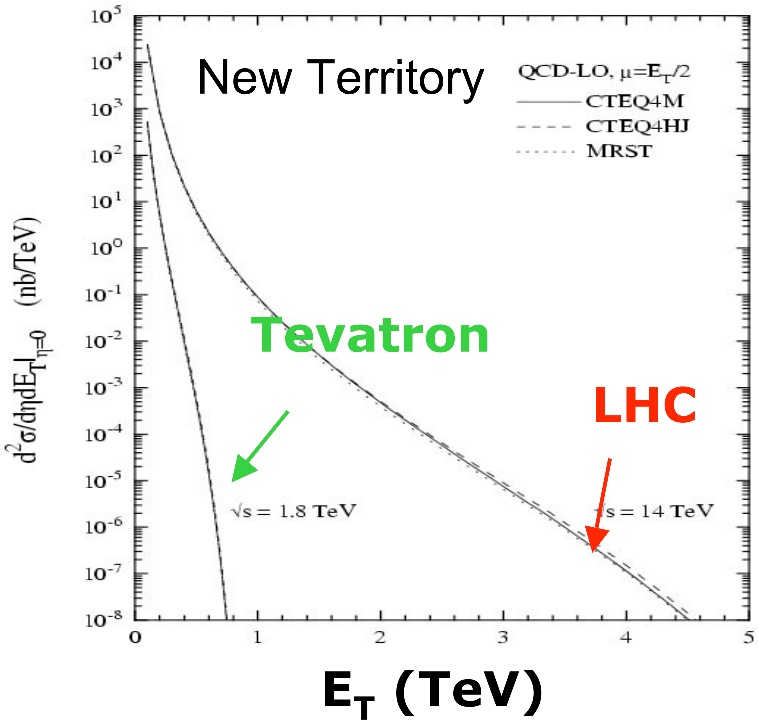
$1 fb^{-1}$ →Λ~10 TeV

$10 fb^{-1}$ →Λ~15 TeV

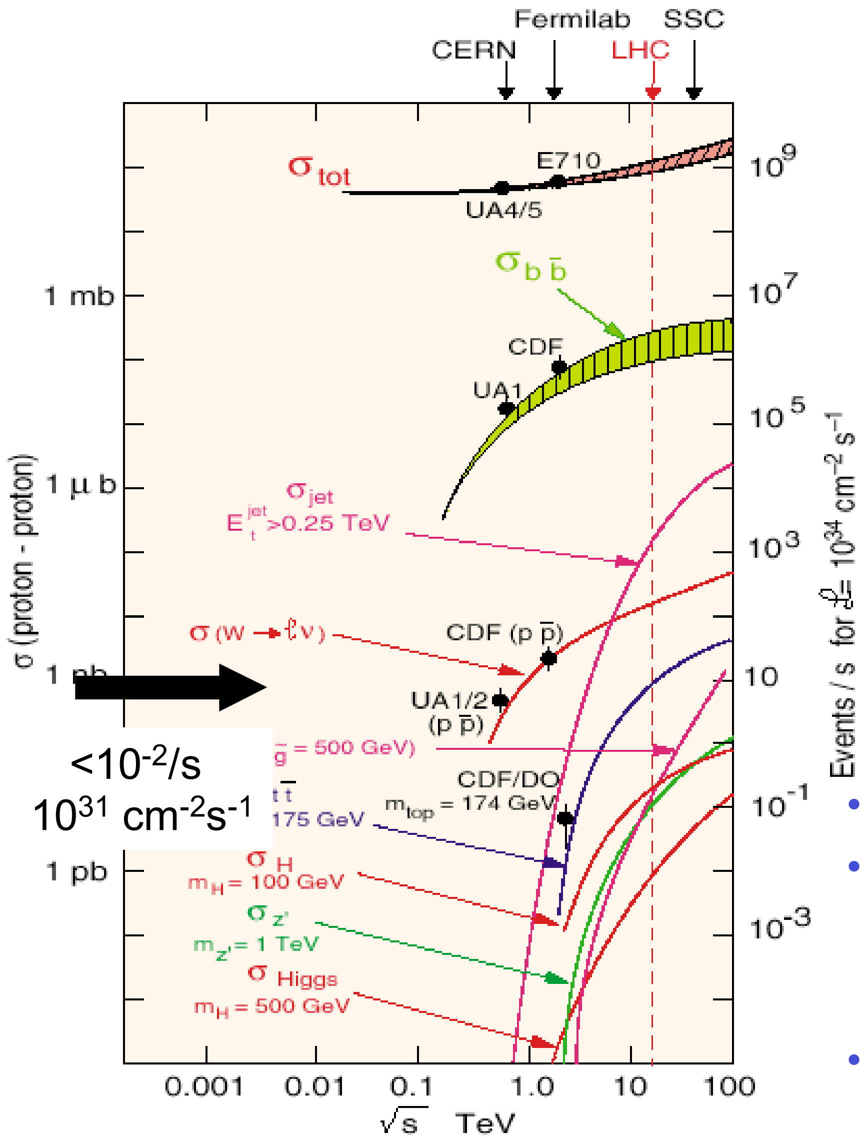
Significant discovery potential: e.g. up to Λ~10 TeV in 2009/2010

Measure Jet Cross Section

- E_T^{Jet} > 500 GeV after few weeks at $10^{31} cm^{-2}s^{-1}$
- Going fast beyond the reach of the Tevatron
- Early sensitivity to compositeness; requires understanding of the jet energy scale, PDF's, …



Third Phase



Rediscover the SM

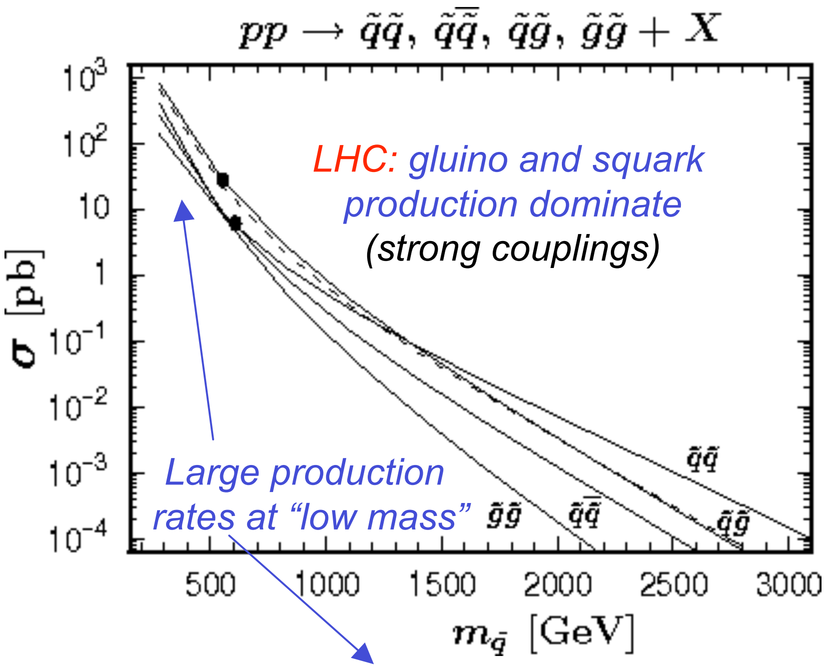
- Reestablish the Standard Model
- Most SM cross sections are significantly higher than at the Tevatron
  e.g. σ_{ttbar} (LHC)> 100 x σ_{ttbar} (Tevatron)
- Crucial for final Detector and Physics Commissioning

THE path to new physics!

Early SUSY Searches

Imperial College
London

SUSY Searches @ LHC

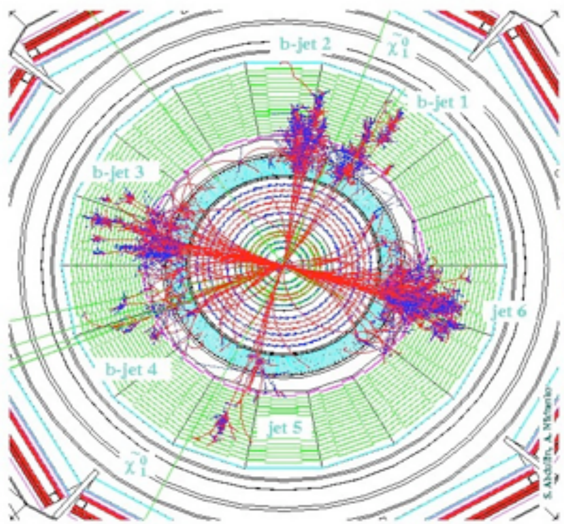


M_{sp}(GeV)	σ (pb)	Evts/yr
500	100	10^6-10^7
1000	1	10^4-10^5
2000	0.01	10^2-10^3

For low masses the LHC becomes a real ***SUSY factory***

Huge number of theoretical models

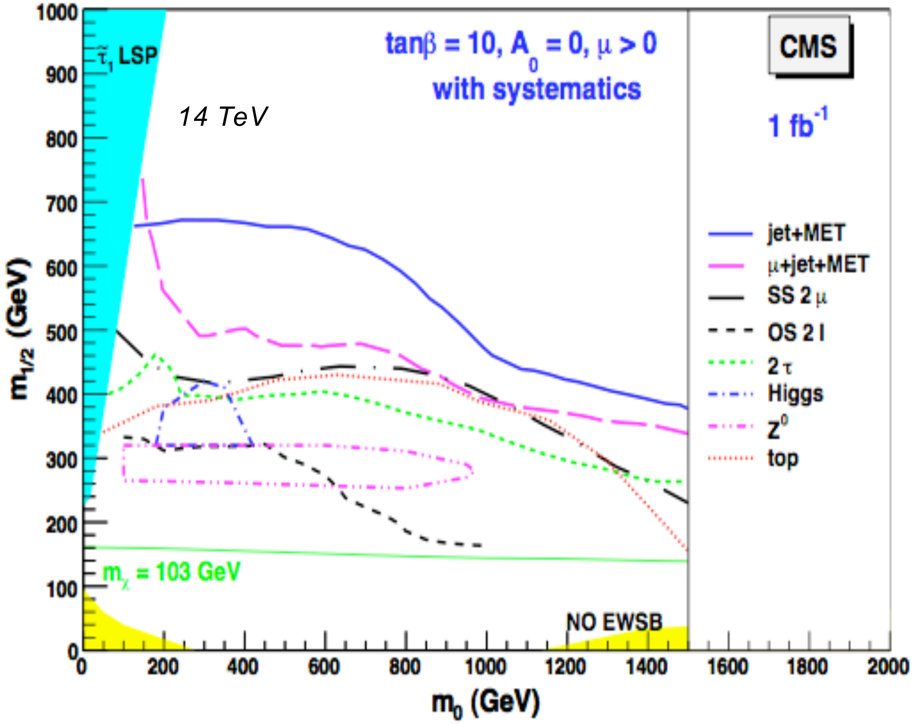
- Very complex analysis; MSSM >100 parameter
- To reduce complexity we have to choose some "reasonable", "typical" models; use a theory of dynamical SUSY breaking
  - mSUGRA (main model)
  - GMSB (studied in less detail)
  - AMSB (studied in less detail)
- Use models to study different SUSY signatures in the detector.

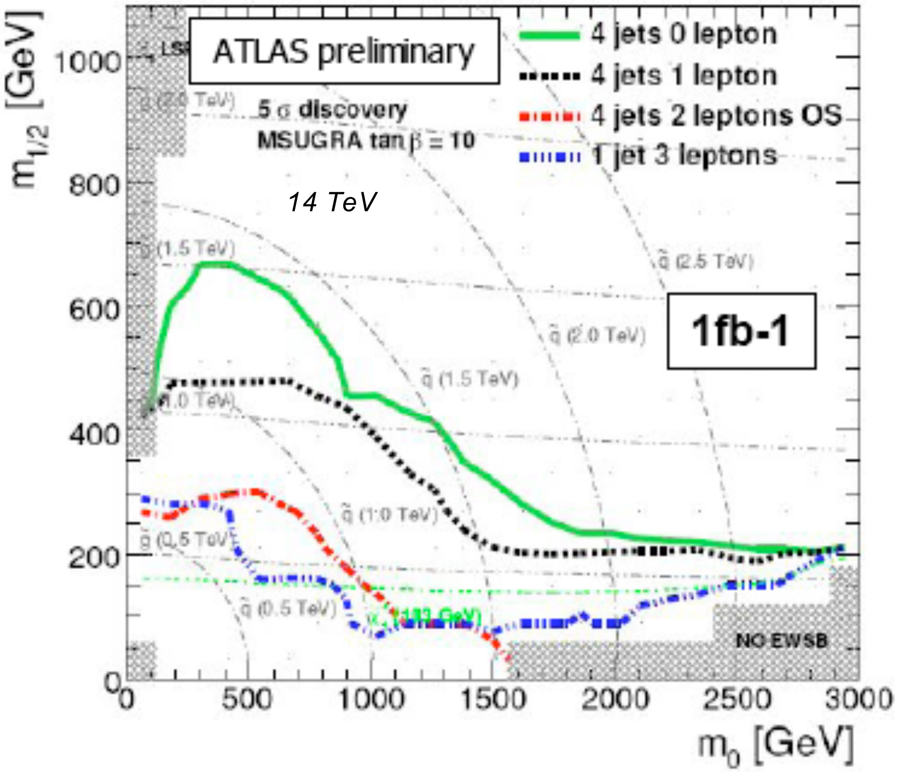


Clear signatures of large missing energy, hard jets and many leptons!
(assume R-Parity)

Could be very spectacular!

SUSY Discovery Potential - CMSSM





Discover Potential for "muli-jet, multi-lepton and missing energy search" is described in the CMSSM.

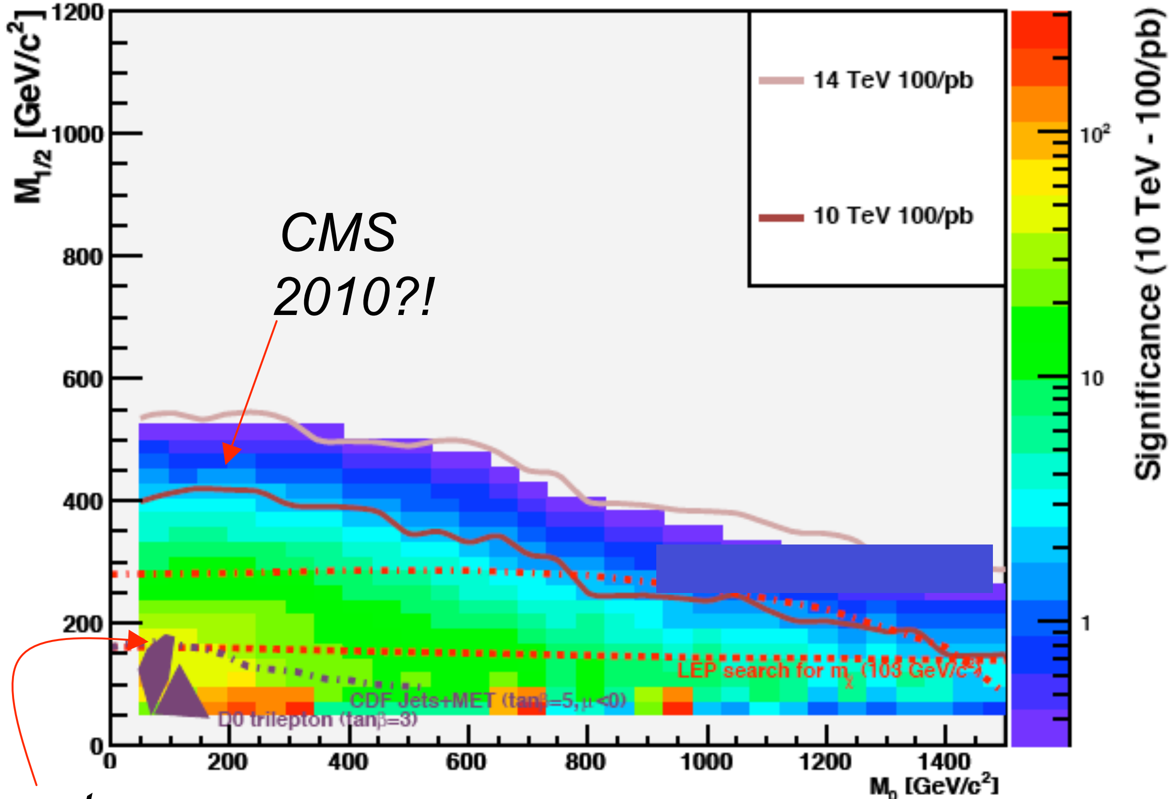
Both ATLAS and CMS have very similar performance (as expected).

First LHC Running 2010 - Expectations

Expectations are high!

With as little as ~50/pb @ 10 TeV or ~200/pb @ 7 TeV of (understood!) data we should be able to go significantly beyond the reach of the Tevatron!

All-hadronic Reach project to 10 TeV

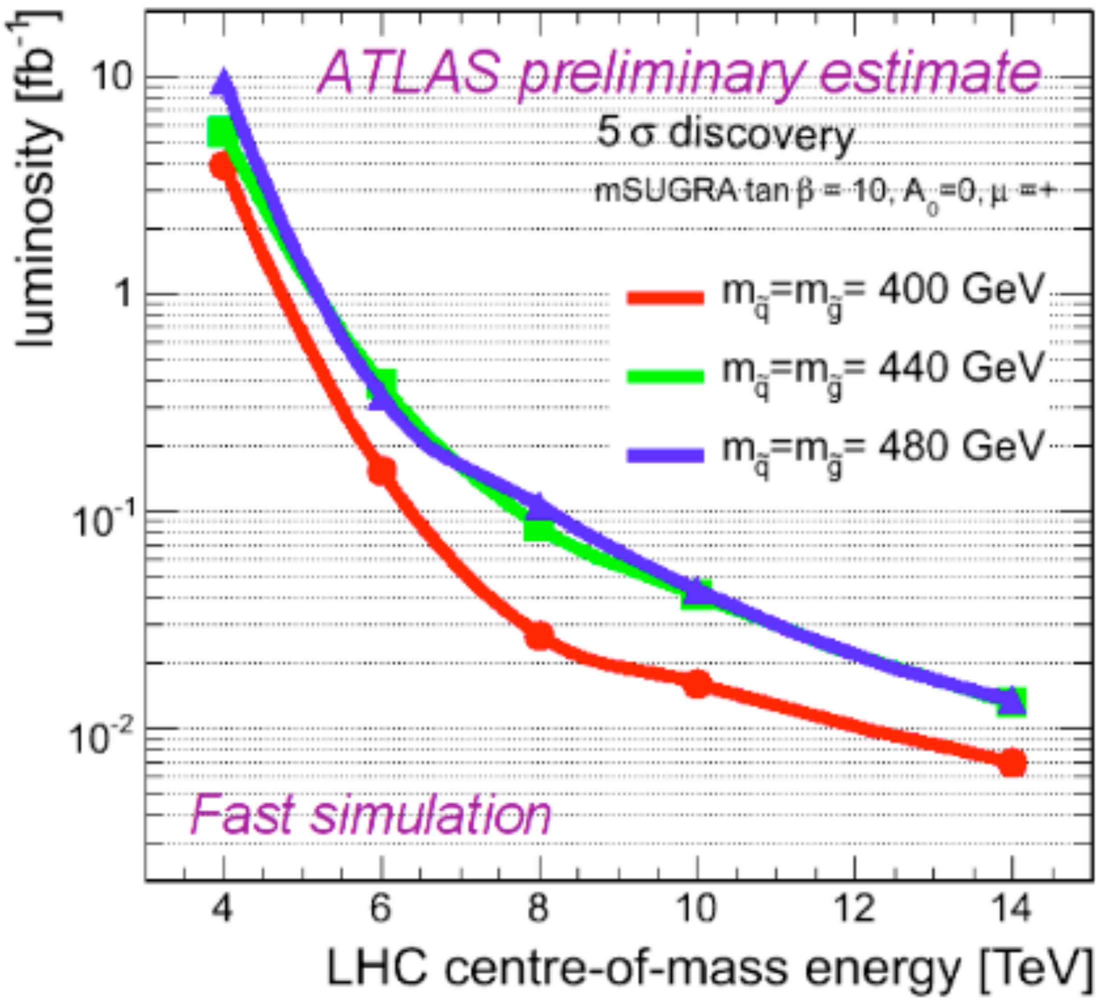


Tevatron Today

Simple rule of thumb:

1/pb @ 10 TeV equals approximately 3.5/pb @ 7 TeV

First LHC Running 2010 - Expectations



ATLAS study confirms CMS projection!

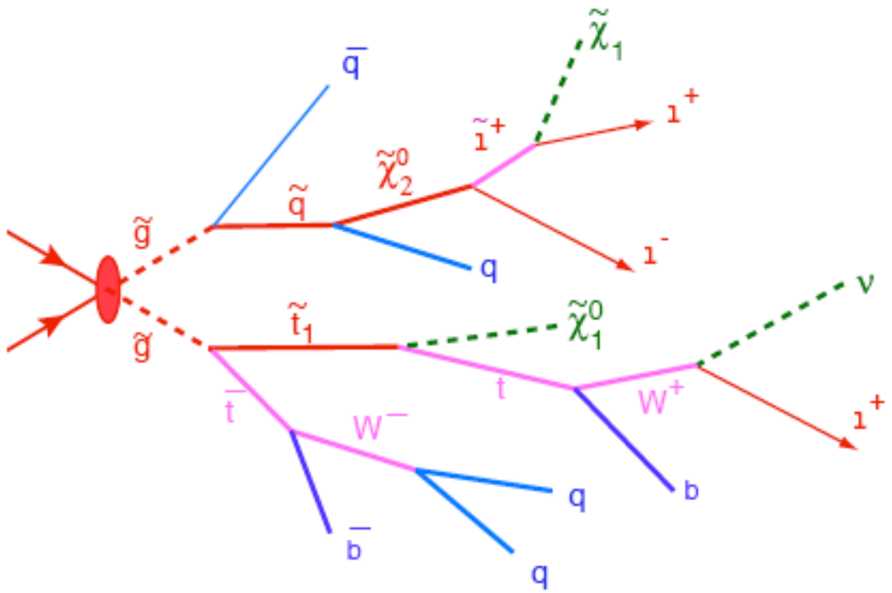
2010 promises to be an exciting year for (SUSY) searches

What do we call a "SUSY search"?

The definition is purely derived from the experimental signature.

Therefore, a "SUSY search signature" is characterized by

Lots of missing energy, many jets, and possibly leptons in the final state



Missing Energy:
- *from LSP*

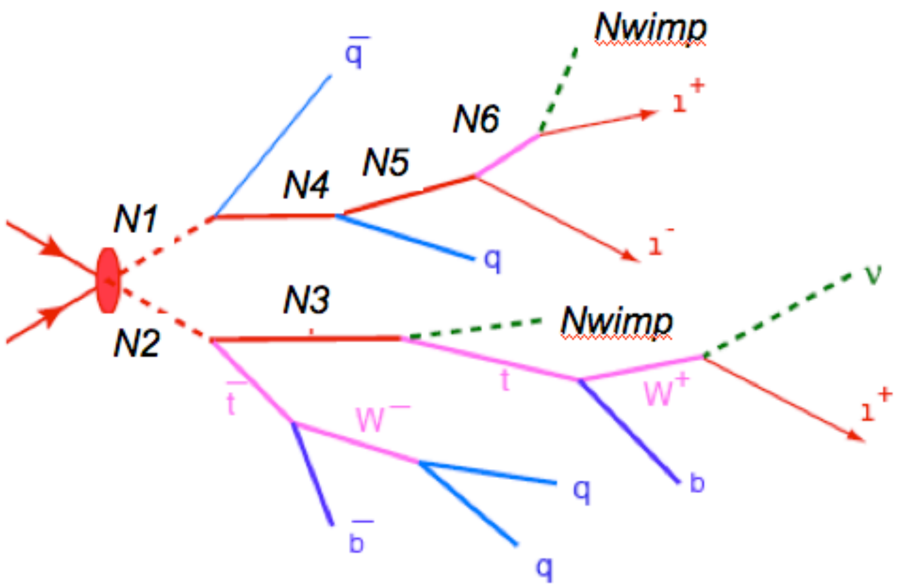
Multi-Jet:
- *from cascade decay (gaugino)*

Multi-Leptons:
- *from decay of charginos/neutralios*

RP-Conserving SUSY is a very prominent example predicting this famous signature but …

What is its experimental signature?

… by no means is it the only New Physics model predicting this experimental pattern. Many other NP models predict this genuine signature



Missing Energy:
• *Nwimp - end of the cascade*

Multi-Jet:
• *from decay of the Ns (possibly via heavy SM particles like top, W/Z)*

Multi-Leptons:
• *from decay of the N's*

Model examples are Extra dimensions, Little Higgs, Technicolour, etc
but a more generic definition for this signature is as follows.

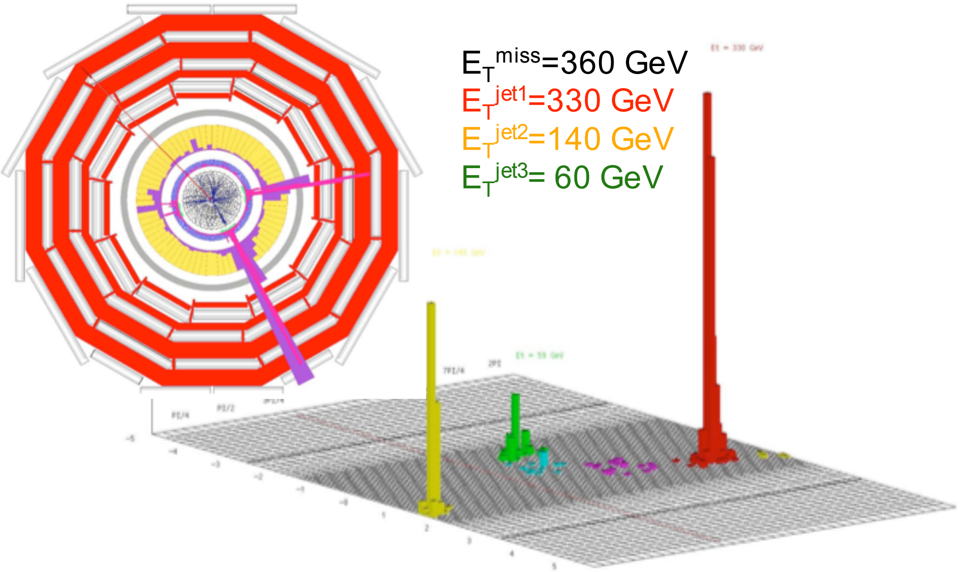
"SUSY Searches" - What are we searching for?

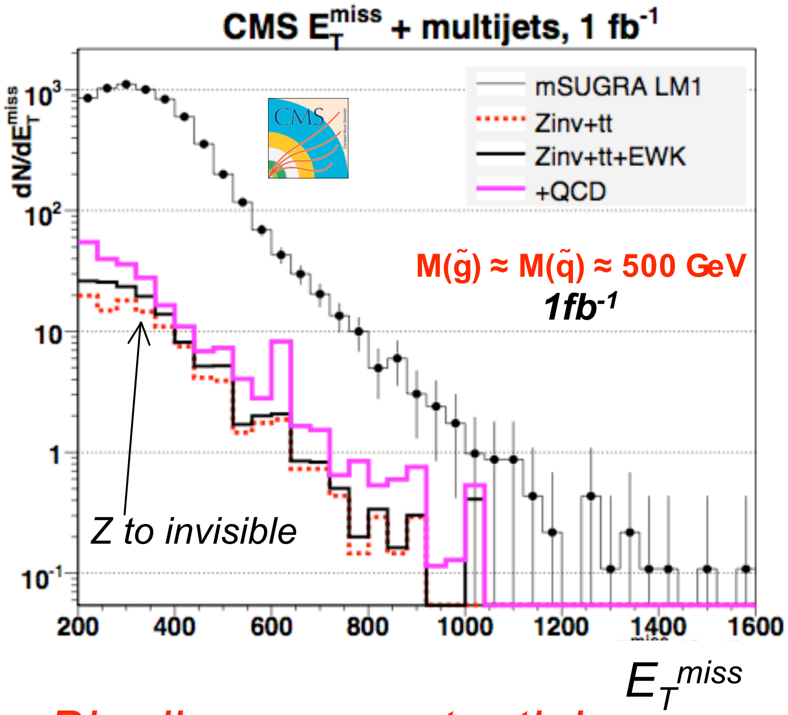
- Pair-produced new particles N with a colour charge and a mass of O(TeV/2)
- N decays via a cascade into other new particles as well as SM particles like bosons, leptons and quarks
- At the end of the cascade decay is a weakly interacting new particle - i.e. a dark matter candidate

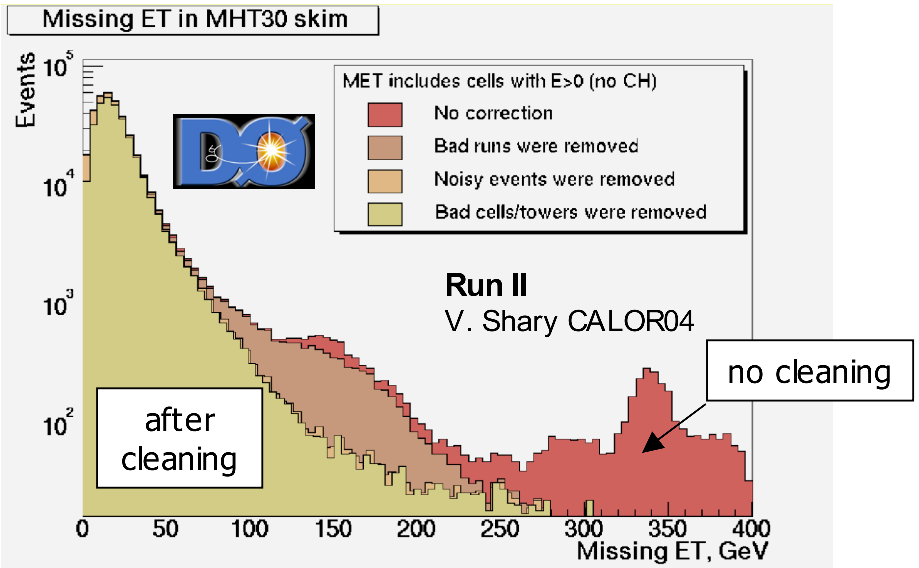
In other words, a "SUSY search" is a search for a weakly interacting (stable) particle that was produced in the cascade decay of a heavy new particle.

Use "SUSY" as a convenient tool to characterize this search!

Jets + E_T^{miss} - Inclusive Search







<u>*Big discovery potential*</u>

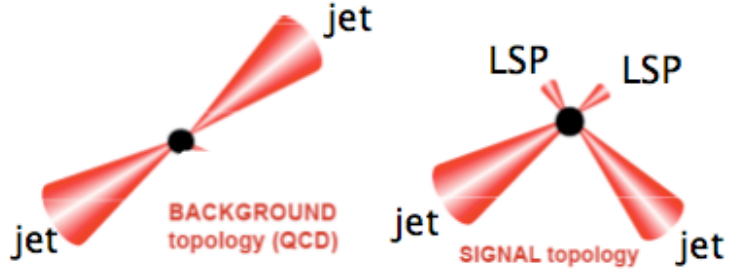
But requires a very good detector understanding and background control:

Analysis Strategy:

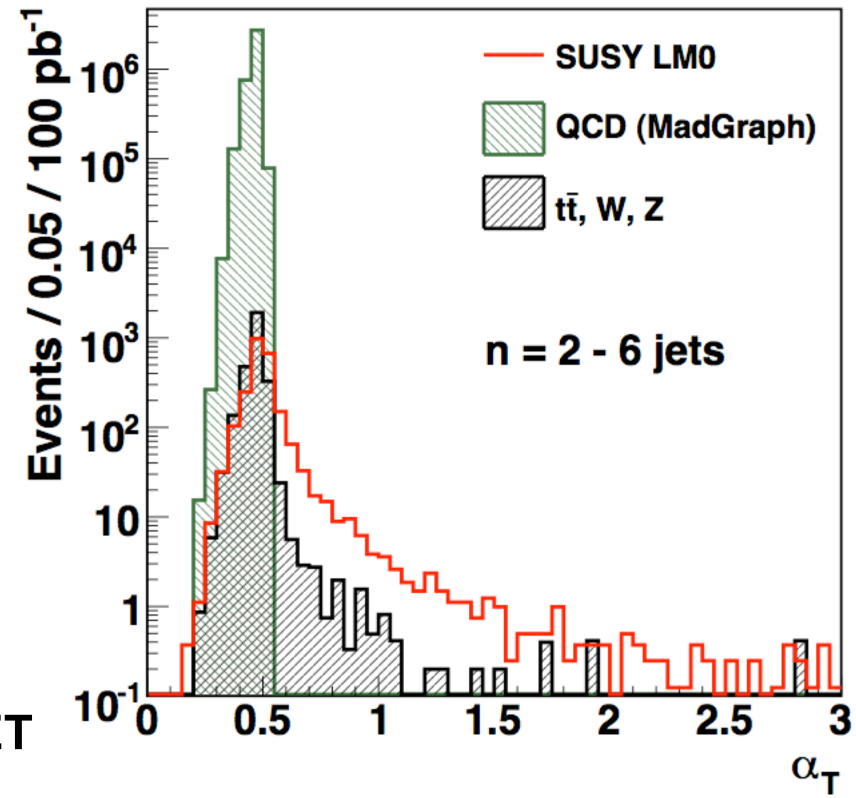
- Be brave
- Fight background and noise
- Use data control samples
- Estimate background from data

New Approaches: Robust SUSY Searches

PRL101:221803 (2008) & CMS-PAS-SUS-09-001



$$\alpha_T = \frac{E_{T\,j2}}{M_{T\,j1j2}} = \frac{\sqrt{E_{T\,j2}/E_{T\,j1}}}{\sqrt{2(1-\cos\Delta\varphi)}}$$

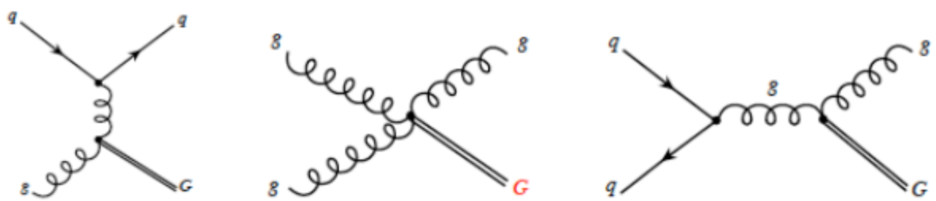


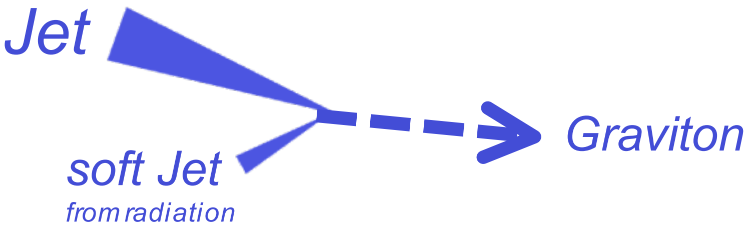
- **A novel approach based on kinematic**
- **No direct dependence on calorimetric MET**
- **Originally proposed for di-jets but now generalized for Njets**
- **Perfectly balanced events (QCD) have α_T = 0.5 (cut at α_T >0.5)**
- **Due to build in correlation α_T is very robust against jet mismeasurements**

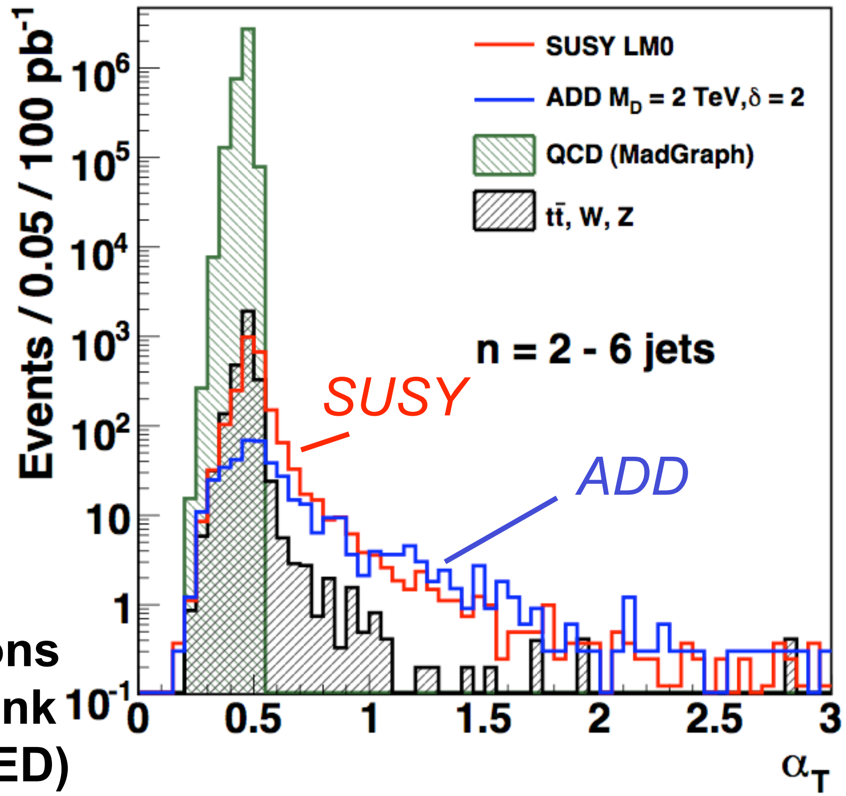
➔ ***α_T search especial designed for the difficult startup environment***

New Approaches: Beyond SUSY

Another missing energy signature.
*This time **extra dimensions (ADD)**.*







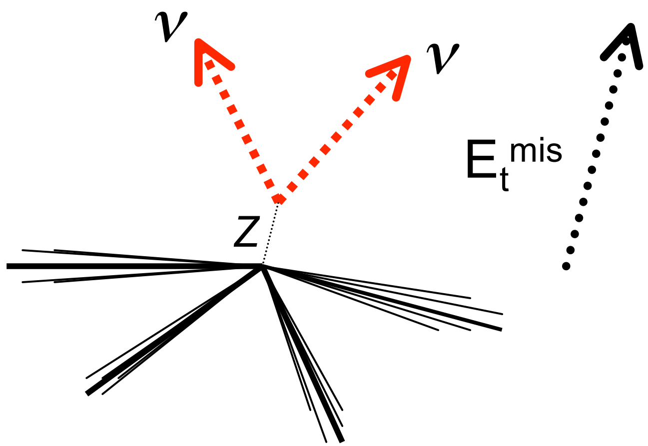
- **ED: unit gravitational and gauge interactions at the weak scale. Leads to reduction of Plank scale to O(TeV): MD (scale) and δ (number ED)**

- **At LHC direct production of KK-gavitons possible. Graviton escapes to ED thus yielding a missing energy signature: *Leading jet+possible soft jet+Etmiss***

➔ ***α_T search is generic and sensitive to missing energy signatures in general***

Data Driven Background Estimations

An illustrative example: $Z \rightarrow \nu\nu$+jets
Irreducible background for Jets+E_t^{mis} search

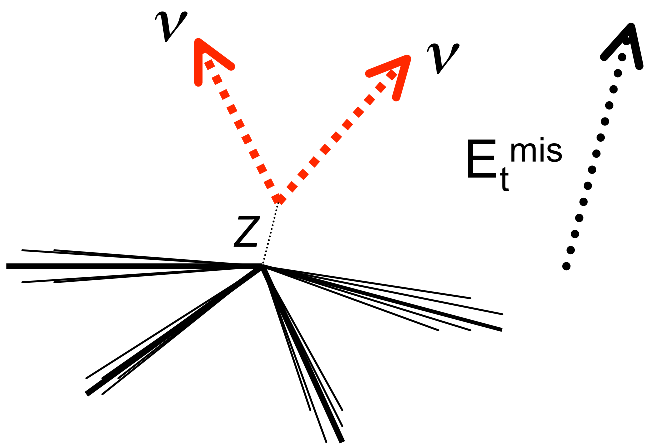


Data-driven strategy:

- *define control samples and understand their strength and weaknesses:*

Data Driven Background Estimations

An illustrative example: Z→νν+jets
Irreducible background for Jets+E_t^{mis} search



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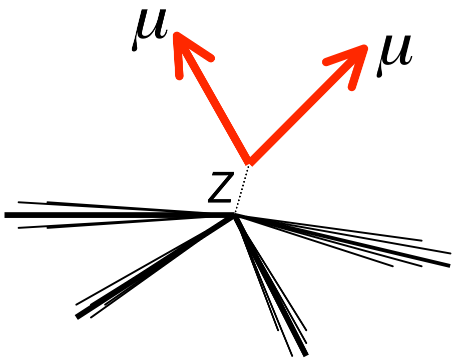


Z→μμ+jets

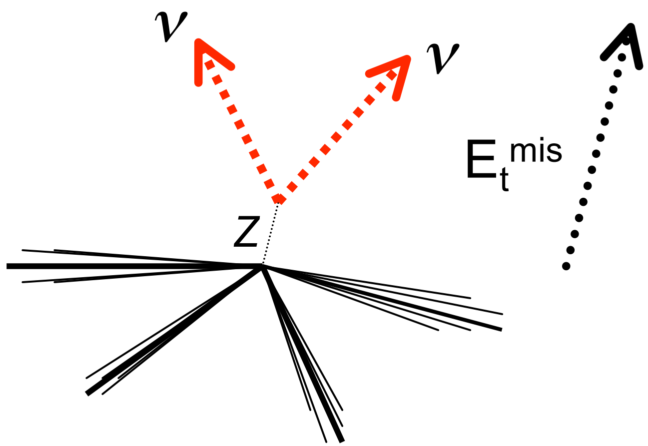
Strength:
- *very clean, easy to select*

Weakness:
- *low statistic: factor 6 suppressed w.r.t. to Z →νν*

Data Driven Background Estimations

An illustrative example: $Z \to \nu\nu$+jets

Irreducible background for Jets+E_t^{mis} search



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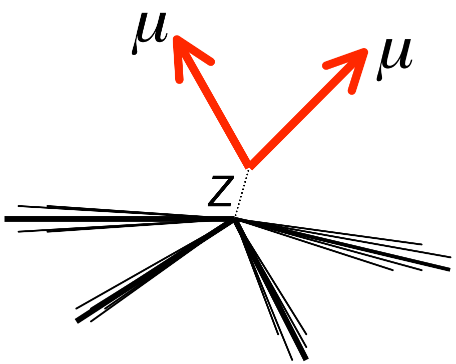


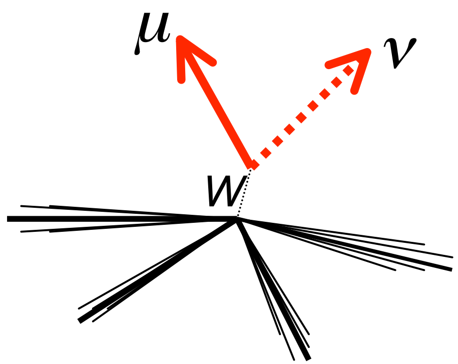
$Z \to \mu\mu$+jets

Strength:

- *very clean, easy to select*

Weakness:

- *low statistic: factor 6 suppressed w.r.t. to $Z \to \nu\nu$*



$W \to \mu\nu$+jets

Strength:

- *larger statistic*

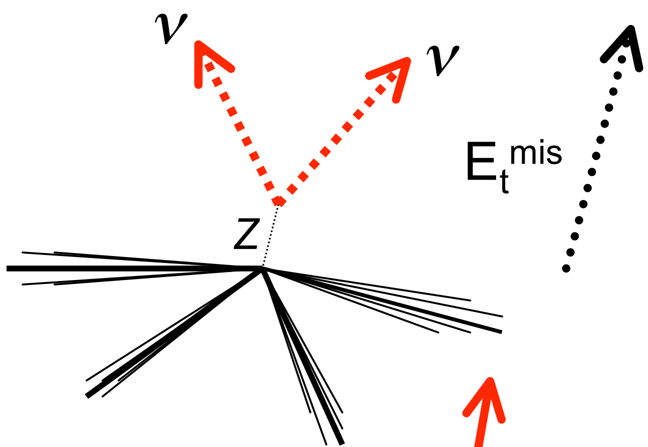
Weakness:

- *not so clean, SM and signal contamination*

Data Driven Background Estimations

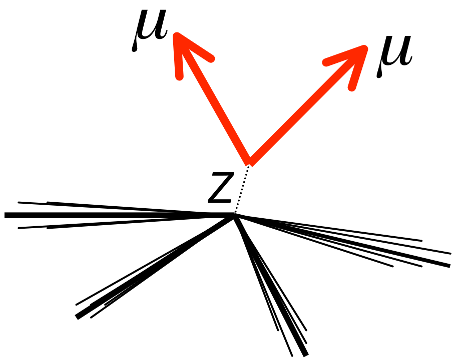
An illustrative example: Z→νν+jets

Irreducible background for Jets+E_t^{mis} search



Data driven strategy:

- *define control samples and understand their strength and weaknesses:*



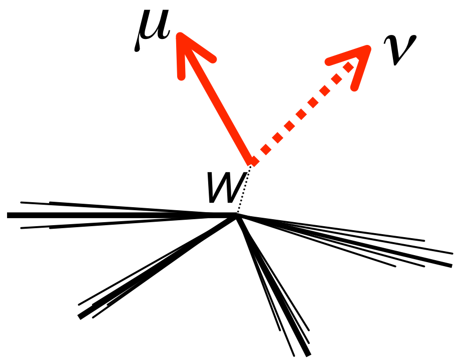
Z→ll+jets

Strength:

- *very clean, easy to select*

Weakness:

- *low statistic: factor 6 suppressed wrt. to Z →νν*



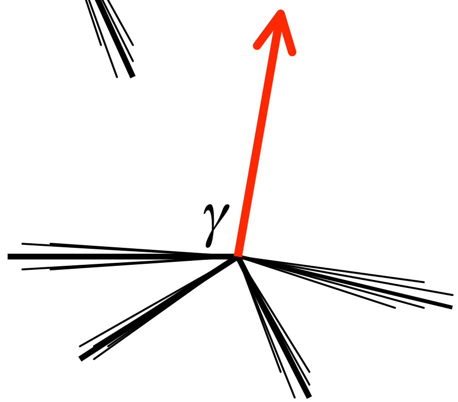
W→lν+jets

Strength:

- *larger statistic*

Weakness:

- *not so clean, SM and signal contamination*



γ+jets

Strength:

- *large stat, clean for high E_γ*

Weakness:

- *not clean for E_γ<100 GeV, possible theo. issues for normalization (u. investigation)*

W/Z+jets: Estimate Z to invisible

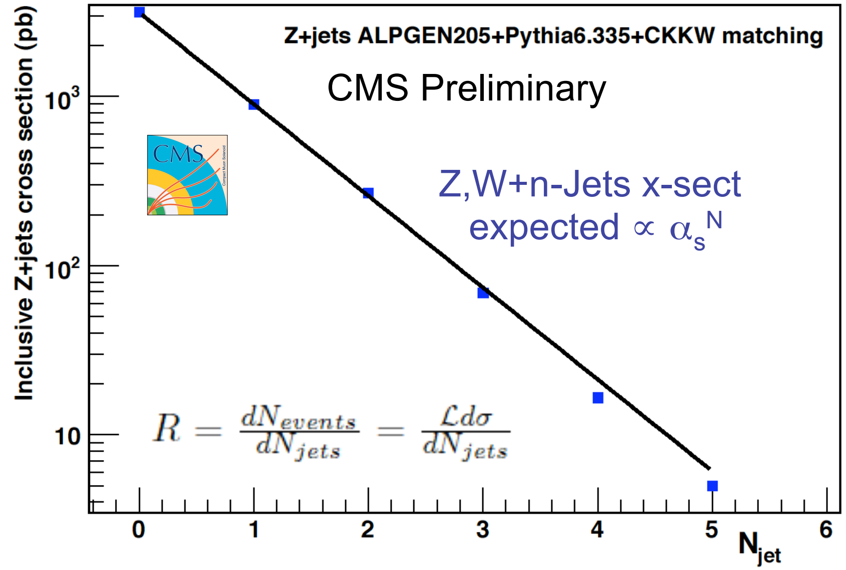
Measure from ≥ 2 Jets from Data:

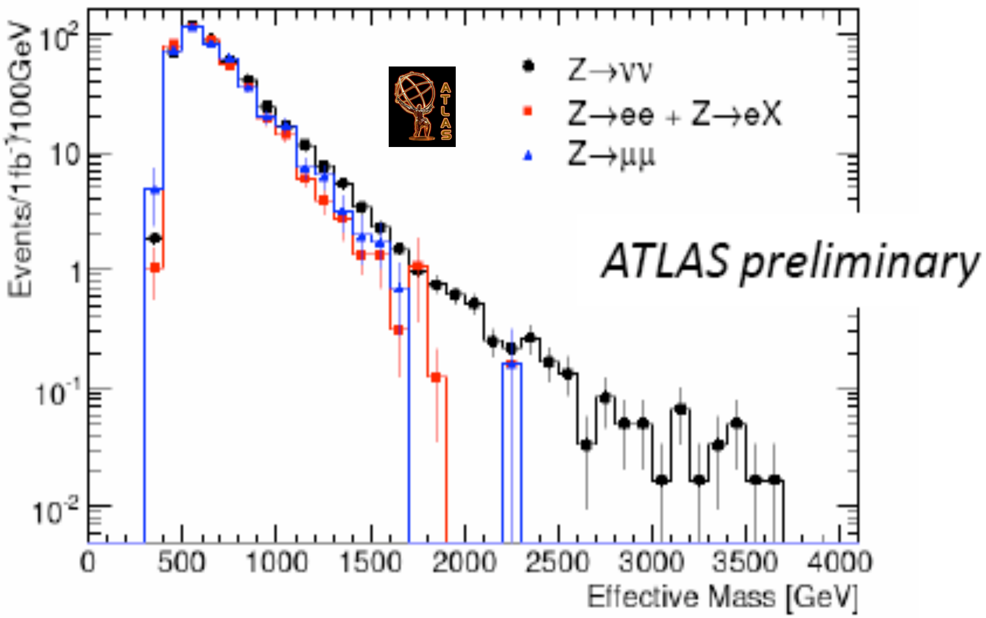
Use:

- $Z(\rightarrow\mu\mu)$ + ≥2 jets
- $Z(\rightarrow ee)$ + ≥2 jets

to estimate directly

- $Z(\rightarrow\nu\nu)$ + ≥2 jets





W/Z Ratio from data & MC tuning

- Assume lepton universality
- Measure W/Z ratio as function of N jets

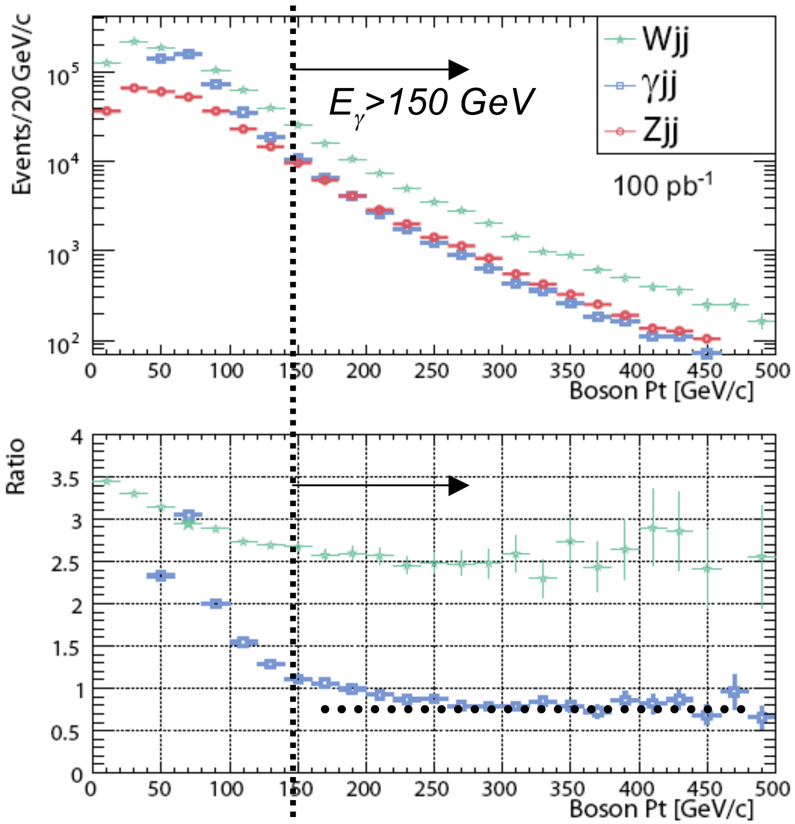
$$\rho \equiv \frac{\sigma(pp\rightarrow W(\rightarrow\mu\nu)+jets)}{\sigma(pp\rightarrow Z(\rightarrow\mu^+\mu^-)+jets)}$$

- Tune MC with <=2 Jets and use it to extrapolate in signal ratio e.g. >=3Jets

γ+jets: Estimate Z to invisible

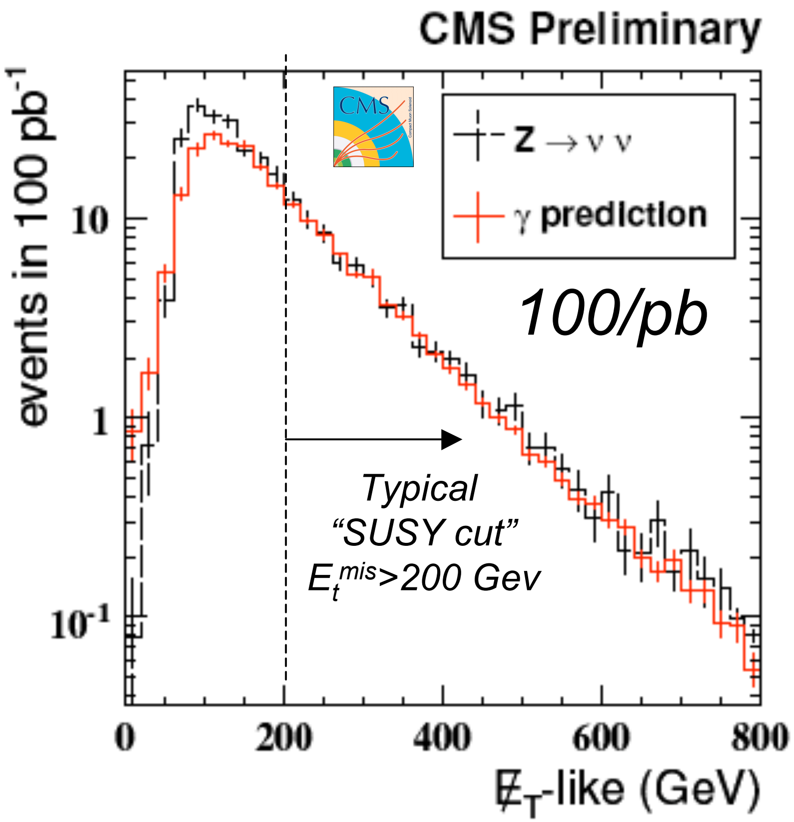
γ+jets selection & properties:

• E_γ>150 GeV
→ clean sample: S/B>20
→ ratio σ(Z+jet)/σ(γ+jet) constant



γ+jets: Strategy:

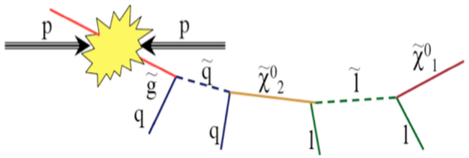
• remove γ from the event:
→ γ becomes E_T^{mis}
• take σ(Z+jet)/σ(γ+jet) for E_γ>200 GeV from MC or measure in data



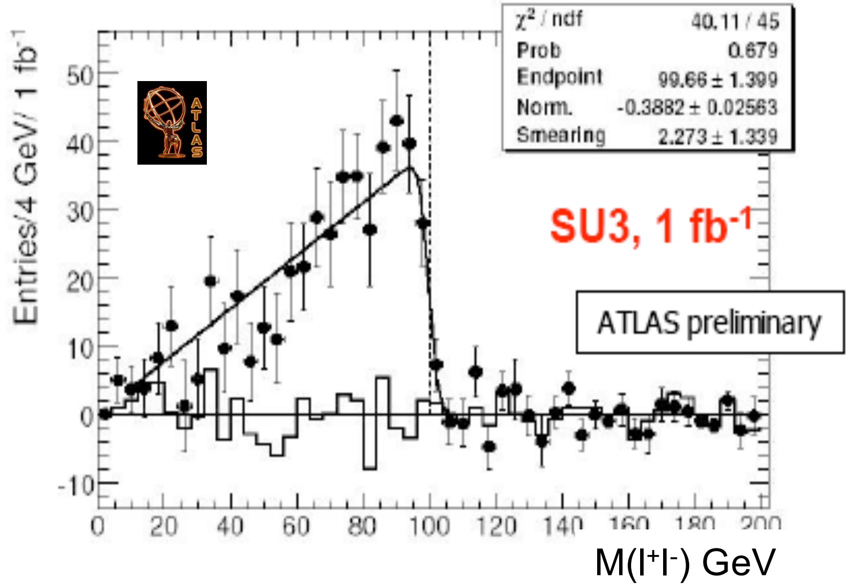
First Kinematic Measurements

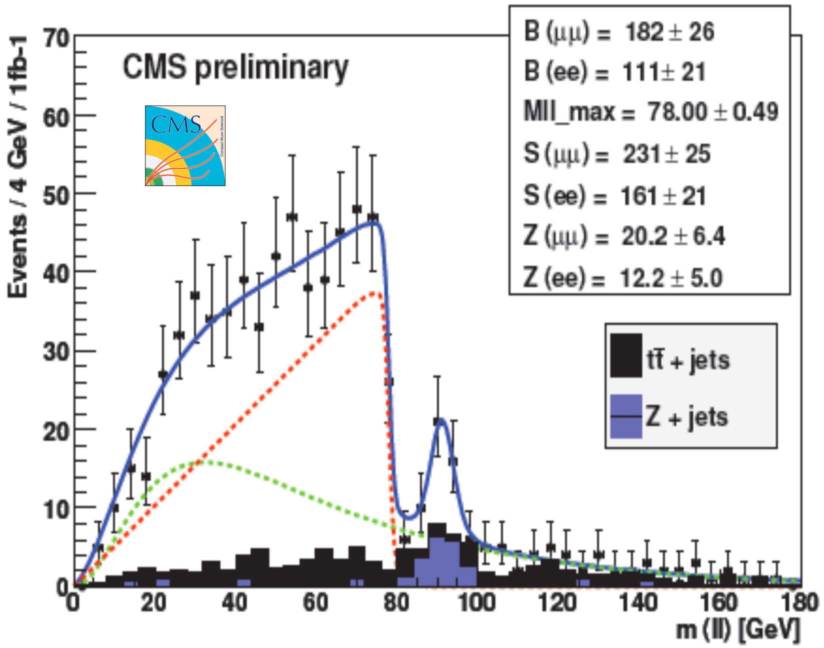
...and if we are a bit lucky we might see such spectacular signals already in the early days!

Look for generic signatures of cascade decays:



Jets + E_t^{miss}
+SFOS di-leptons



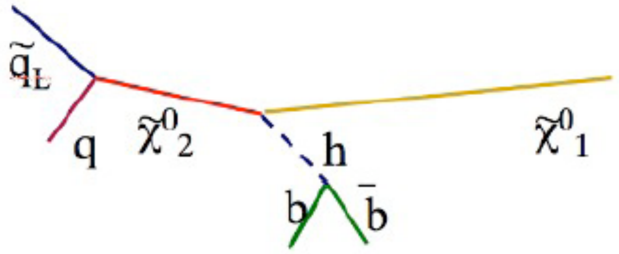


Extract: $$M_{\ell\ell}^{max} = M(\tilde{\chi}_2^0)\sqrt{1-\frac{M^2(\tilde{\ell}_R)}{M^2(\tilde{\chi}_2^0)}}\sqrt{1-\frac{M^2(\tilde{\chi}_1^0)}{M^2(\tilde{\ell}_R)}}$$

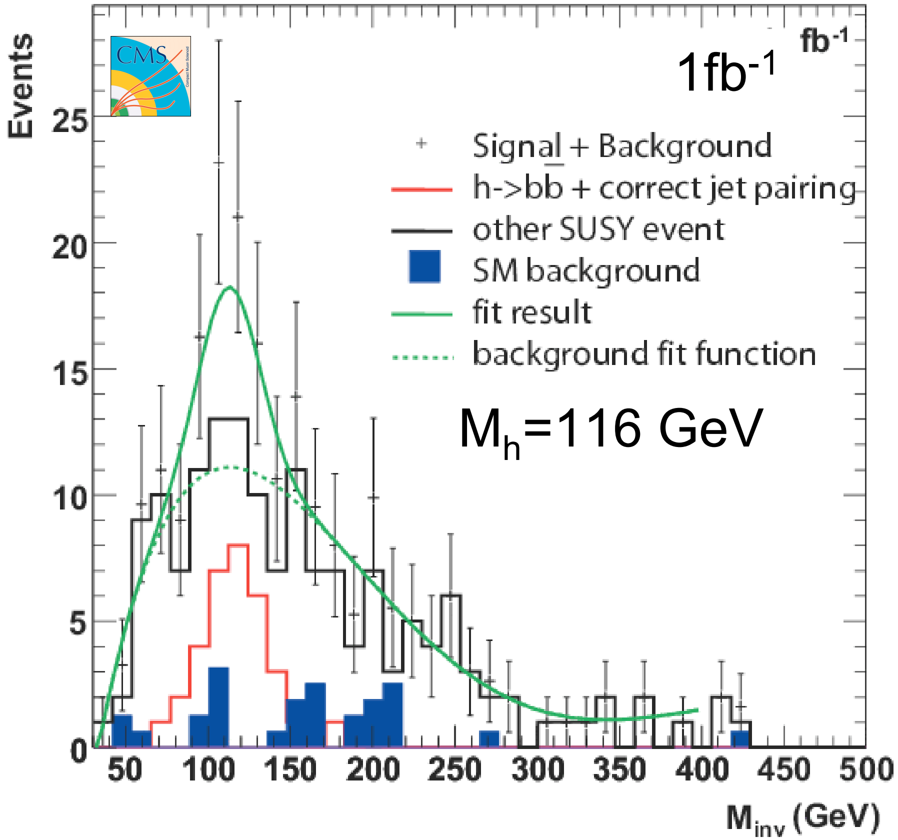
from a fit to the "edge distribution".

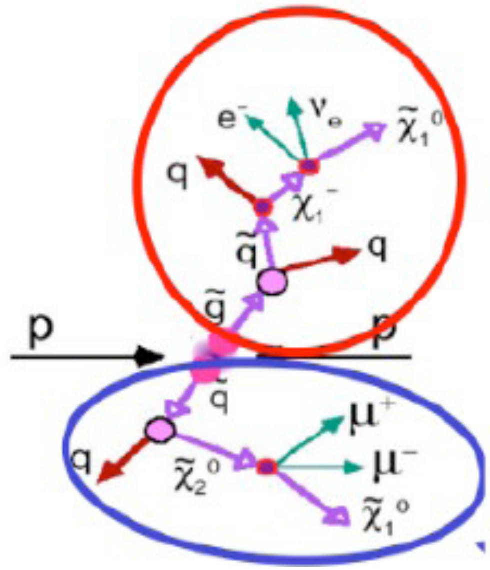
- *$\Delta M_{ee}^{max}=1.07_{stat}\pm0.36_{sys}$ GeV for 1/fb (CMS)*
- *$\Delta M_{\mu\mu}^{max}=0.75_{stat}\pm0.18_{sys}$ GeV for 1/fb (CMS)*
- *Estimate same flavour top and di-boson bkg directly from eμ data*
- *Relatively precise extraction of M_{ll}^{max} in the first few hundred pb^{-1} is still possible.*

"Low Mass M_h" in SUSY Decays



Depending on the SUSY parameter space the h→bb production is possible





Replace μ's with b's

- Separate cascade decay chain in two hemispheres and require two b's in one.
- 5σ Signal (M_h=115 GeV) already with~2fb^{-1}

Could be the first sign of a light higgs but b-tagging is crucial!

New Physics
Interpretation of what we will see!

Confronting Data with Theory: New Physics

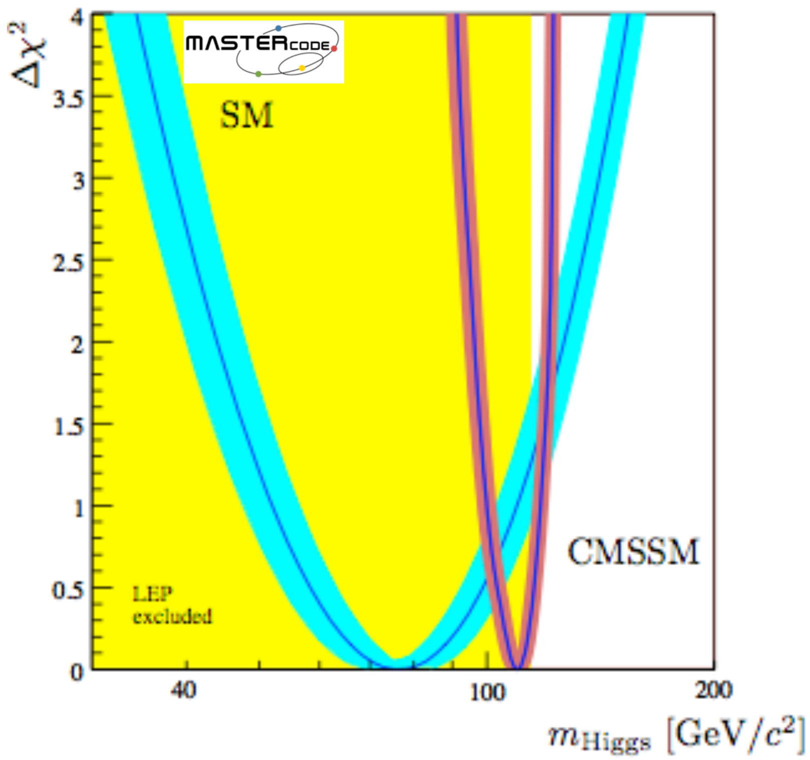
Two years ago we formed a collaboration of experimentalist and theorist to develop a consistent framework for global fits of new physics parameter space in the LHC era.

The MasterCode Collaboration

MasterCode Collaboration

OB (Exp), R. Cavanaugh (Exp), A. De Roeck (Exp), J. Ellis (Theo), H. Flaecher (Exp), S. Heinemeyer (Theo), G. Isidori (Theo), K. Olive (Theo), P. Paradisi, (Theo), F. Ronga (Exp), G. Weiglein (Exp)

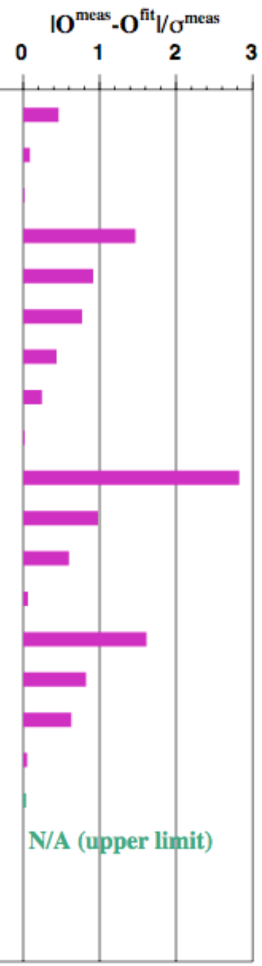
Example: "redo" SM fit in SUSY predicting the lightest higgs boson mass in the Constraint Minimal Supersymmeteric Standard Model (CMSSM)



0707.3447 [hep-ph]

Pull for CMSSM fit

Variable	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02774
m_Z [GeV]	91.1875 ± 0.0021	91.1873
Γ_Z [GeV]	2.4952 ± 0.0023	2.4952
σ^0_{had} [nb]	41.540 ± 0.037	41.486
R_l	20.767 ± 0.025	20.744
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01641
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1479
R_b	0.21629 ± 0.00066	0.21613
R_c	0.1721 ± 0.0030	0.1722
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1037
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0741
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1479
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.398 ± 0.025	80.382
m_t [GeV]	170.9 ± 1.8	170.8
$R(b\to s\gamma)$	1.13 ± 0.12	1.12
$B_s\to\mu\mu$ [$\times 10^{-8}$]	< 8.00	0.33
Δa_μ [$\times 10^{-9}$]	2.95 ± 0.87	2.95
Ωh^2	0.113 ± 0.009	0.113



SUSY vs. SM - Fit Quality

MASTERCODE

0707.3447 [hep-ph]

Pulls from SUSY fit:

$\chi^2/NDF = 17/15$; $P(\chi^2)=26\%$

Variable	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02774
m_Z [GeV]	91.1875 ± 0.0021	91.1873
Γ_Z [GeV]	2.4952 ± 0.0023	2.4952
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$B_s\rightarrow\mu\mu$ [$\times10^{-8}$]	< 8.00	0.33
Δa_μ [$\times10^{-9}$]	2.95 ± 0.87	2.95
Ωh^2	0.113 ± 0.009	0.113

Pulls from official EW fit:

$\chi^2/NDF = 18/13$; $P(\chi^2)=15\%$

Variable	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ^0_{had} [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21586
R_c	0.1721 ± 0.0030	0.1722
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.398 ± 0.025	80.374
m_t [GeV]	170.9 ± 1.8	171.3
Γ_W [GeV]	2.140 ± 0.060	2.091

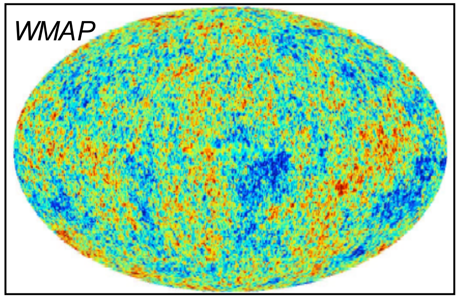
Comparable fit quality but SUSY fit can accommodate additional features like relic density

Confronting Data with Theory: New Physics

Two years ago we formed a collaboration of experimentalist and theorist to develop a consistent framework for global fits of new physics parameter space in the LHC era.

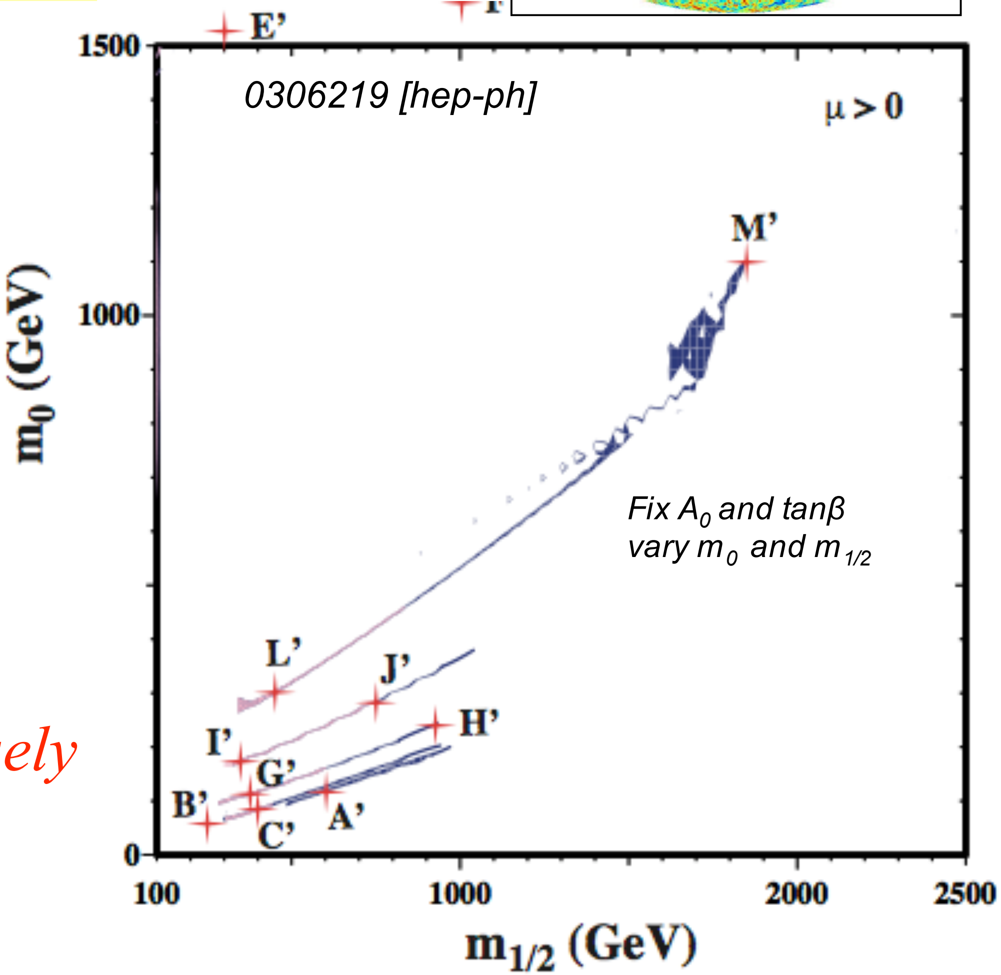
The MASTERCODE *Collaboration*

Consider SUSY model CMSSM with 4 parameter: M_0, $m_{1/2}$, A_0, tanβ and μ>1



Wilkinson Microwave Anisotropy Probe

Example: ***WMAP Strips – are they real?***
WMAP strips are obtained by fixing some of the NP parameters (in this case A_0 and tanβ) to certain values and than vary the remaining NP parameters (here m_0 and $m_{1/2}$). This procedure does not capture all important statistical properties of the considered NP parameter space. A global to fit to all free variables of the model is required to obtain confidence level contours meaningful for the full model.



2003:
WMAP constraints very precisely the relic density $\Omega_\chi h^2$

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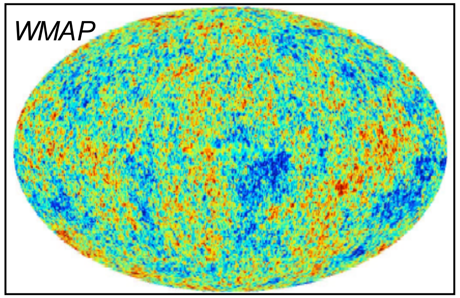
Consider SUSY model CMSSM with 4 parameter: M_0, $m_{1/2}$, A_0, $\tan\beta$ and μ>1



Wilkinson Microwave Anisotropy Probe

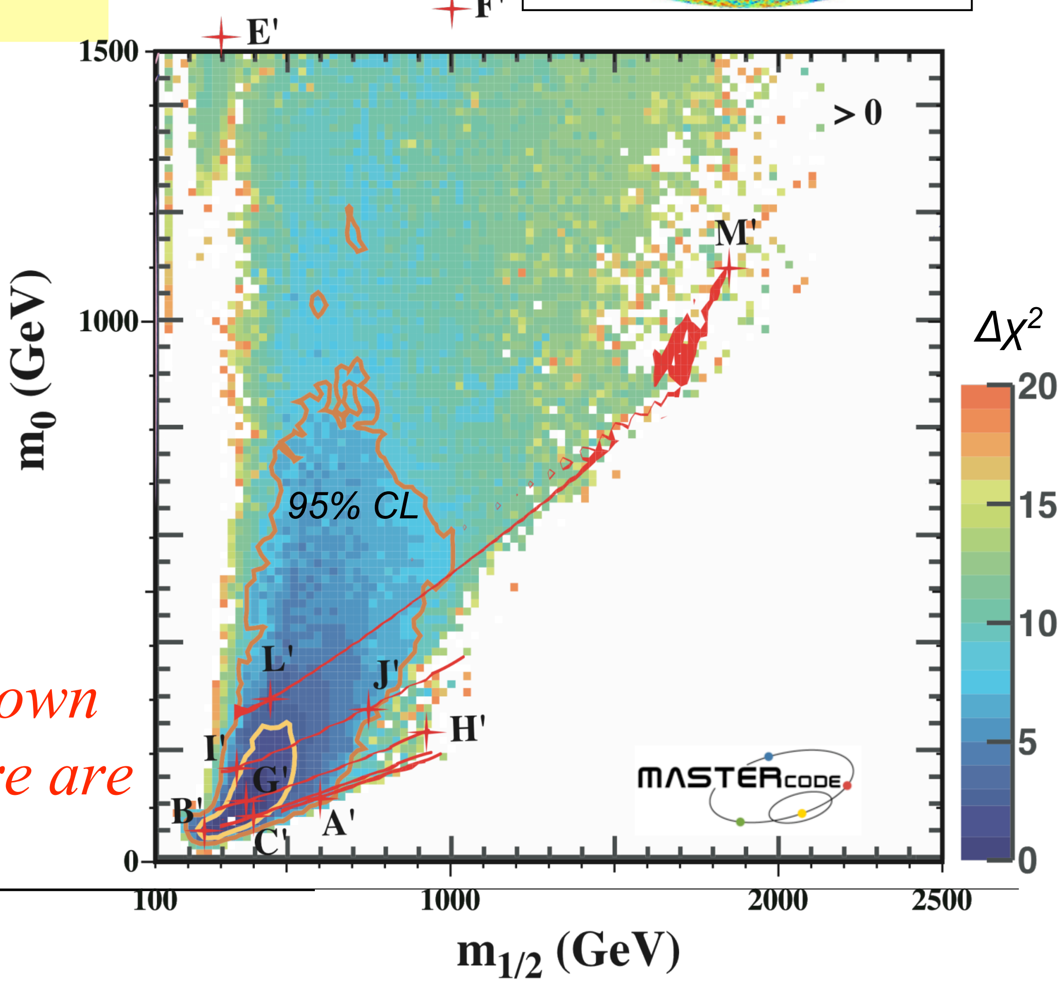
Example: ***Wmap Strips – are they real?***

Wmap strips are obtained by fixing some of the NP parameters (in this case A_0 and $\tan\beta$) to certain values and than vary the remaining NP parameters (here m_0 and $m_{1/2}$). This procedure does not capture all important statistical properties of the considered NP parameter space. A global to fit to all free variables of the model is required to obtain confidence level contours meaningful for the full model.

Today:

Relic density is even better known

But global fit reveals that there are no "WMAP strips".

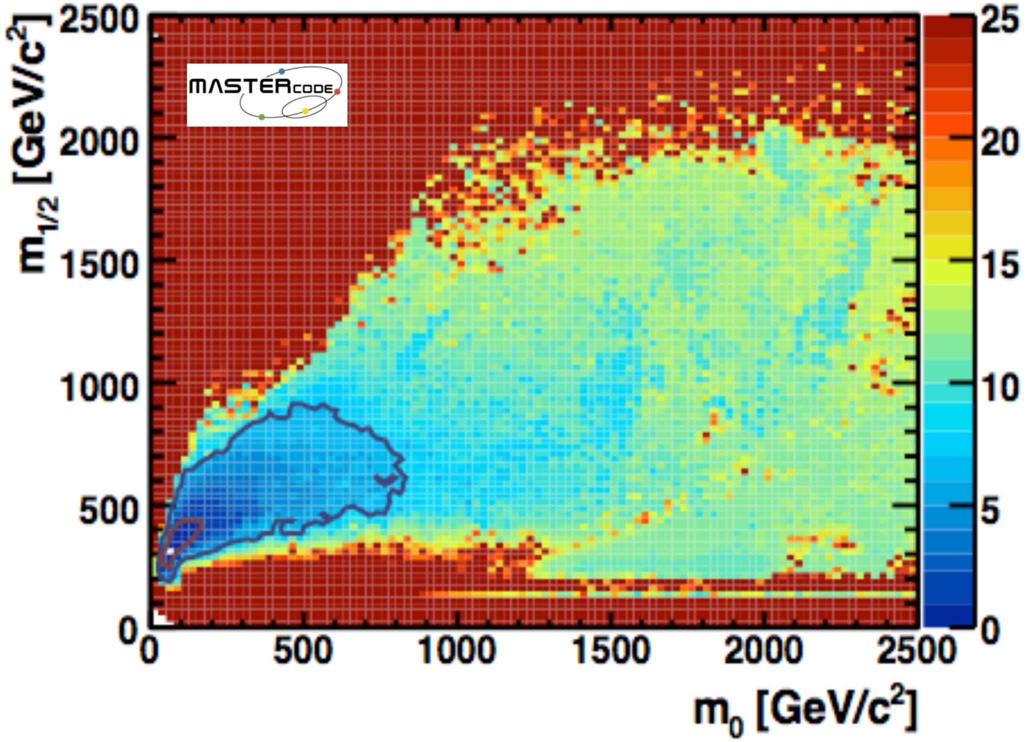


Confronting Data with Theory: New Physics

Two years ago we formed a collaboration of experimentalist and theorist to develop a consistent framework for global fits of new physics parameter space in the LHC era.

The MASTERCODE Collaboration

Example: *Predict preferred parameter space for SUSY searches at the LHC (here CMSSM).*



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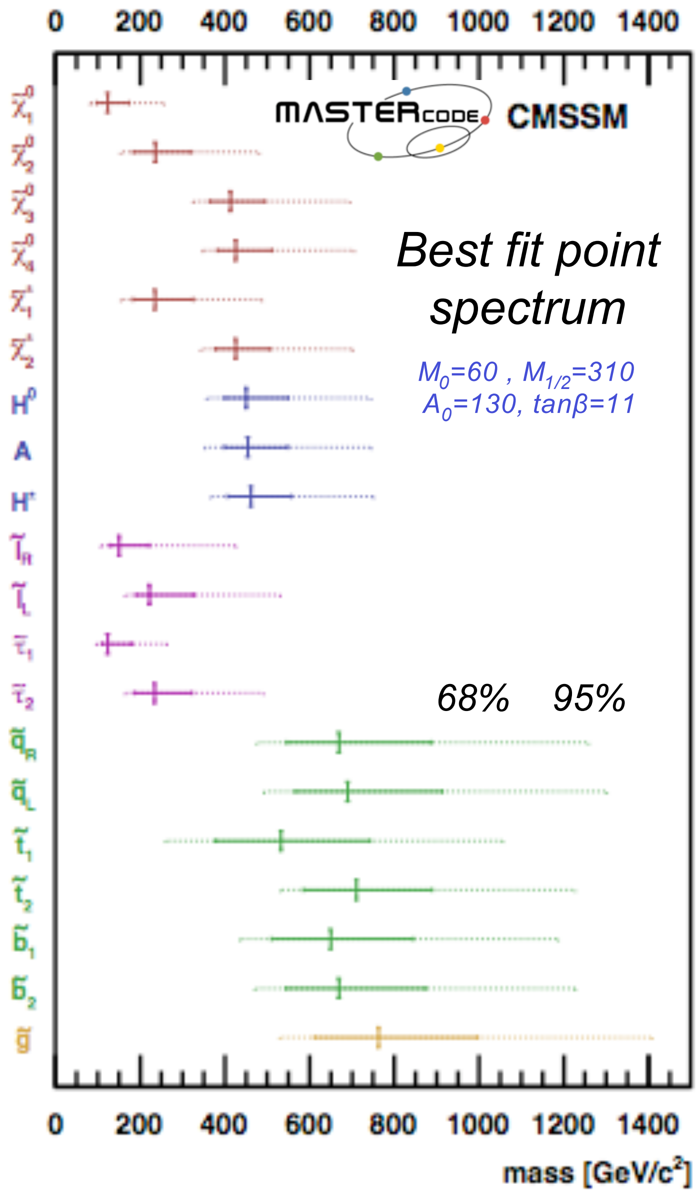

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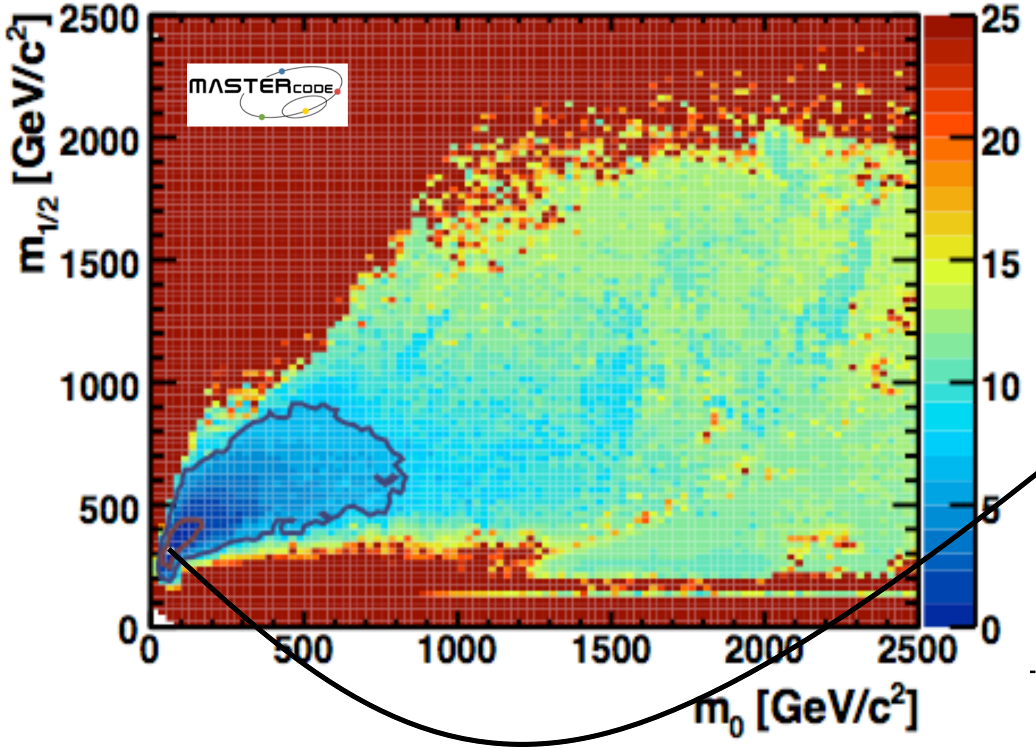

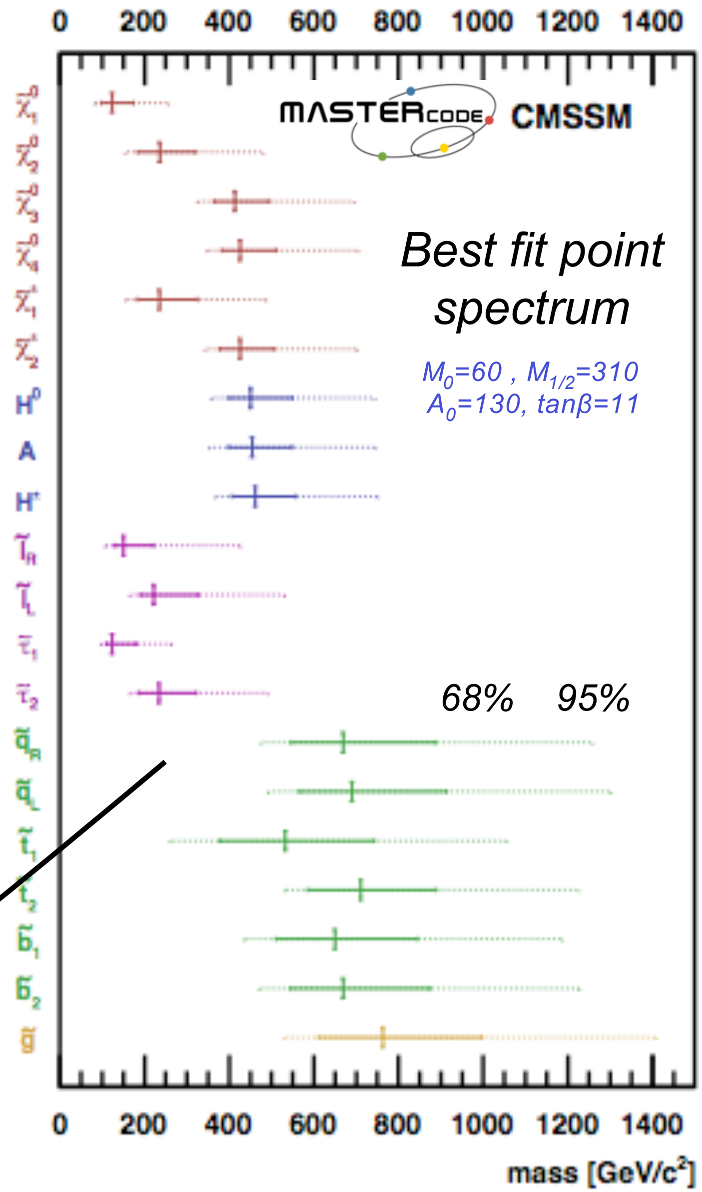

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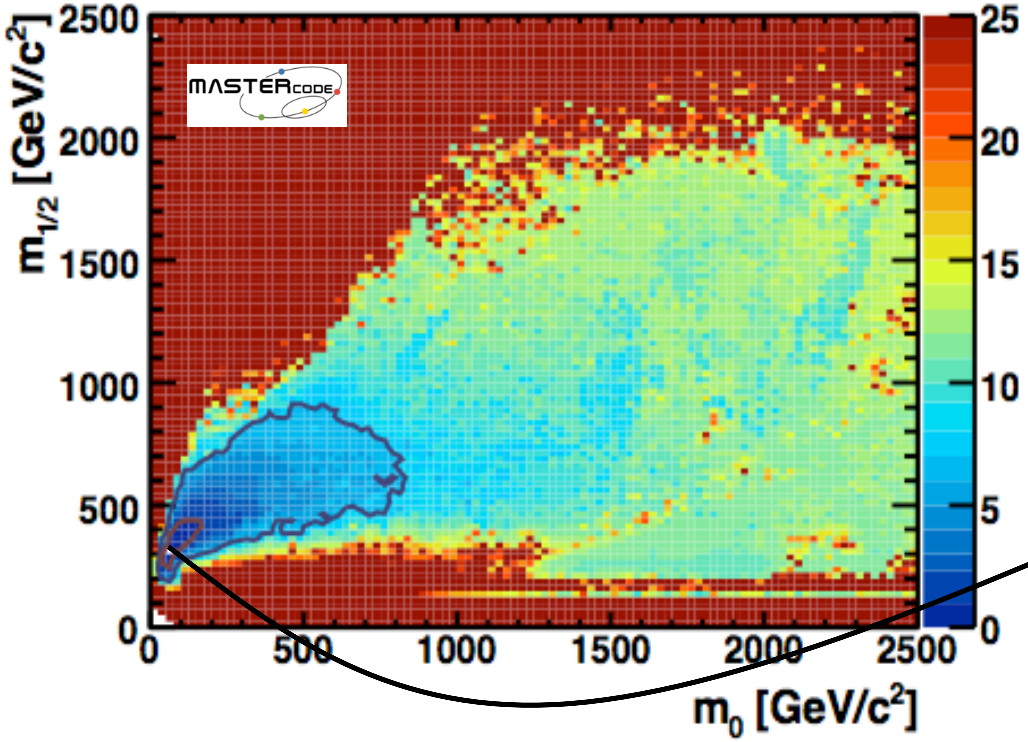
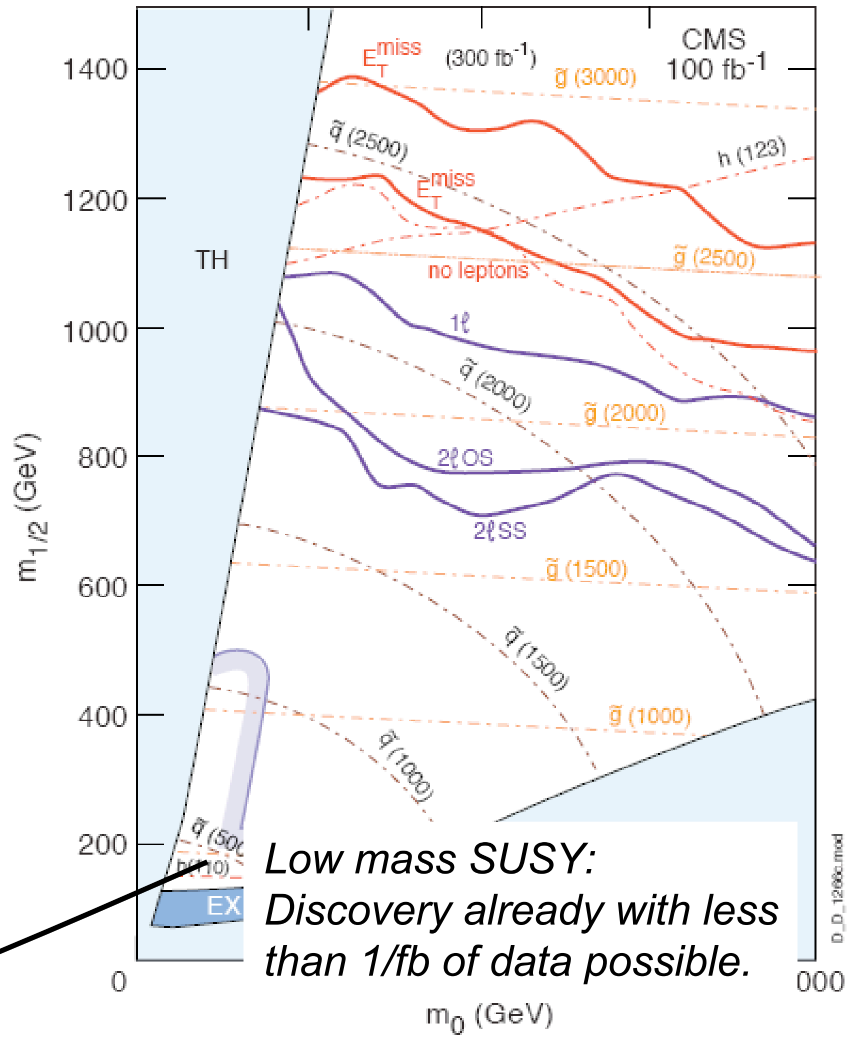


CMS Discovery Potential



Low mass SUSY: Discovery already with less than 1/fb of data possible.

Confronting Data with Theory: New Physics

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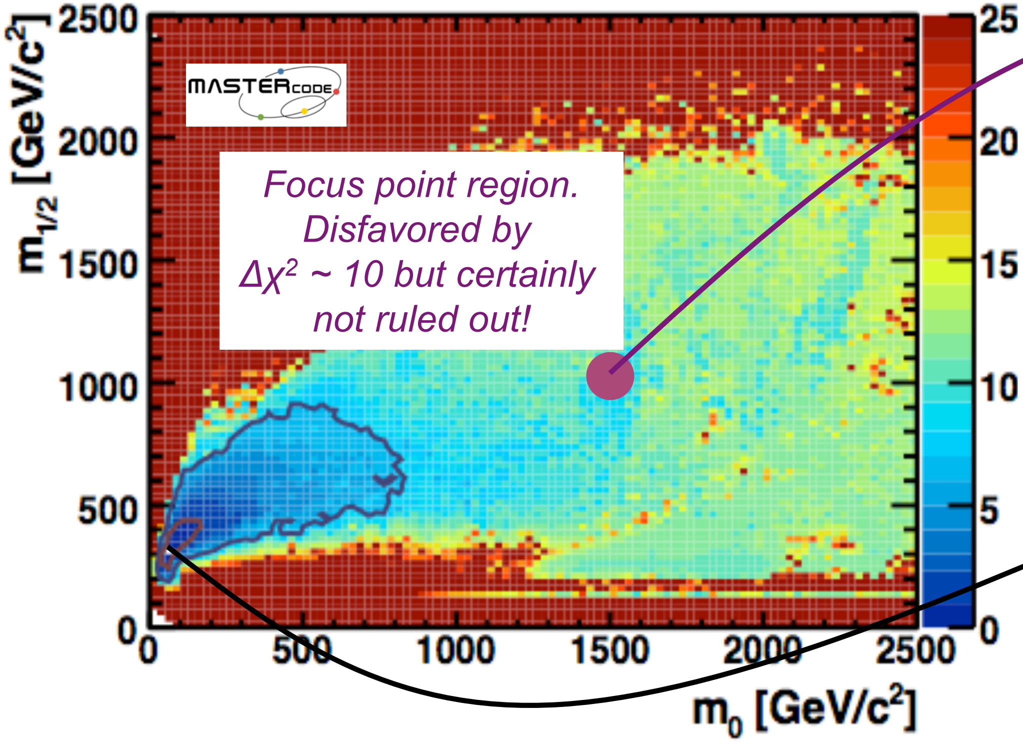
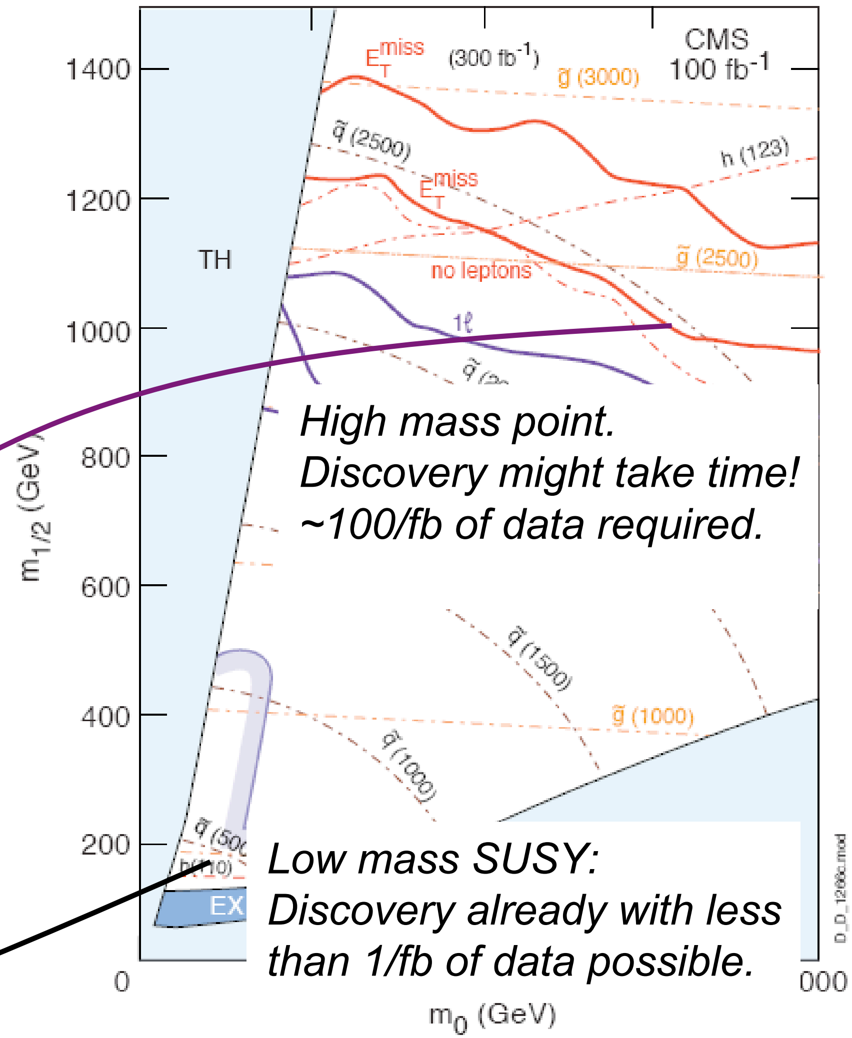
Example: Predict preferred parameter space for SUSY searches at the LHC (here CMSSM).



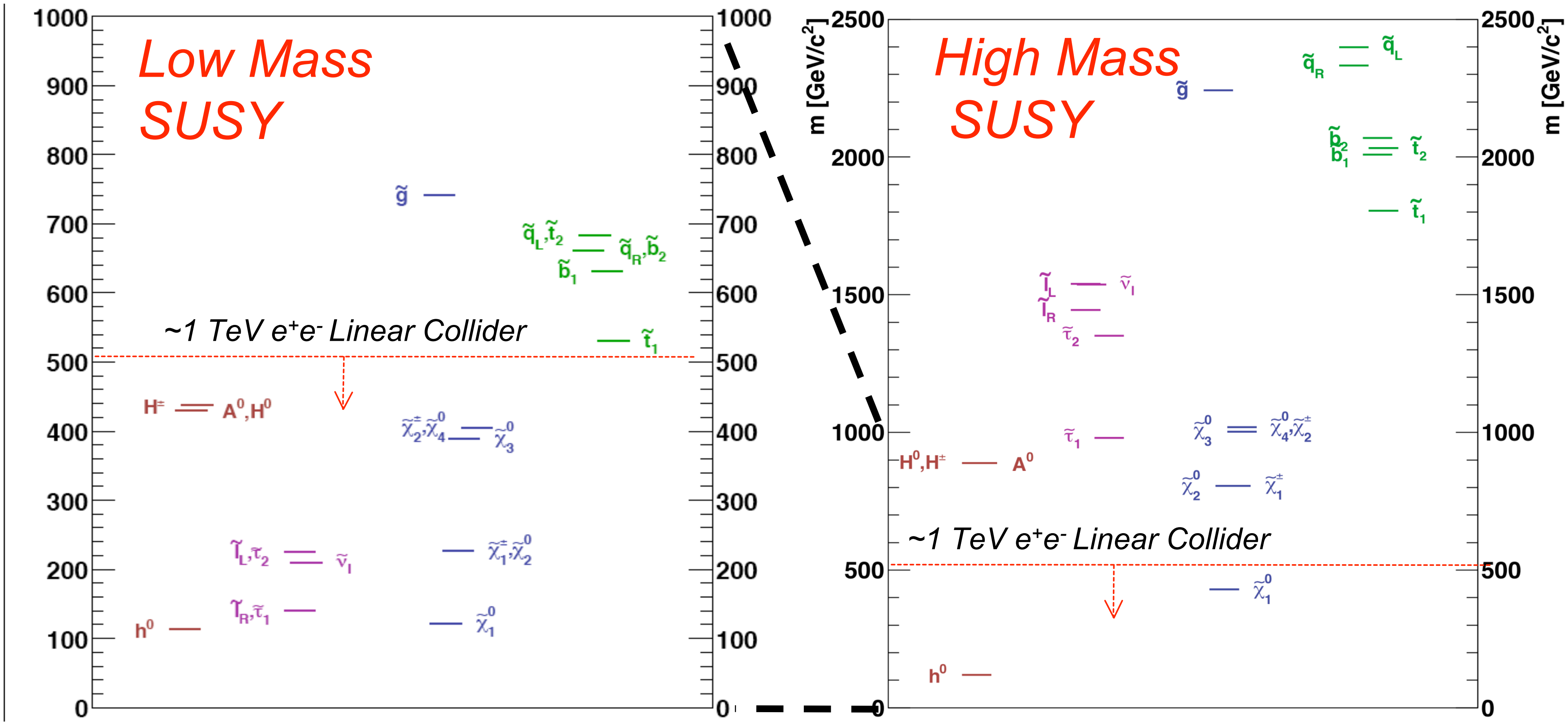
CMS Discovery Potential



What do we know Today?

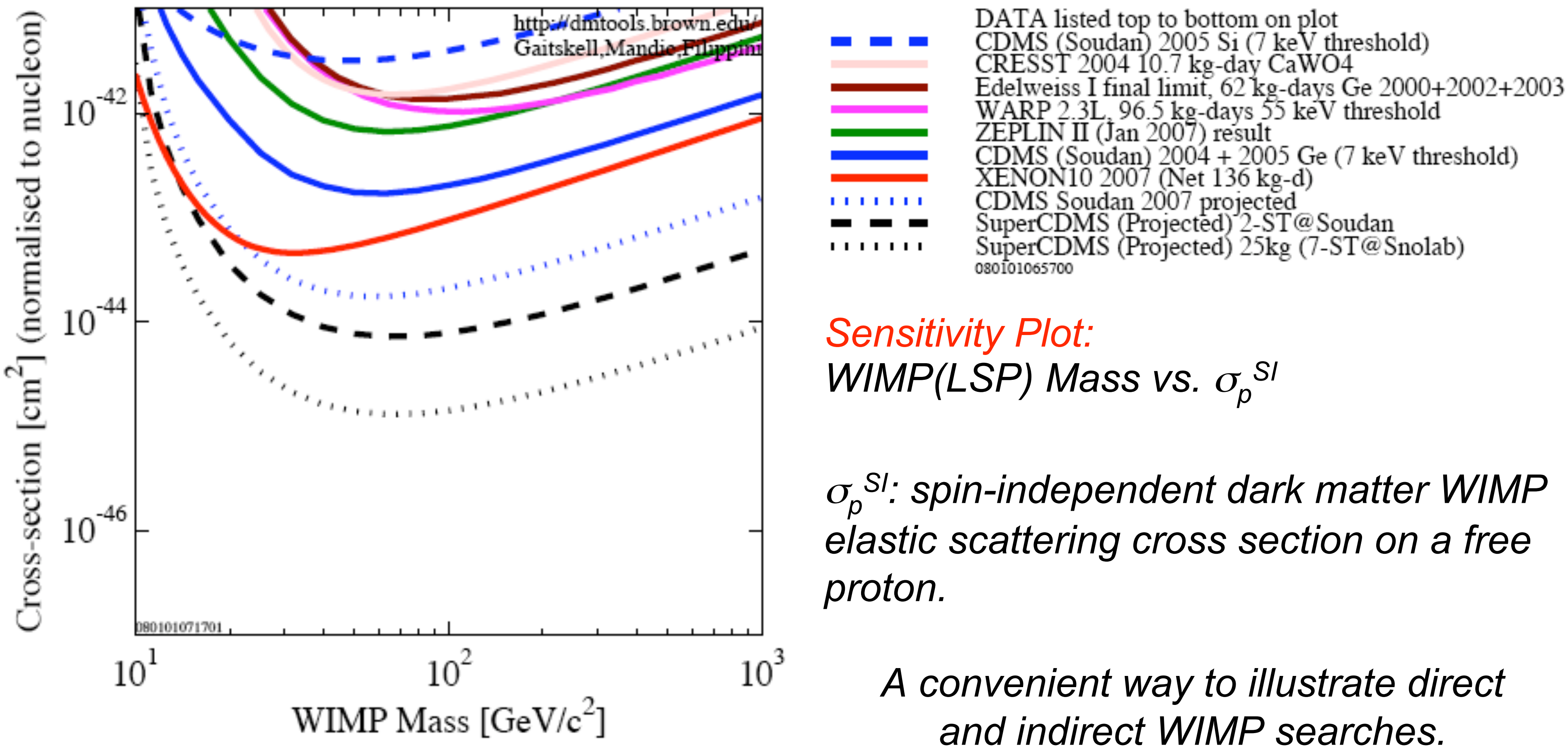
Still no (significant) deviation from the SM.
Need LHC to reveal the New Physics mass scale to converge on the future program.
This can go fast but could also take some time.

Broadly speaking – physics benchmarks used 20 years ago
Higgs, SUSY and Z'
are still valid today.



Link to Cosmology: Dark Matter

Direct detection of WIMP (LSP) Dark Matter



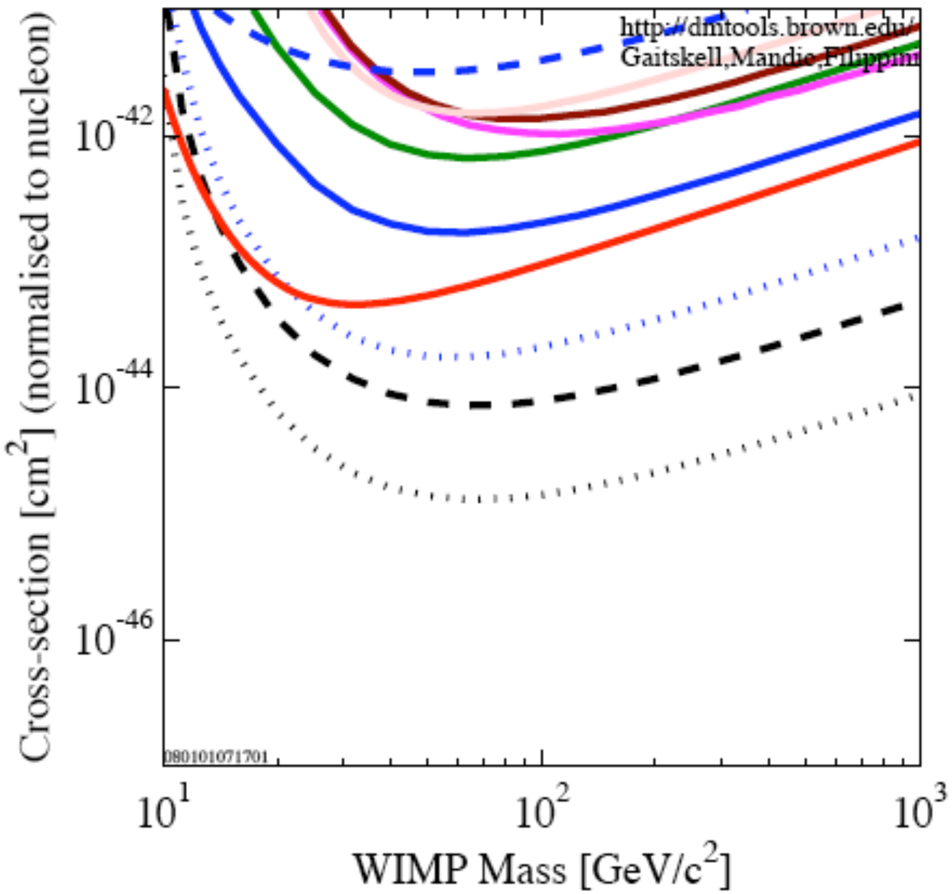
Sensitivity Plot:
WIMP(LSP) Mass vs. σ_p^{SI}

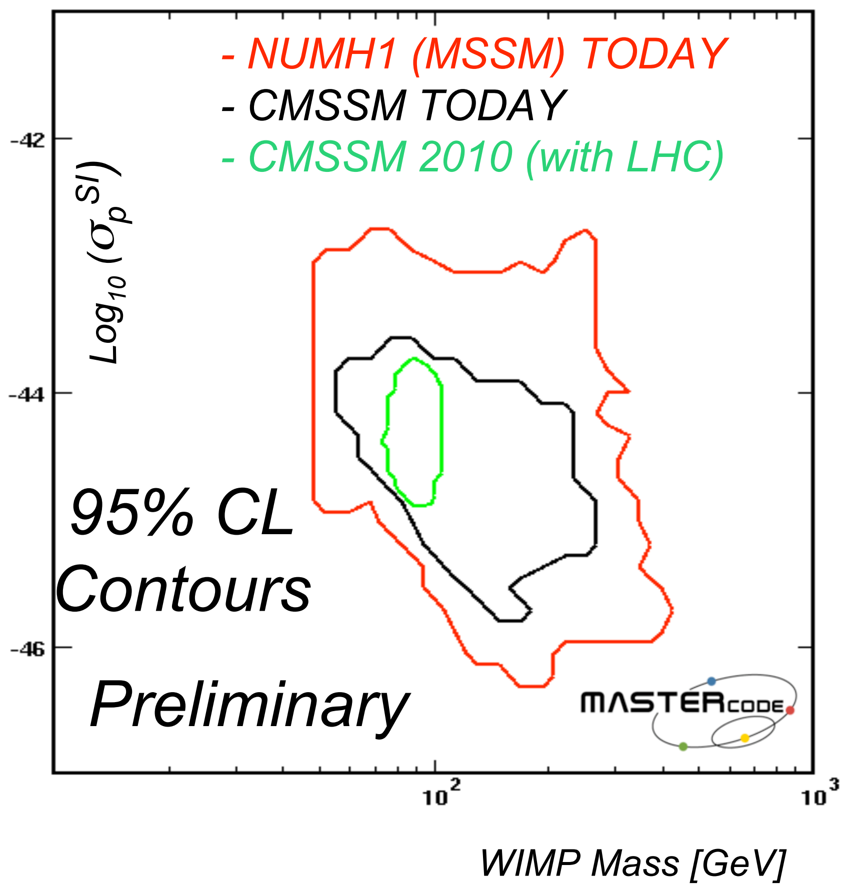
σ_p^{SI}: spin-independent dark matter WIMP elastic scattering cross section on a free proton.

A convenient way to illustrate direct and indirect WIMP searches.

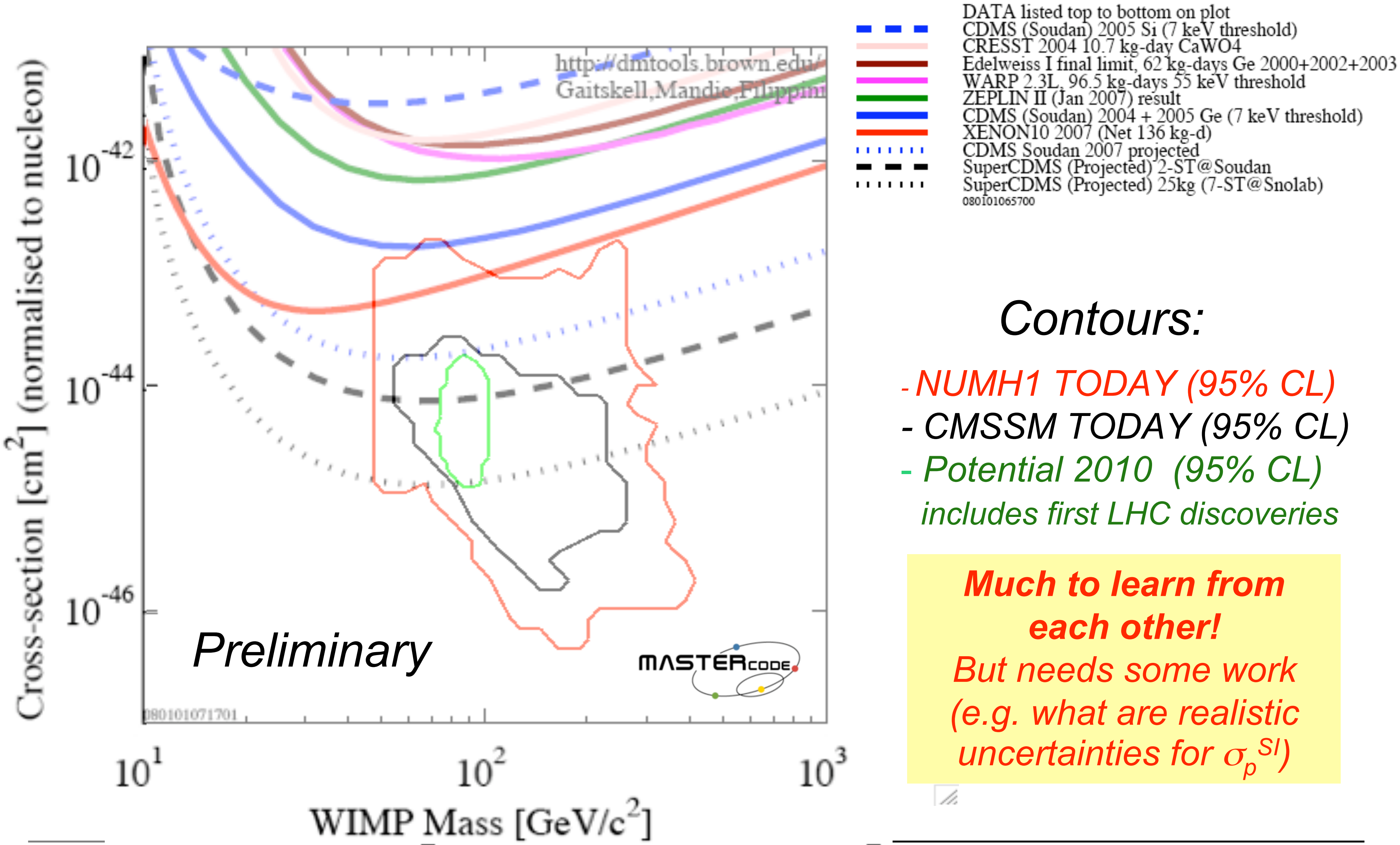
Direct WIMP Search vs. Indirect & LHC Prediction

An additional handle to make sense out of our discoveries!





Making the Connection:WIMP/LSP Sensitivity Plot



Contours:

- NUMH1 TODAY (95% CL)
- CMSSM TODAY (95% CL)
- Potential 2010 (95% CL) includes first LHC discoveries

Much to learn from each other!

But needs some work (e.g. what are realistic uncertainties for σ_p^{SI})

Summary

- LHC is back and the Experiments have recorded the first collisions!
  - Challenge: commissioning of machine and detectors of unprecedented complexity, technology and performance
- We expect the year 2010 to be a “SUSY search year”
  - With as little as 300/pb @ 7 TeV we will be beyond the reach of the Tevatron for all missing energy searches
  - Discovery could be easy but could also take more time, data, and ingenuity before we can claim it.
  - First signals might already emerge in the first data in 2010 but will we understand them?
- The LHC results will shape the future of Particle Physics for the years to come.

In other words – the next years will be an exciting time for us . . .