LHC Physics

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"It is wrong to think that the task of Physics is to find out how Nature is. Physics concerns what we can say about Nature."

[Niels Bohr, Nobel laureate 1922]

LHC Main Goals

Elucidate mechanism for EW symmetry breaking

Search or Higgs boson in O(100 GeV)-O(1 TeV) range

If no light Higgs is found, study WW scattering at high mass

Look for evidence of new physics at TeV-scale

Deviations from SM predictions

SM only low-energy "effective theory" of more fundamental theory valid at higher energies

What's on the Physics Menu

Higgs Boson

Supersymmetry (SUSY)

Non-SUSY BSM physics

} Multipurpose detectors (ATLAS and CMS)

No CP-violation (LHCb)

No Heavy Ions (ALICE)

Outline

Introduction
- The LHC
- ATLAS and CMS

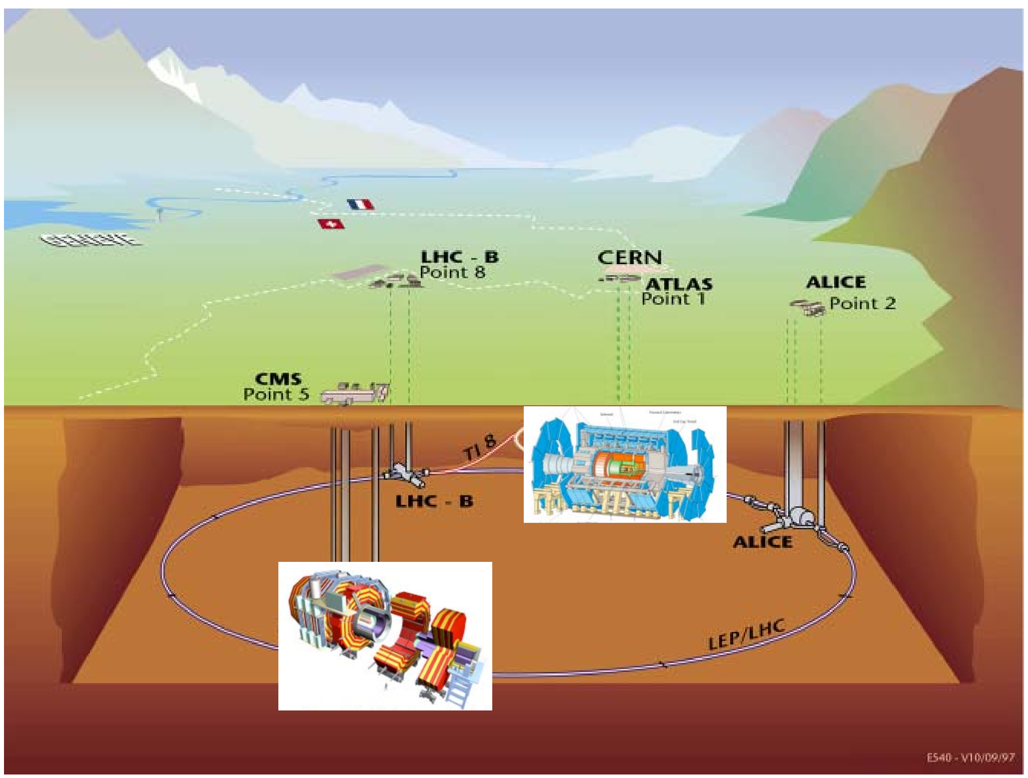
EW Symmetry Breaking
- Higgs boson

Supersymmetry
- mSUGRA

Beyond SUSY
- Extra Dimensions

Not an exhaustive list!

THE LHC



The LHC – some basic facts

LHC housed in former LEP tunnel
- 27 km circumference

Proton-proton machine

$$\sqrt{s} = 14\,\text{TeV}$$

Superconducting magnets
- B = 8.4 T
- Limiting factor for total energy
- (Only 60% of circumference is magnetised)

$$p[\text{GeV/c}] = 0.3\,B[\text{T}]\,R[\text{m}]$$

Luminosity

Rate (= no. of interactions per unit time):

$$R = \sigma L$$

Integrated number of interactions:

$$N = \int \sigma L(t)\, dt$$

σ = cross section

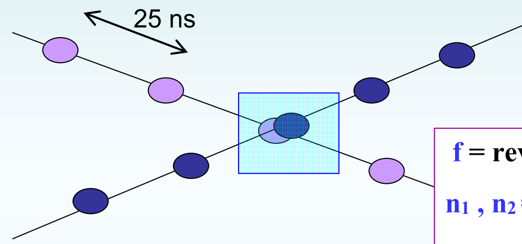
L = luminosity

Design luminosity:

"Low" = 10^{33} cm^{-2} s^{-1} (O(10 fb^{-1}) / yr)

"High" = 10^{34} cm^{-2} s^{-1} (O(100 fb^{-1}) / yr)

Luminosity – cont'd



$$L = \frac{f\, n_1\, n_2}{A}$$

f = revolution frequency

n_1 , n_2 = # of particles per beam

A = effective beam x-sectional area

25 ns bunch crossing (→ 40 MHz crossing frequency)

2835 / 3564 "full" bunches

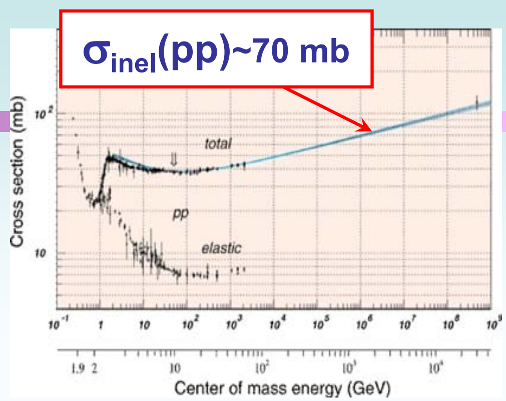
n1 = n2 = 10^{11}

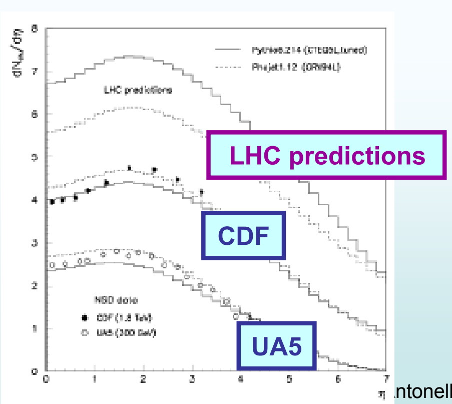
σ_{beam} = 16 μm (gaussian transverse beam profile, $A = 4\pi\sigma_{beam}^2$)

Minimum Bias

Non-single diffractive interactions (soft partons)

"Operational" definition of "minimum bias" depends on experimental trigger





Measured at lower energies (SppS and Tevatron)

Large uncertainties on extrapolation to LHC energies

Minimum Bias and Pile-up

At nominal high luminosity ($L = 10^{34}$cm^{-2}s^{-1}=10^{7}mb^{-1} Hz), on average 23 minimum bias events superimposed on any rare discovery signal

And ~1000 low-pt tracks per event !

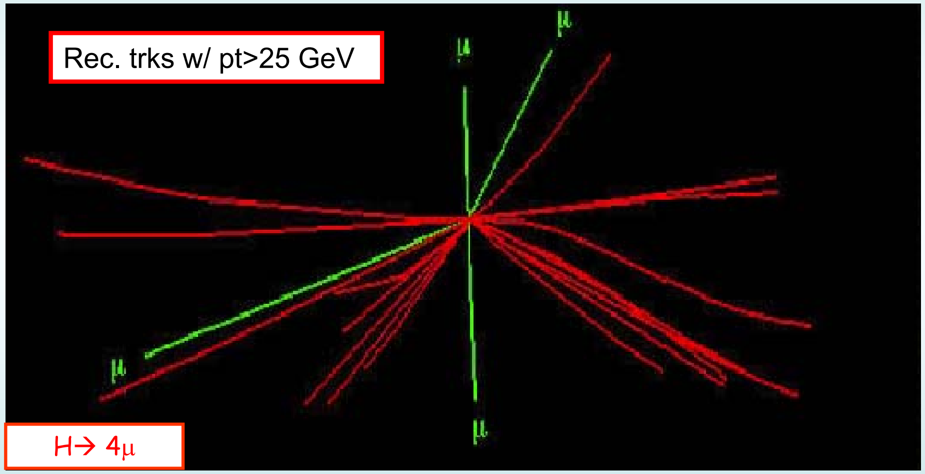
Moreover, due to finite detector response time, out-of-time pile-up from different bunch crossings

Event must be "time stamped"

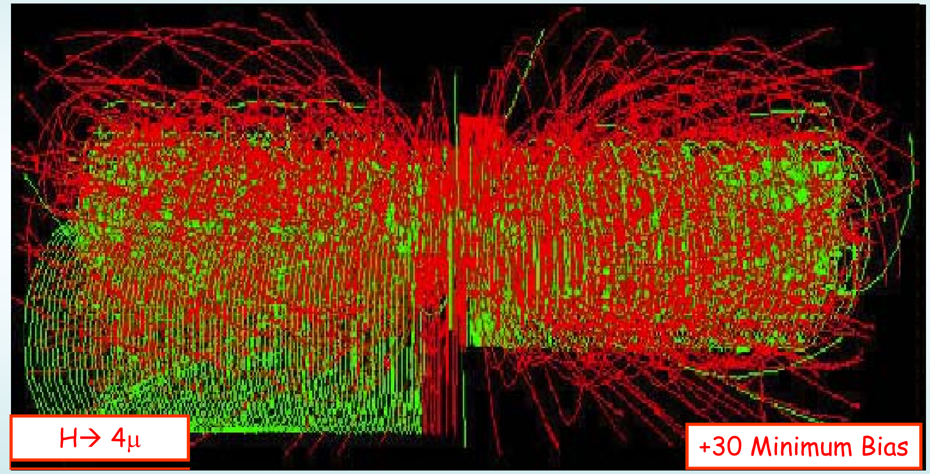
Important impact on detector design

Fast electronics, high granularity, radiation hardness

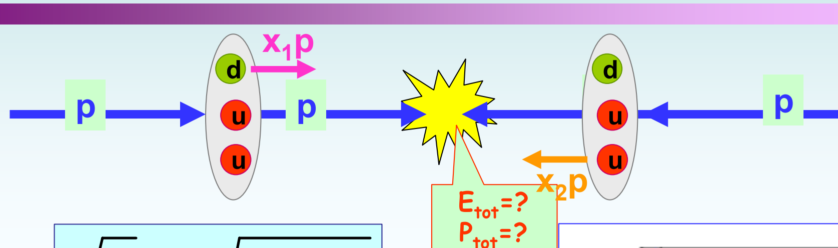
The Challenge



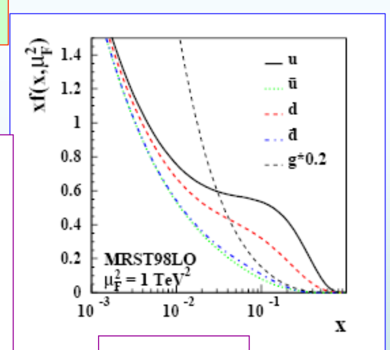
The Challenge



Collisions at a hadron collider



$$\sqrt{\hat{s}} = \sqrt{x_1 x_2 s}$$



PDFs

No constraint on total initial energy

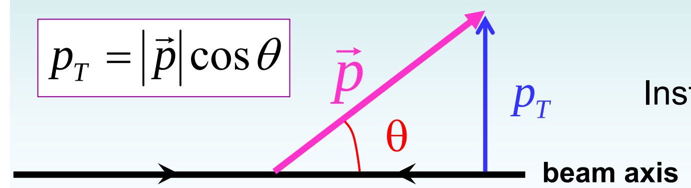
Broad range of √s → good for discovery

(All possible processes are "on" simultaneously)

Typically $x_1 \neq x_2$ → hard scatter boosted along beam direction

Event kinematics – p_T and η

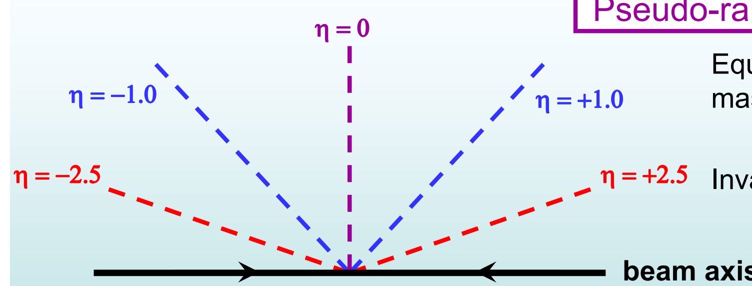
$$p_T = |\vec{p}|\cos\theta$$



Instead of polar angle θ :

$$\eta = -\log\left(\tan\frac{\theta}{2}\right)$$

Pseudo-rapidity



Equivalent to rapidity for massless particles

Invariant under boost

Event kinematics – Etmiss

Total energy and momentum are always conserved

For a hadron collider, this does not result in a constraint on the total transverse momentum p_T (initial partons have unknown initial momenta)

Assuming that the partons in the initial state move parallel to the proton beams, and that the total p_T of the unseen proton remnants (lost along the beam pipe) is ~0 :

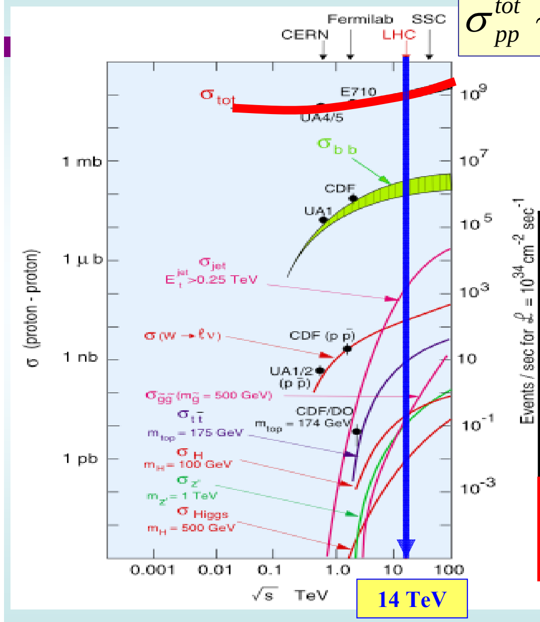
$$\vec{p}_T^{\,miss} = -\vec{p}_T^{\,vis} = -\sum_{i \in vis} \vec{p}_T^{\,(i)}$$

Can be used to infer the presence of "neutrino-like" particles that leave the detector unseen

Total missing p_T approximated by vector sum of all energy deposits in calorimeters (→Etmiss)

Cross Sections

$\sigma_{pp}^{tot} \sim 110$ mb $\quad (\sigma_{pp}^{inel} \sim 70$ mb)



Minimum Bias rate: O(10^9 Hz) !!

Process	σ (nb)	#evts [10 fb⁻¹]	Rates(Hz) ["high" L]
$b\bar{b}$	500 μb	5×10^{12}	5×10^{6}
$W \to e\nu$	15 nb	$\sim10^{8}$	150
$Z \to ee$	1.5 nb	$\sim10^{7}$	15
$t\bar{t}$	800 pb	$\sim10^{7}$	10
$\tilde{g}\tilde{g}$ (1 TeV)	~1 pb	$\sim10^{4}$	10^{-2}
$H(200\text{ GeV}) \to 4\ell$	~10 fb	$\sim10^{2}$	10^{-4}

"Needle in haystack"

Search Strategy for Rare Processes

High-pT physics largely dominated by QCD processes, while interesting physics has EW cross sections

Purely hadronic channels essentially hopeless

Must rely on distinctive final state signatures

- leptons (e, mu and taus)
- photons
- b-jets
- missing ET

→ Further signal suppression from branching ratios

Detector Requirements

Excellent position and momentum resolution in central tracker

- b-jets, taus

Excellent ECAL performance

- electrons, photons
- v. good granularity (energy and position measurements)

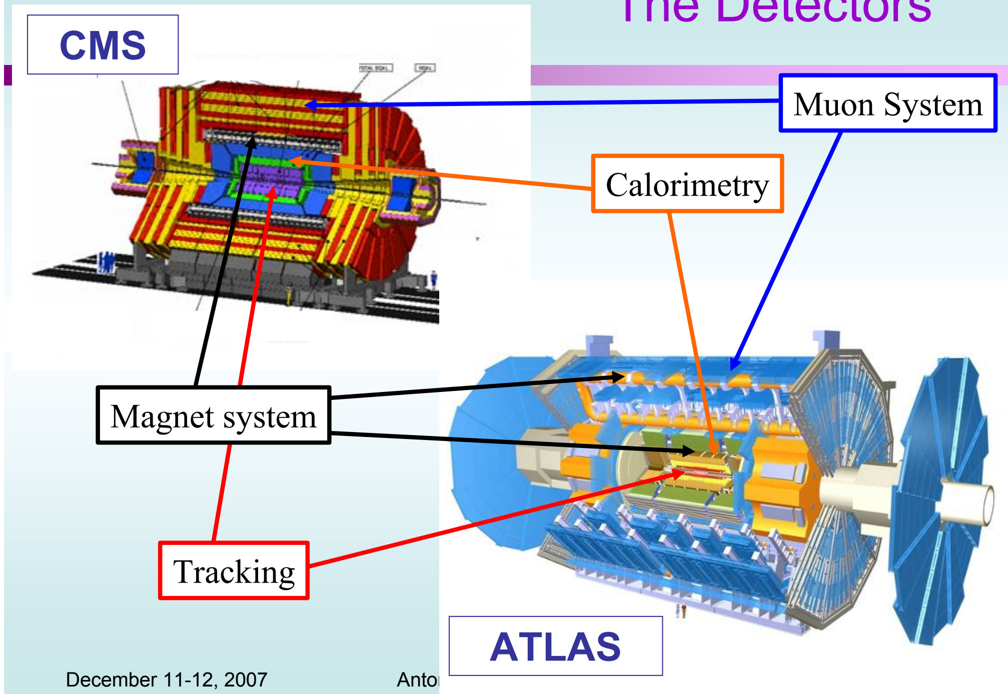
Good HCAL performance

- jets, Etmiss (neutrinos, SUSY stable LSP, etc)
- good granularity (energy and position measurements)
- good η coverage (hermeticity for Etmiss measurements)

Excellent muon identification and momentum resolution

- from "combined" muons in external spectrometer + central tracker

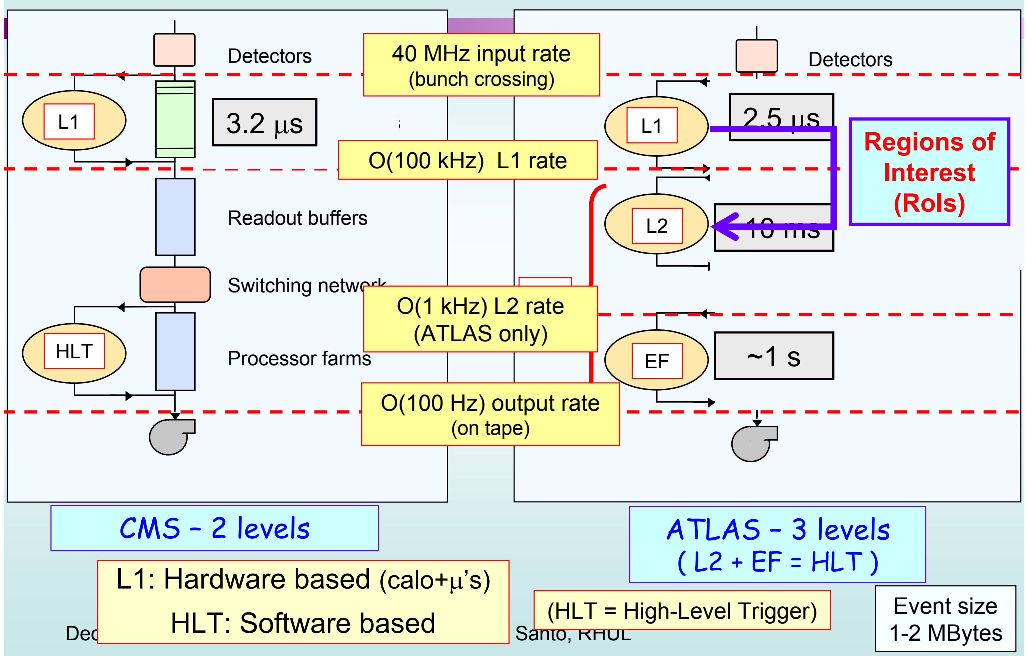
The Detectors

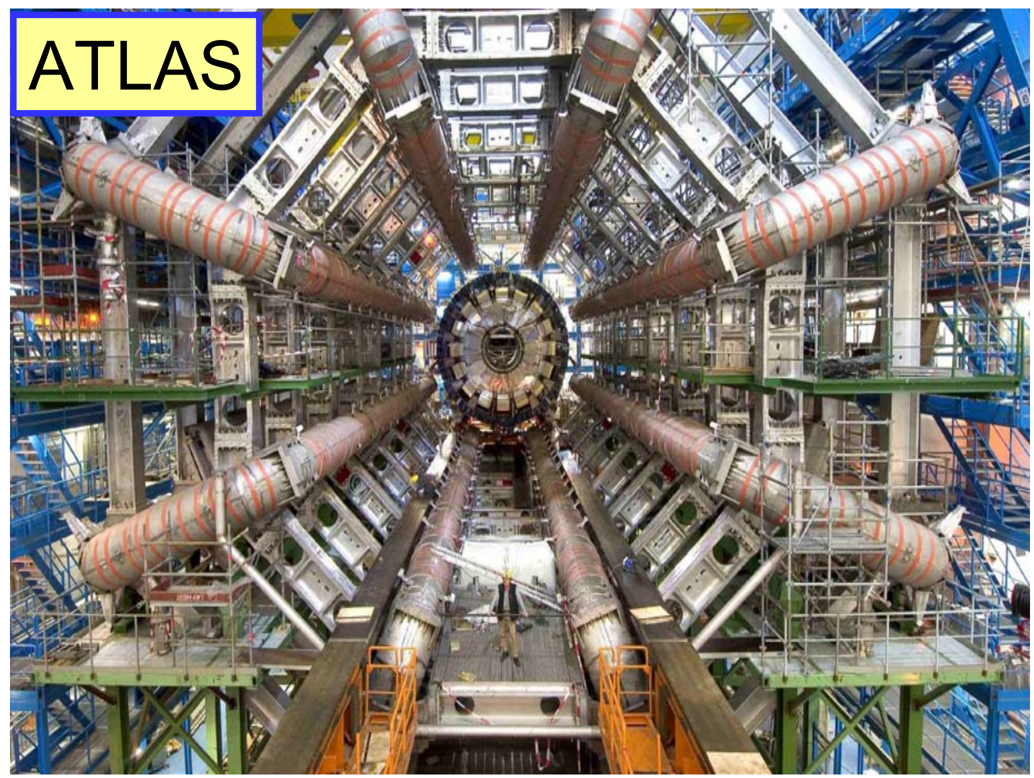


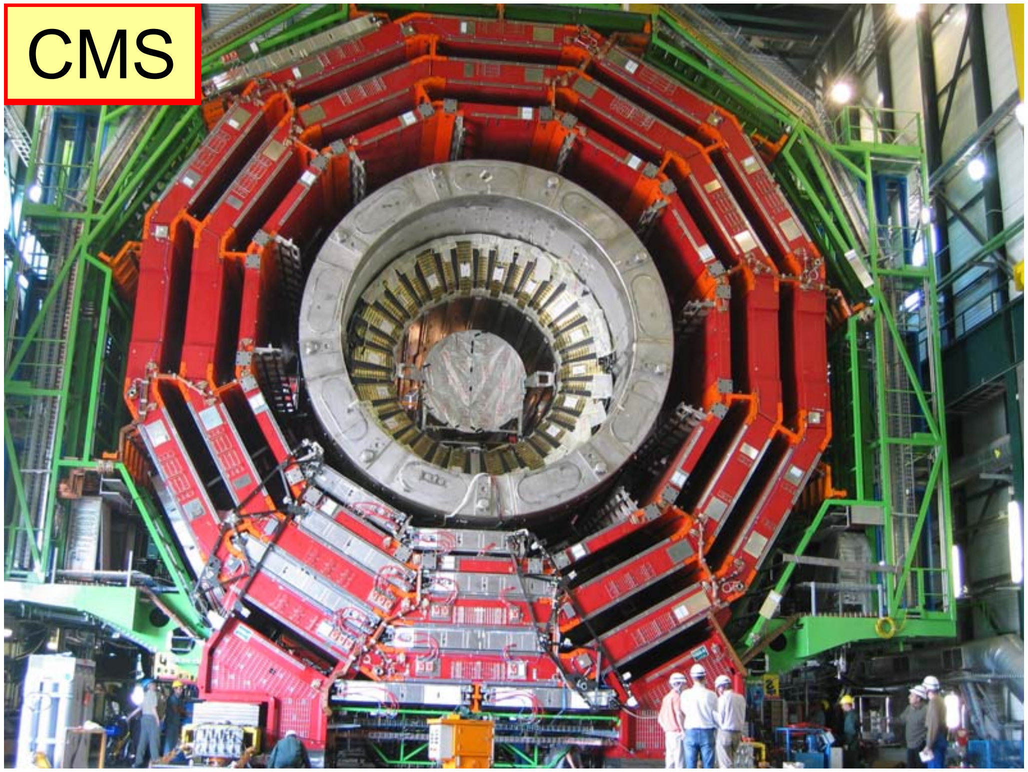
ATLAS vs CMS

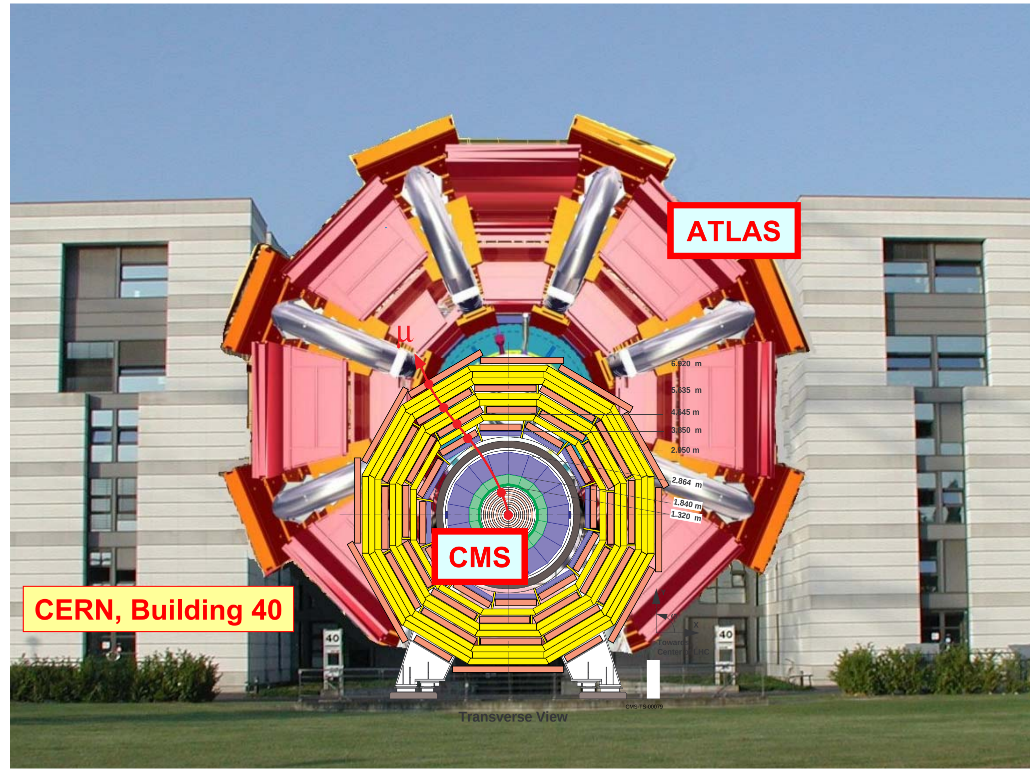
	ATLAS	CMS
Magnet system	Air-core toroids + solenoid Calorimeter outside field B = 2 T (barrel)	Solenoid Calorimeters inside field B = 4 T
Central tracker	Si pixel + strips, TRT (e/had) $\sigma(p_T)/p_T \sim 5\times10^{-4}\, p_T \oplus 0.01$	Si pixel+strips $\sigma(p_T)/p_T \sim 1.5\times10^{-4}\, p_T \oplus 0.005$
ECAL	Pb + Liquid Ar (LAr) $\sigma_E/E \sim 10\%/\sqrt{E}$ (uniform) longitudinal segmentation	$PbWO_4$ crystals $\sigma_E/E \sim 3\text{-}5\%/\sqrt{E}$ no longitudinal segmentation
HCAL	Fe-scintillator + Cu-LAr (10 λ) $\sigma_E/E \sim 50\%/\sqrt{E} \oplus 0.03$	Cu-scintillator (5.8 l + catcher) $\sigma_E/E \sim 65\%/\sqrt{E} \oplus 0.05$
μ–Det	Air $\rightarrow \sigma(p_T)/p_T \sim 7\%$ at 1TeV (standalone)	Fe $\rightarrow \sigma(p_T)/p_T \sim 5\%$ at 1TeV ("combined" muons)

Overview of the CMS and ATLAS Triggers









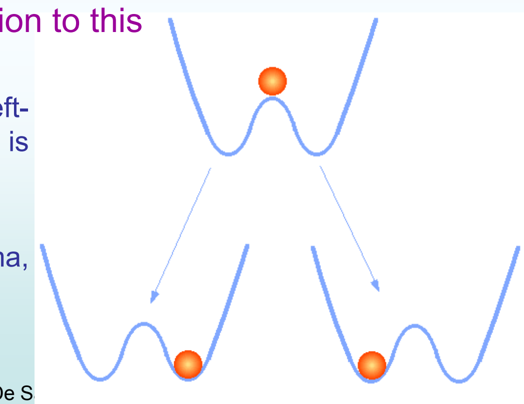
EW SYMMETRY BREAKING AND HIGGS BOSON

Electroweak Symmetry Breaking

- SU(2)⊗U(1) must be a broken symmetry
  - photon is mass less, W and Z are not
- Don't want to destroy gauge invariance of theory (SM)
  - no explicit symmetry breaking term in lagrangian
- Higgs mechanism offers a solution to this

Laws of Nature (lagrangian) are left-right symmetric, equilibrium state is not

By choosing one of the two minima, particle breaks l-r symmetry

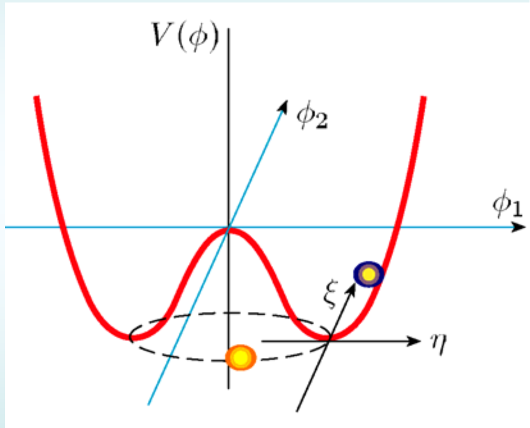


Higgs Mechanism

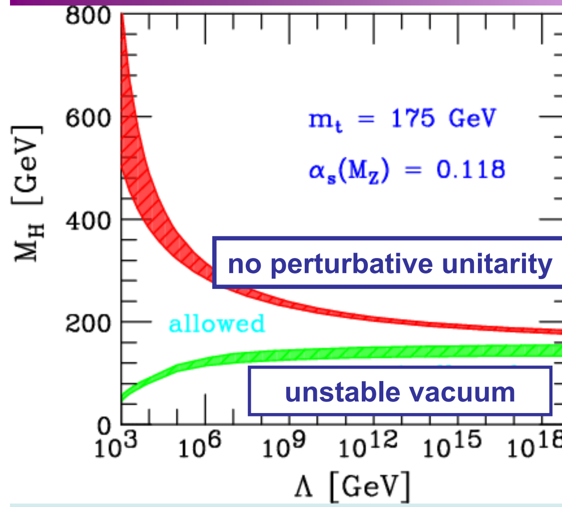
Two independent fields
and two independent "motions"

Excitations in one direction (along potential) produce physical Higgs boson

Excitations in the "horizontal plane" correspond to gauge transformation:
- "global" → unseen
- "local" → extra polarization state (gives mass to gauge bosons)



Theoretical Constraints on Higgs Mass



Upper bound
(triviality) :

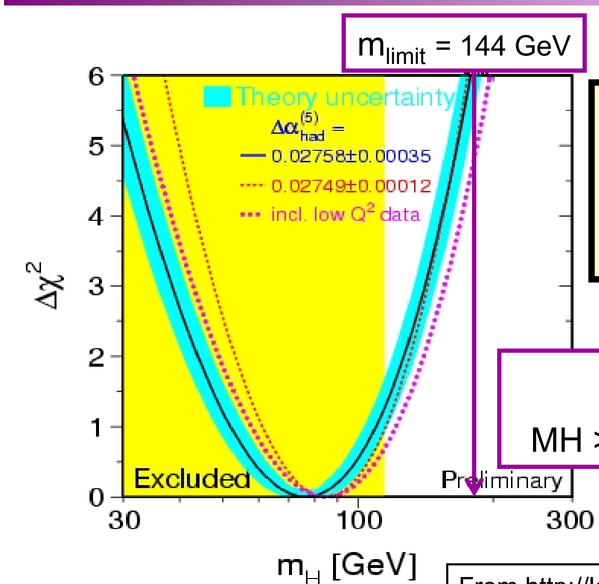
$$\Lambda \le M_H \exp\left(\frac{4\pi^2 v^2}{3M_H^2}\right)$$

Lower bound
(vacuum stability) :

$$M_H^2 > \frac{3G_F\sqrt{2}}{8\pi^2} F \log\left(\Lambda^2 / v^2\right)$$

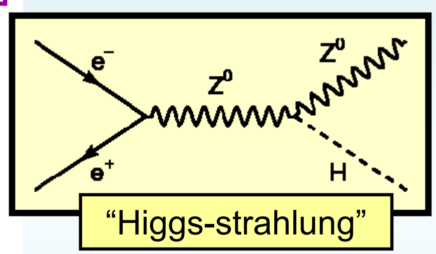
(Λ = cut-off scale at which new physics becomes important)

Experimental Constraints on Higgs Mass



From http://lepewwg.web.cern.ch/LEPEWWG/

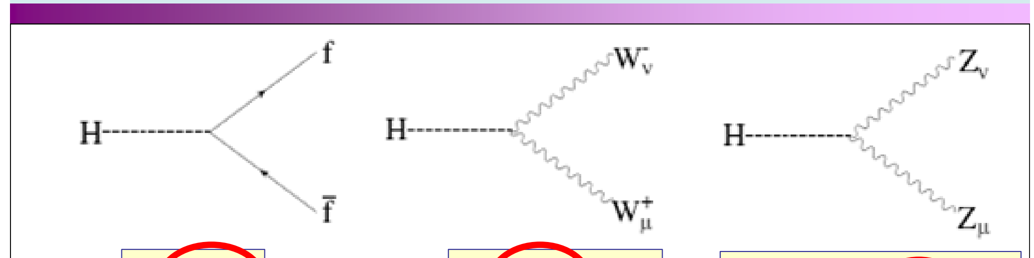
At LEP-2 :



Direct LEP limit :

MH >114.4 GeV (95% C.L.)

SM Higgs Couplings

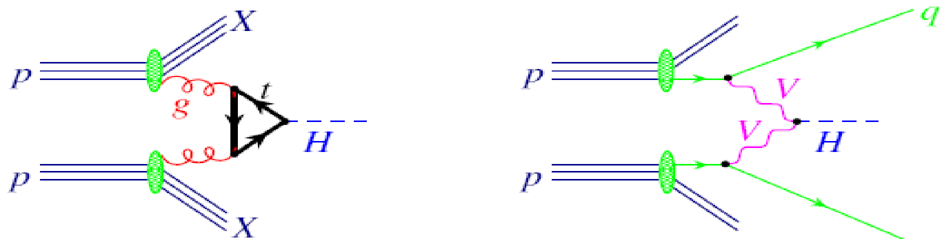


$$-i\frac{m_f}{v} \qquad ig\, m_W\, g_{\mu\nu} \qquad ig\frac{1}{\cos\theta_W} m_Z\, g_{\mu\nu}$$

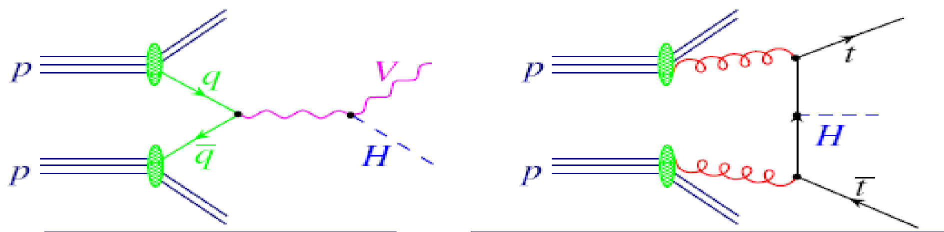
Different Feynman rules for fermions and gauge bosons, but in all cases

Higgs couplings proportional to mass

SM Higgs Production at the LHC

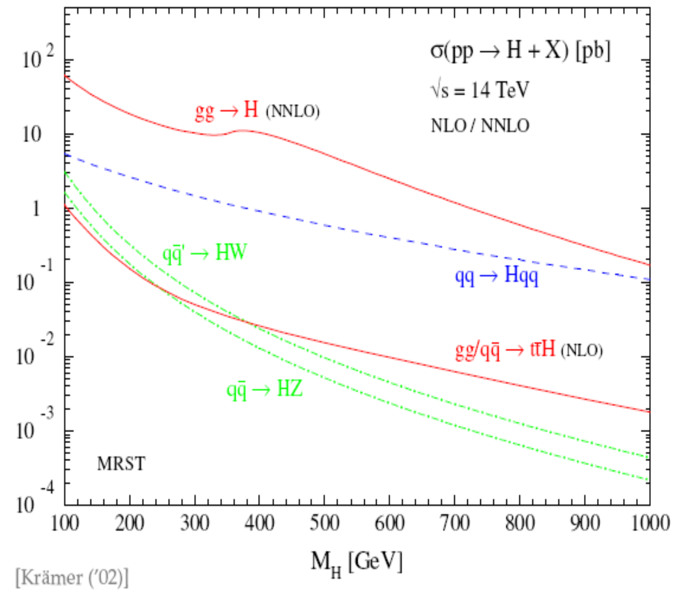


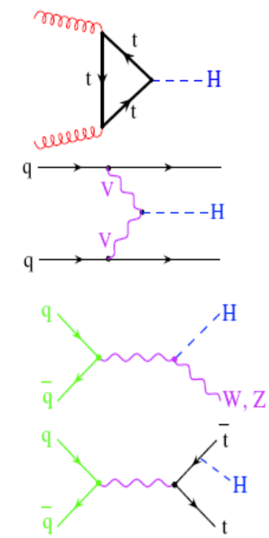
Gluon Fusion | **Vector Boson Fusion**



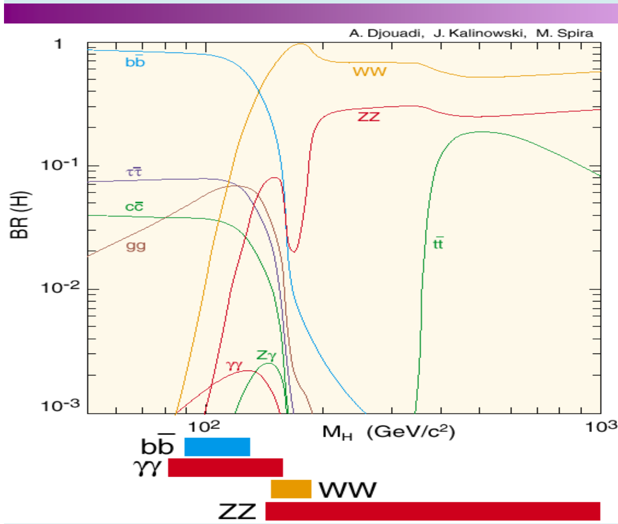
Higgs-strahlung | **ttbar H ("associated" production)**

SM Higgs Production Cross Sections





Standard Model Higgs Decays

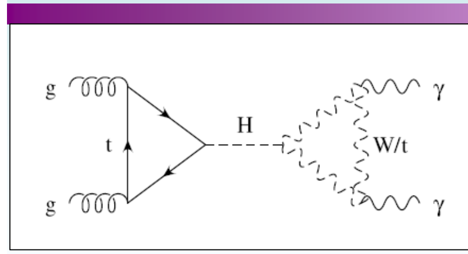


Heaviest quark (b-bbar) BR dominates at low masses, until there is enough energy to produce gauge boson pairs (WW, ZZ)

But b-bbar very difficult due to huge QCD background and limited b-jet resolution (O(15%))

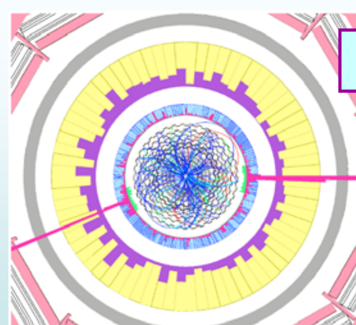
Despite much lower BR, H→γγ via intermediate ttbar loop has better Signal/Bkgd ratio for low Higgs mass

Low Mass Higgs (M_H<140 GeV) – H → γγ



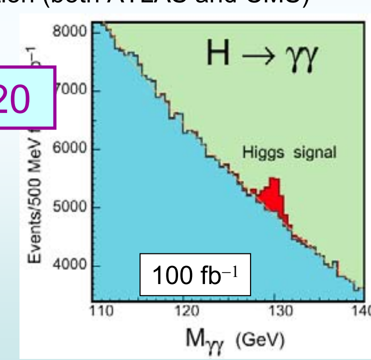
Direct Higgs coupling to γγ forbidden, as photon is mass less

Low branching ratio (~10^{-3}), but nice mass peak thanks to excellent ECAL energy resolution (both ATLAS and CMS)



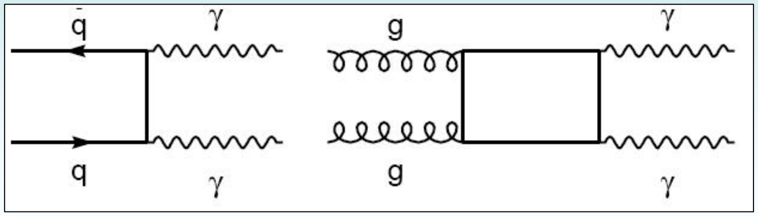
S/B ≈1:20

CMS Physics TDR, 2006

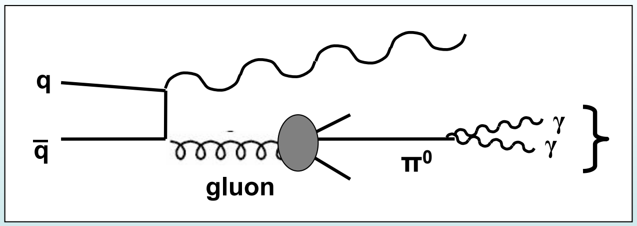


Resolution ~1 GeV at 100 GeV

H → γγ – Backgrounds

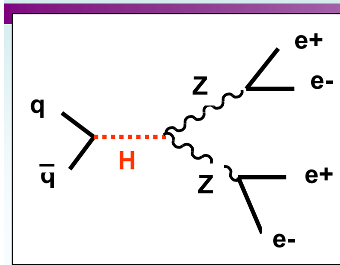


Irreducible (from physics)
– Intrinsically v. similar to signal



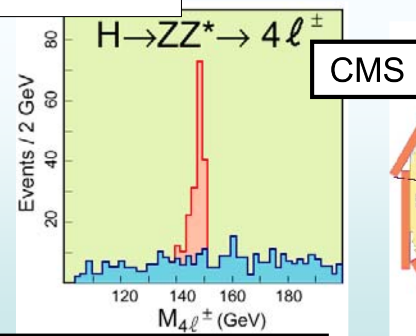
Reducible (can be suppressed in principle) –
e.g. increased calo segmentation

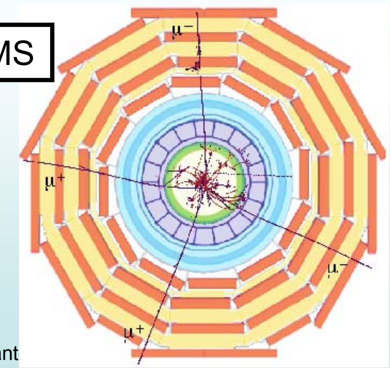
High Mass Higgs ($M_H > 2M_Z$) – H → 4 lep



$H \to ZZ^* \to \ell^+\ell^- \ \ell^+\ell^-$ (ℓ =e,μ)

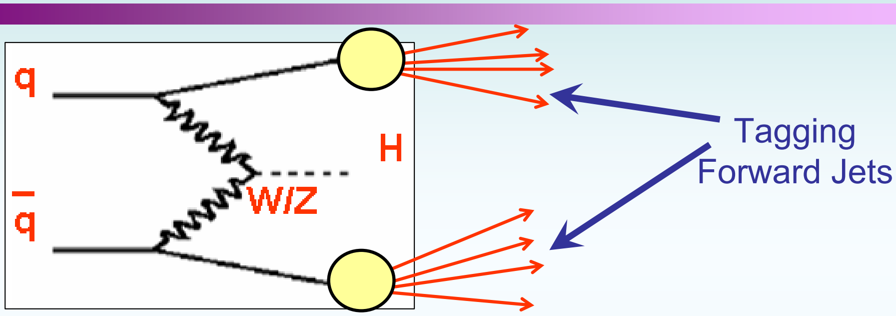
Very little background (ZZ, Zbb, t-ttbar)



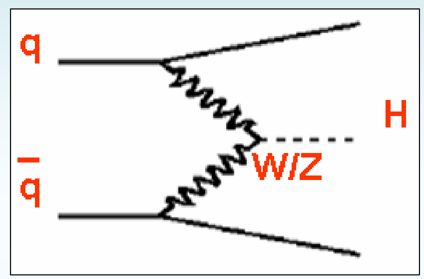


Resolution <1 GeV at 100 GeV

Vector Boson Fusion



Vector Boson Fusion

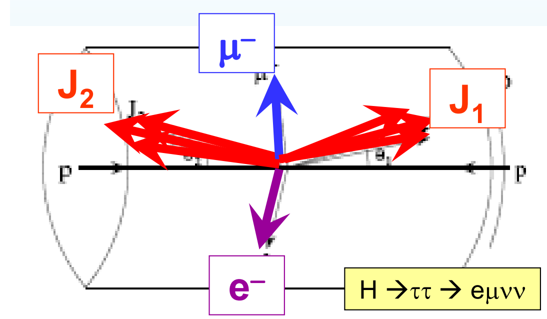


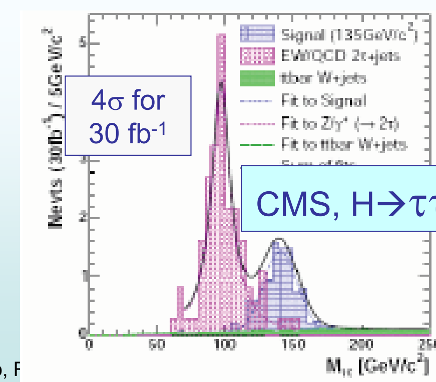
Two tagging forward jets

Higgs decay products in central region

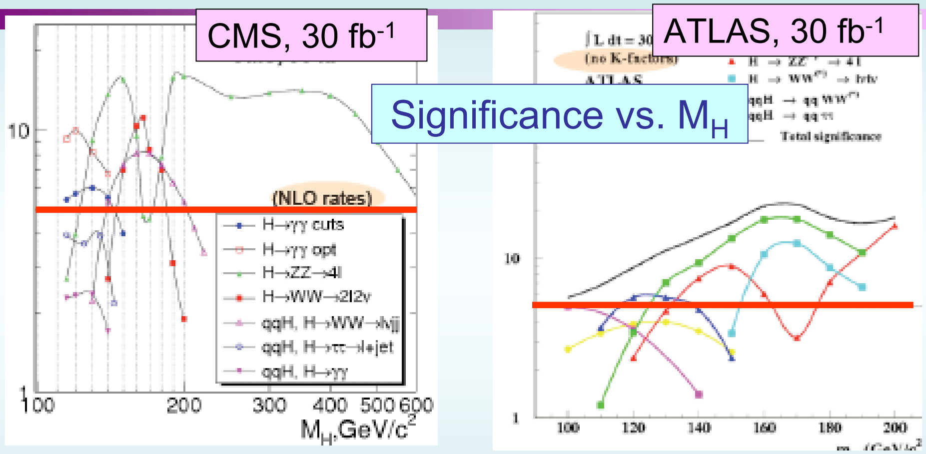
Lep-lep or lep-had signature for H→ττ

High-p_T jet veto





SM Higgs – Discovery Potential



"Significance" σ measures how likely it is that observed signal is the product of statistical fluctuations in the data

For example, **σ = S/sqrt(S+B) > 5** usually taken as "threshold" for discovery (S=signal, B=background)

Higgs Boson Properties

Once Higgs boson is discovered, want to measure its properties…

- mass, width
- spin, CP (SM predicts 0^{++})
- coupling to other bosons and to fermions
- self-coupling

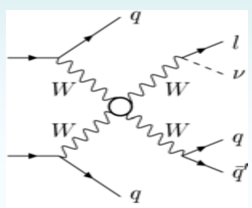
… and check whether it's a SM Higgs, or if for example it is compatible with theories beyond the SM (e.g. SUSY)

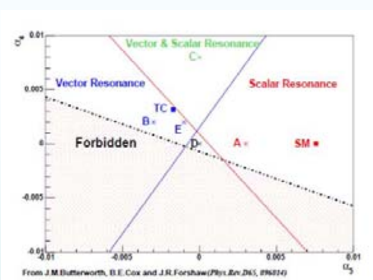
- in principle there could be more than one Higgs boson
- perform direct searches for extra Higgs bosons

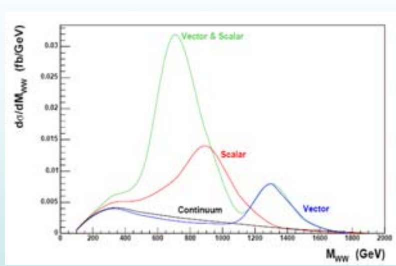
What If No Higgs?...

If no Higgs boson is found at the TeV scale, new mechanism is required to avoid divergencies at high energy

Study of the WW cross section may hold the key in this case, as WW scattering becomes strong at the TeV scale in the absence of a light Higgs







No further discussion here

SUPERSYMMETRY

Why go Beyond the Standard Model?

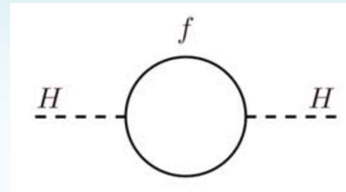
Despite its many successes, Standard Model is widely believed to be only an effective theory, valid up to a scale $\Lambda << M_{Planck}$

- Gravity not included in SM
- Hierarchy/naturalness problem:
  - $M_{EW} << M_{Planck}$
  - Fine-tuning
- Unification of couplings

Need a more fundamental theory of which SM is only a low-energy approximation

Hierarchy Problem and Naturalness

In SM, loop corrections to Higgs boson mass:



$$\delta m_H^2 = O\left(\frac{\alpha}{\pi}\right)\Lambda^2$$

Theory cut-off

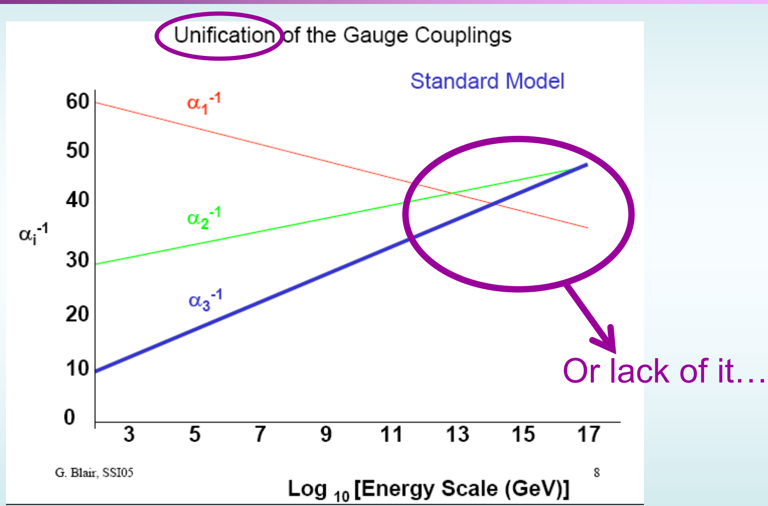
Natural scale of scalar mass is very large!

These corrections, which are large, give rise to fundamental problems when requiring that:

- m_H << fundamental mass scale (i.e. M_{Planck}) (hierarchy problem)
- Corrections δm_H^2 to Higgs mass should not be >> m_H^2 (naturalness)

Need either fine-tuning or protective symmetry!

Unification of Coupling Constants in the SM



Slope of $1/\alpha$ lines depends on matter and couplings of entire theory

Supersymmetry (SUSY)

- Space-time symmetry that relates fermions (matter) and bosons (interactions)

$$Q|boson\rangle = |fermion\rangle \quad \text{and} \quad Q|boson\rangle = |fermion\rangle$$

- Further doubling of the particle spectrum
  - Every SM field has a "superpartner" with same mass
  - Spin differs by 1/2 between SUSY and SM partners
  - Identical gauge numbers
  - Identical couplings
- Superpartners have not been observed
  - SUSY must be a broken symmetry
- But SUSY-breaking terms in Lagrangian must not re-introduce quadratic divergences in theory !

Minimal Supersymmetric Standard Model

Standard Model Particles and Fields		Supersymmetric Partners			
		Interaction Eigenstates		Mass Eigenstates	
Symbol	Name	Symbol	Name	Symbol	Name
$q = u,d,c,s,t,b$	quark	$\tilde{q}_L, \tilde{q}_R$	squark	$\tilde{q}_1, \tilde{q}_2$	squark
$l = e, \mu, \tau$	lepton	$\tilde{l}_R, \tilde{l}_L$	slepton	$\tilde{l}_1, \tilde{l}_2$	slepton
$l = \nu_e, \nu_\mu, \nu_\tau$	neutrino	$\tilde{\nu}$	sneutrino	$\tilde{\nu}$	sneutrino
g	gluon	$\tilde{g}$	gluino	$\tilde{g}$	gluino
$W^\pm$	W-boson	$\tilde{W}^\pm$	wino	$\tilde{\chi}^\pm_{1,2}$	chargino
H_u^+, H_d^-	charged Higgs boson	$\tilde{H}_u^+, \tilde{H}_d^-$	charged higgsino		
B	B-field	$\tilde{B}$	bino	$\tilde{\chi}^0_{1,2,3,4}$	neutralino
W^0	W^0-field	$\tilde{W}^0$	wino		
H_u^0, H_d^0	neutral Higgs boson	$\tilde{H}_u^0, \tilde{H}_d^0$	neutral higgsino		

Minimal Supersymmetric Standard Model – II

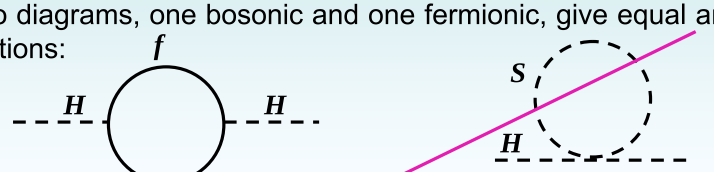
Standard Model Particles	Spin	Superpartners	Spin
quarks	1/2	squarks	0
leptons	1/2	sleptons	0
gauge bosons	1	gauginos	1/2
Higgs bosons	0	higgsinos	1/2

Gauginos and higgsinos mix → 2 charginos and 4 neutralinos

Two Higgs doublets → 5 physical Higgs bosons (h,H; A; $H^\pm$)

Supersymmetric Solution to Divergencies

Now two diagrams, one bosonic and one fermionic, give equal and opposite contributions:



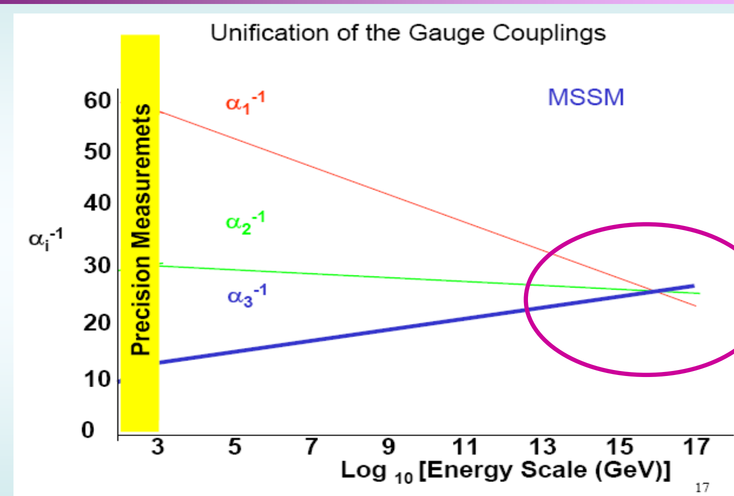
$$\delta m_H^2 = \left(\frac{g_f^2}{16\pi^2}\right)\left(\Lambda^2 + m_f^2\right) - \left(\frac{g_S^2}{16\pi^2}\right)\left(\Lambda^2 + m_S^2\right) = O\left(\frac{\alpha}{4\pi}\right)\left| m_S^2 - m_f^2 \right|$$

If #boson = #fermions and they have equal masses and couplings, the quadratic divergencies cancel

Higgs mass correction $\delta m_H^2 < m_H^2$ if $\left| m_S^2 - m_f^2 \right| <\sim \mathrm{TeV}^2$

Gauge boson contribution cancelled by gaugino contribution

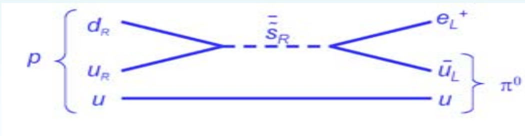
Unification of Coupling Constants in MSSM



Now unification of strong, weak and e.m. forces achieved at ~M_{GUT}

R-parity

MSSM contains L- ad B-violating terms, which could in principle allow proton decay via sparticle diagrams:



This can be prevented by introducing a new symmetry in the theory, called R-parity:

$$R = (-1)^{3(B-L)+2S}$$

R=+1 (SM particles), R=-1 (SUSY particles)

Two important consequences:

- LSP (=Lightest SUSY Particle) is stable – typically neutralino
- Sparticles can only be produced in pairs (in scattering of SM particles)

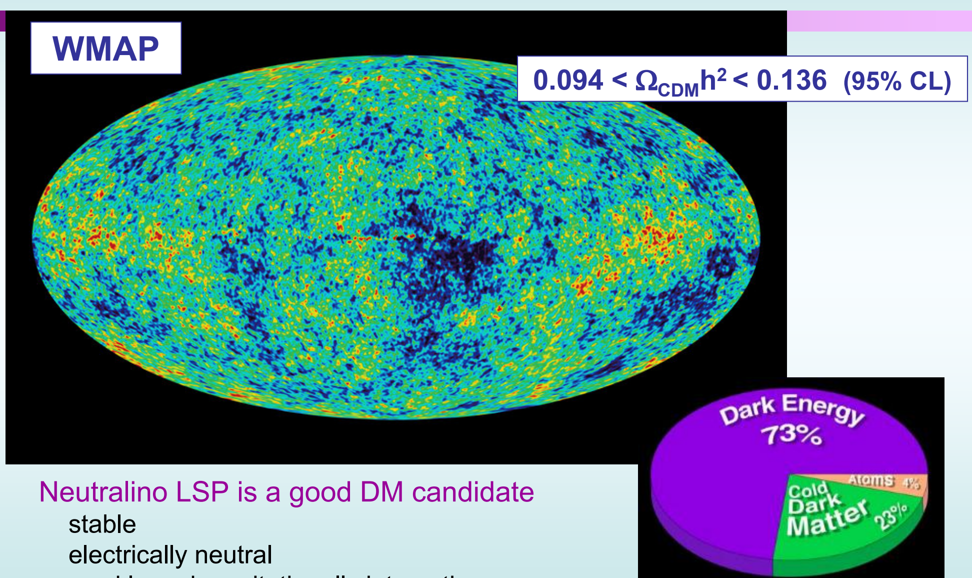
R-parity

In the following, assume R-parity conservation

$$R = (-1)^{3(B-L)+2S}$$

Stable LSP (neutralino)

Neutralino as Dark Matter Constituent



Neutralino LSP is a good DM candidate

- stable
- electrically neutral
- weakly and gravitationally interacting

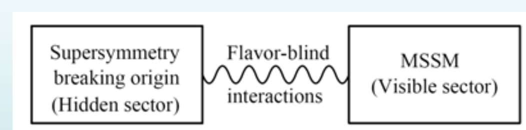
SUSY Soft Breaking

Empirically we know that SUSY must be a broken symmetry (no sparticles with same mass as particles)

Spontaneous breaking not possible in MSSM

- otherwise sparticles with mass less than their SM partners would exist (Ferrara-Girardello-Palumbo)

SUSY breaking must be confined to a hidden sector, which communicates indirectly with the visible one via flavour-blind interactions (i.e. gravity)



SUSY-breaking lagrangian terms do not re-introduce quadratic divergencies ("soft" breaking)

mSUGRA (or CMSSM)

Soft SUSY breaking mediated by gravitational interaction at GUT scale

Only five parameters:

- m_0 – universal scalar mass
- $m_{1/2}$ – universal gaugino mass
- A_0 – trilinear soft breaking parameter at GUT scale
- $\tan\beta$ – ratio of Higgs vevs
- $\mathrm{sgn}(\mu)$ – sign of SUSY Higgs mass term (|μ|determined by EW symmetry breaking)

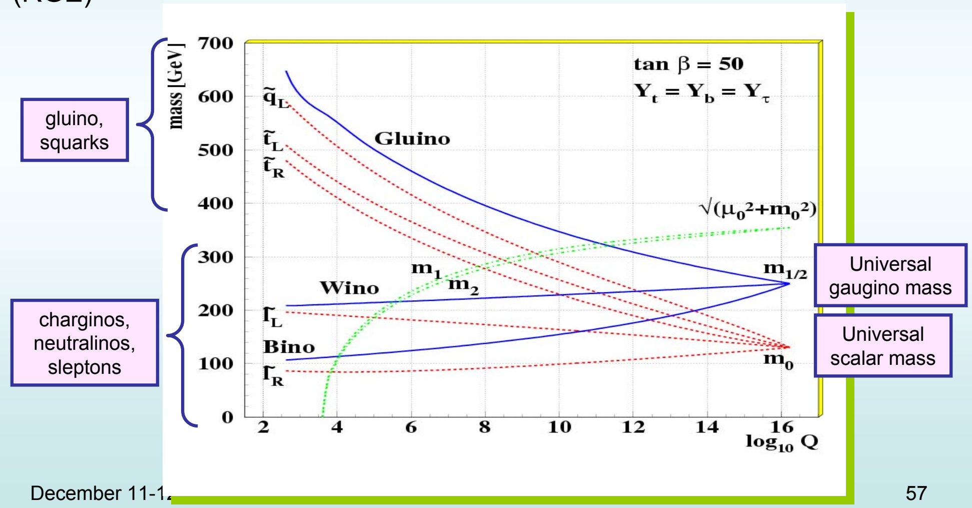
Highly predictive – masses determined mainly by m_0 and $m_{1/2}$

Useful framework to provide benchmark scenarios

RGE Evolution

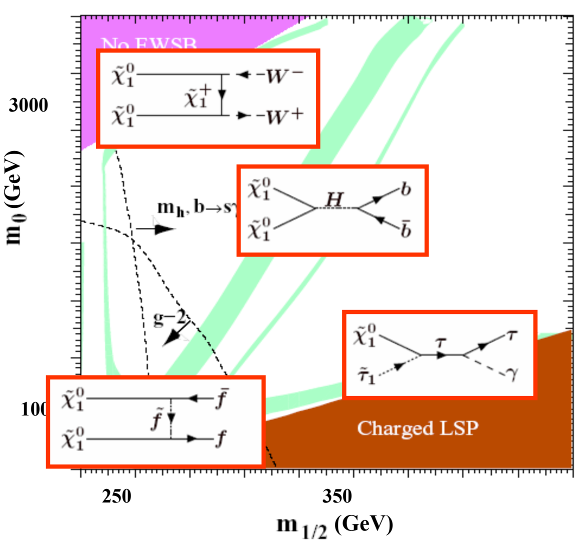
Universal boundary conditions at some high scale (GUT)

Evolution down to EW scale through Renormalisation Group Equations (RGE)



mSUGRA Parameter Space

Four regions compatible with WMAP value for Ωh^2, different mechanisms for neutralino annihilation:



bulk

neutralino mostly bino, annihilation to ff via sfermion exchange

focus point

neutralino has strong higgsino component, annihilation to WW, ZZ

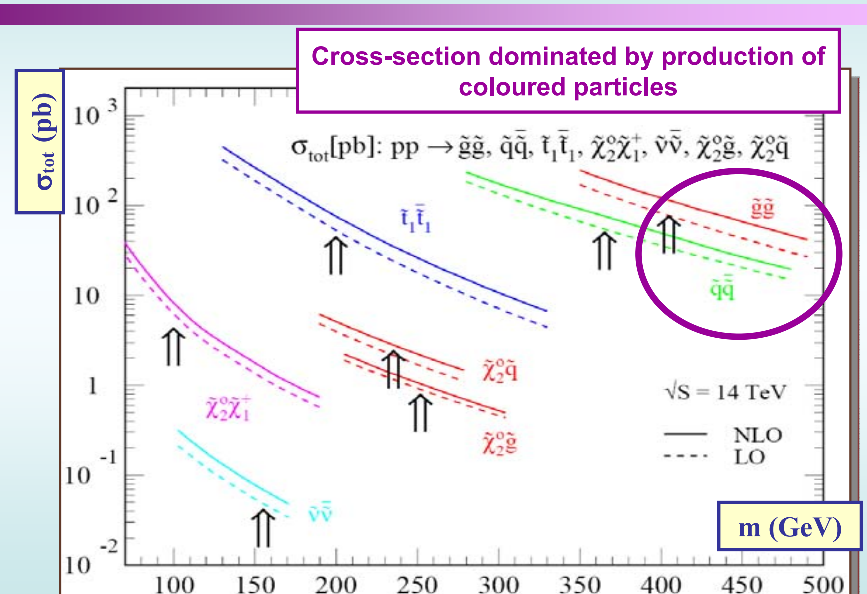
co-annihilation

pure bino, small NLSP-LSP mass difference, typically coannihilation with stau

Higgs funnel

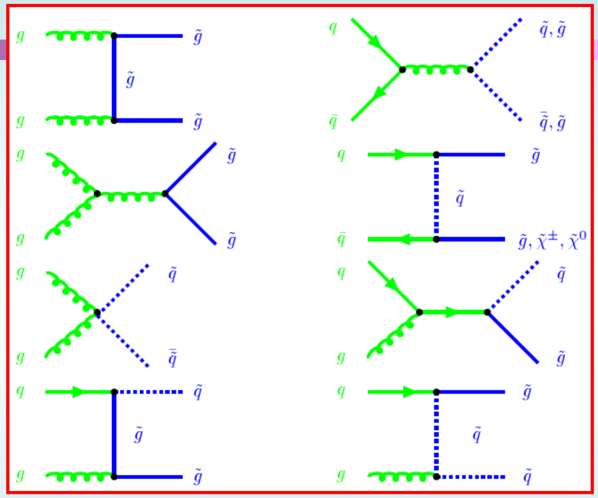
decay to fermion pair through resonant A exchange $\left(m_A \approx 2\,\tilde{\chi}_1^0\right)$ – high tanβ

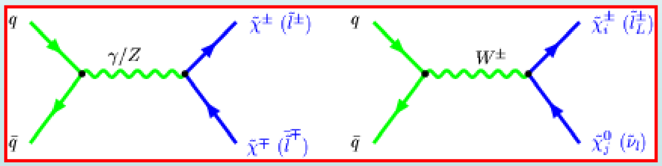
SUSY Cross-Sections



Production Mechanisms

Squark/Gluino Production



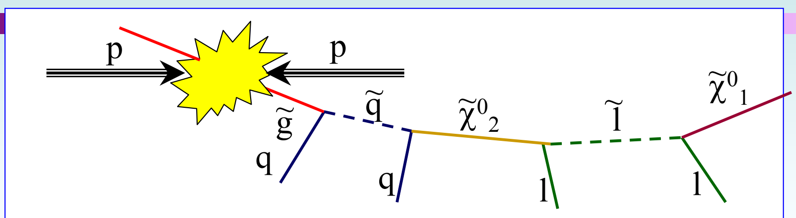


Direct Gaugino Production

Possible Final States

Production	Key Decay Modes	Signatures
• $\tilde{g}\tilde{g}, \tilde{q}\tilde{q}, \tilde{g}\tilde{q}$	$\tilde{g} \to q\bar{q}\tilde{\chi}_1^0$, $q\bar{q}'\tilde{\chi}_1^{\pm}$, $g\tilde{\chi}_1^0$ } $m_{\tilde{q}} > m_{\tilde{g}}$	$\not{E}_T$ + multijets (+leptons)
	$\tilde{q} \to q\tilde{\chi}_i^0$, $\tilde{q} \to q'\tilde{\chi}_i^{\pm}$ } $m_{\tilde{g}} > m_{\tilde{q}}$	
• $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$	$\tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^0 l^{\pm}\nu,\ \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 ll$	Trilepton + $\not{E}_T$
	$\tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^0 q\bar{q}', \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 ll$	Dilepton + jet + $\not{E}_T$
• $\tilde{\chi}_1^{+}\tilde{\chi}_1^{-}$	$\tilde{\chi}_1^{+} \to l\tilde{\chi}_1^0 l^{\pm}\nu$	Dilepton + $\not{E}_T$
• $\tilde{\chi}_i^0\tilde{\chi}_i^0$	$\tilde{\chi}_i^0 \to \tilde{\chi}_1^0 X, \tilde{\chi}_i^0 \to \tilde{\chi}_1^0 X'$	$\not{E}_T$ + Dilepton + (jets) + (leptons)
• $\tilde{t}_1\tilde{t}_1$	$\tilde{t}_1 \to c\tilde{\chi}_1^0$	2 acollinear jets + $\not{E}_T$
	$\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^0 l^{\pm}\nu, \tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^0 q\bar{q}'$	single lepton + $\not{E}_T$ + $b's$
	$\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^0 l^{\pm}\nu, \tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^0 l^{\pm}\nu$	Dilepton + $\not{E}_T$ + $b's$
• $\tilde{l}\tilde{l}, \tilde{l}\tilde{\nu}, \tilde{\nu}\tilde{\nu}$	$\tilde{l}^{\pm} \to l \pm \tilde{\chi}_i^0, \tilde{l}^{\pm} \to \nu_l\tilde{\chi}_i^{\pm}$	Dilepton + $\not{E}_T$
	$\tilde{\nu} \to \nu\tilde{\chi}_1^0$	Single lepton + $\not{E}_T$ + $(jets)$
		$\not{E}_T$

Inclusive Searches



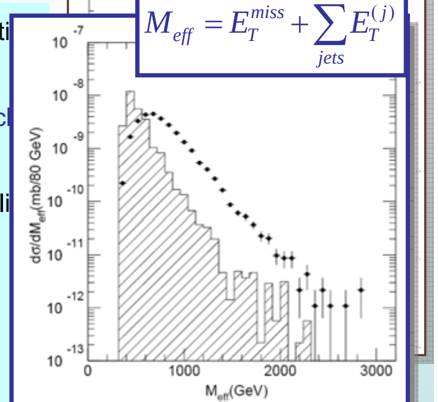
In most scenarios, squark and gluino producti dominates

Squarks and gluinos typically heaviest partic (heavier than sleptons, gauginos, etc)

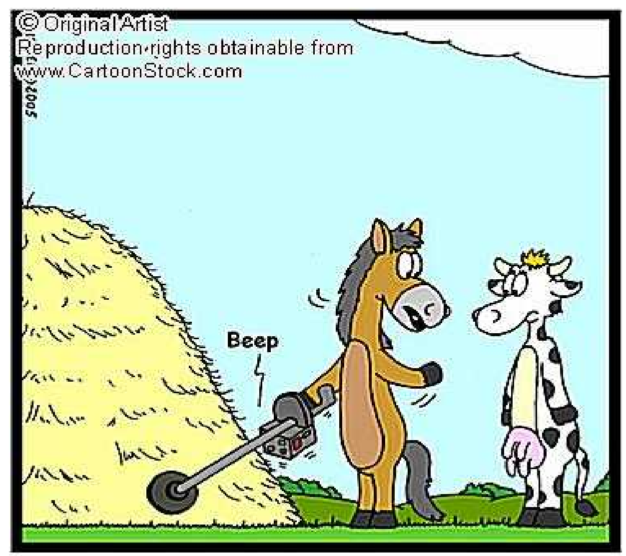
Complex long decay chains to undetected neutrali (stable in RPC models) – Inclusive search:

- high multiplicity of high-p_T jets
- large E_T^{miss} (from escaping LSP)
- ≥ 0 (high-pT) leptons

$$M_{eff} = E_T^{miss} + \sum_{jets} E_T^{(j)}$$

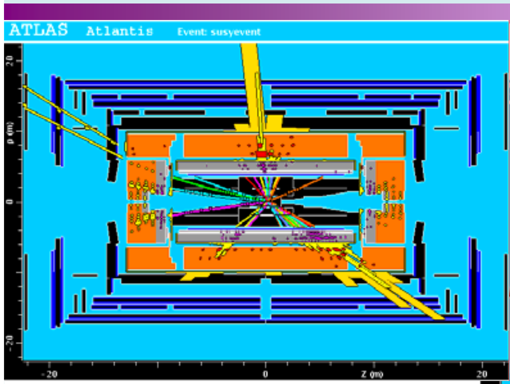


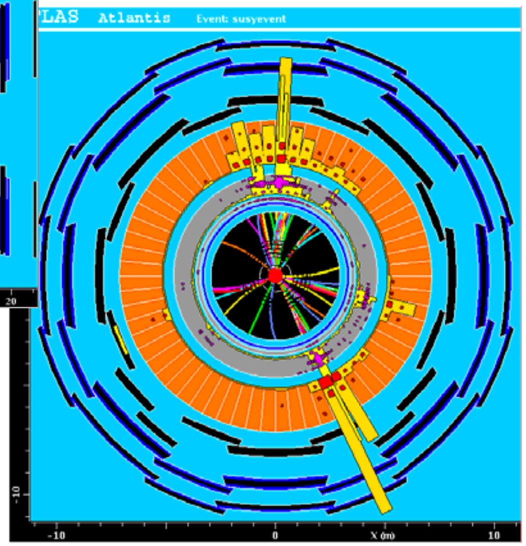
The "Needle in the Haystack"…



You were right: There's a needle in this haystack...

… a SUSY event in ATLAS…



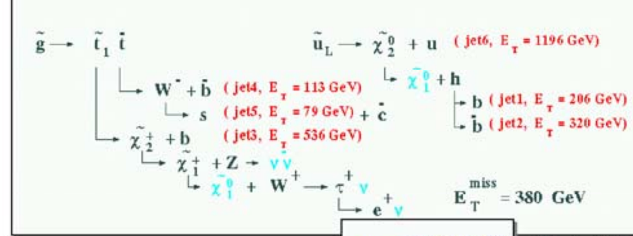


Multi-jet event in Bulk Region

- 6 jets
- 2 high-pt muons
- Large missing E_T

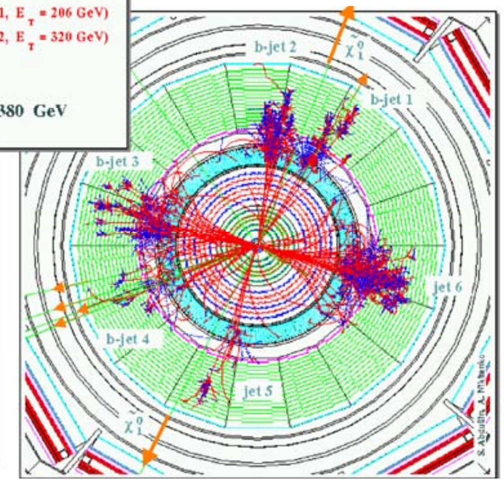
… and one in CMS

mSUGRA : $m_0 = 1000$ GeV, $m_{1/2} = 500$ GeV, $A_0 = 0$, $\tan\beta = 35$, $\mu > 0$

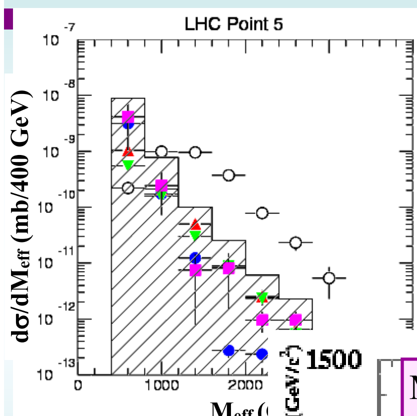


$m_{\tilde{g}} = 1266$ GeV
$m_{\tilde{u}_L} = 1450$ GeV
$m_{\tilde{t}_1} = 1026$ GeV
$m_{\tilde{\chi}_2^0} = 410$ GeV
$m_{\tilde{\chi}_1^0} = 214$ GeV
$m_h = 119$ GeV

Multi-jet event with large missing E_T



SUSY Mass Scale

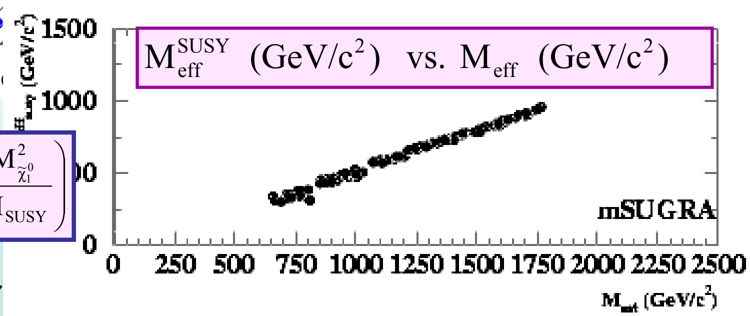


SUSY mass scale defined as cross-section weighted mean of masses of initial SUSY particles produced in pp collision

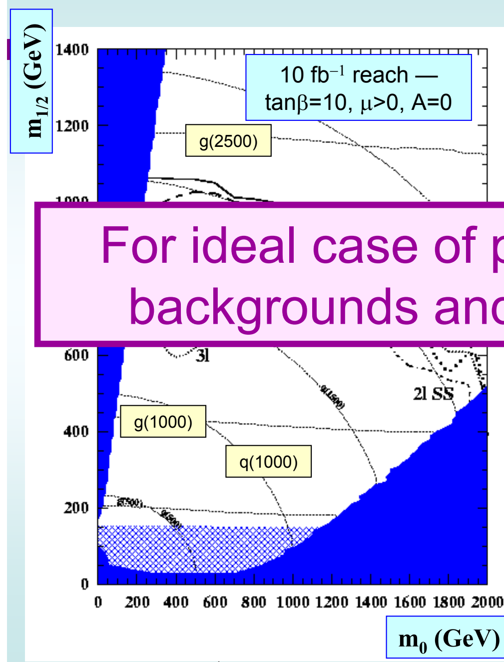
Effective SUSY mass scale M_{eff}^{SUSY} takes into account mass of undetected LSP (neutralino)

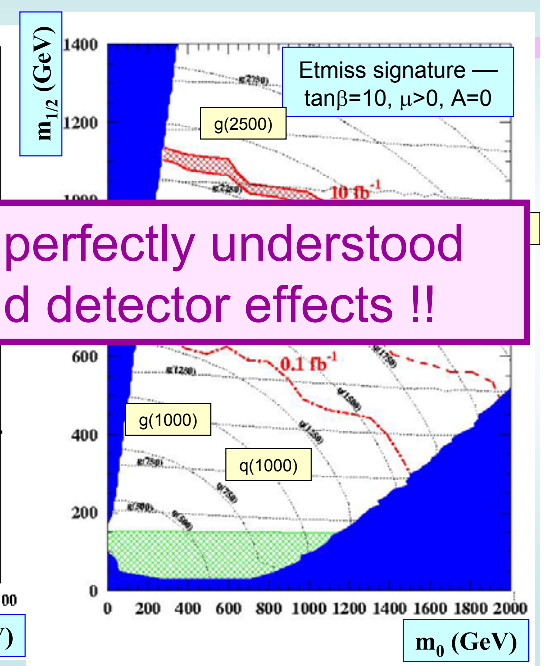
M_{eff} a good estimator for M_{eff}^{SUSY}

$$M_{eff}^{SUSY} = \left(M_{SUSY} - \frac{M_{\tilde{\chi}_1^0}^2}{M_{SUSY}} \right)$$



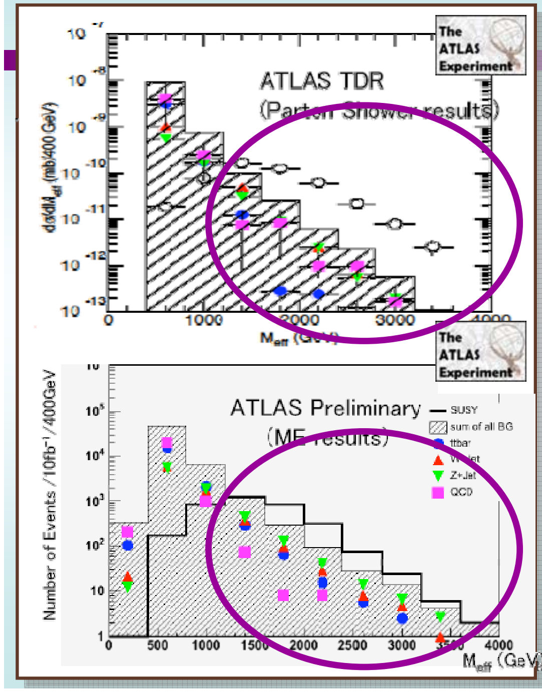
ATLAS mSUGRA Reach





For ideal case of perfectly understood backgrounds and detector effects !!

If Only Life Were That Easy…



Significant discrepancy observed between PS (e.g. Pythia) and ME (e.g. ALPGEN) calculations of multiparton emission amplitudes

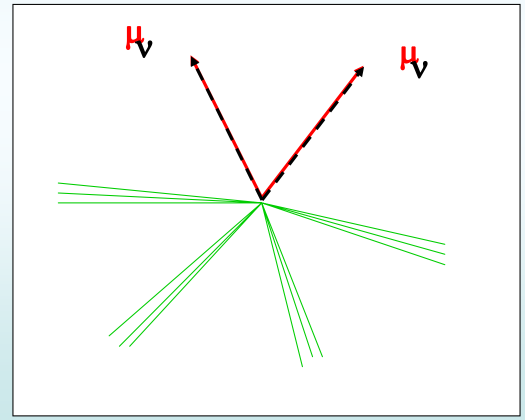
Background rate larger in ME generator, which also predicts a more similar shape to that of signal

Reliance on MC simulated events must be minimized and backgrounds estimated using data-driven techniques

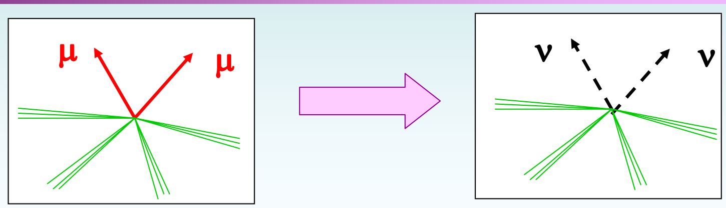
Also need good understanding of detector response

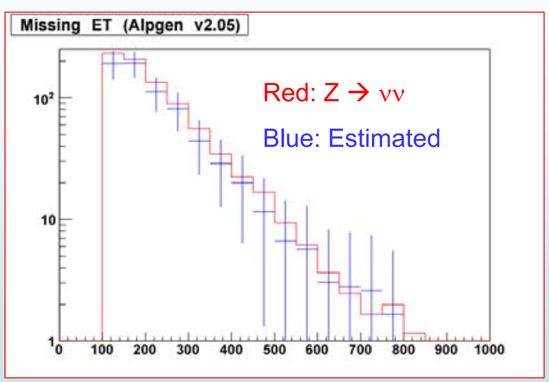
Example of Data-Driven Bkgd Estimation

Z+jets (Z→νν) background from Drell-Yan (Z→ee, μμ)



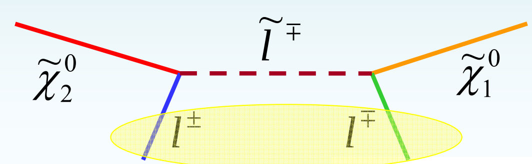
Example of Data-Driven Bkgd Estimation





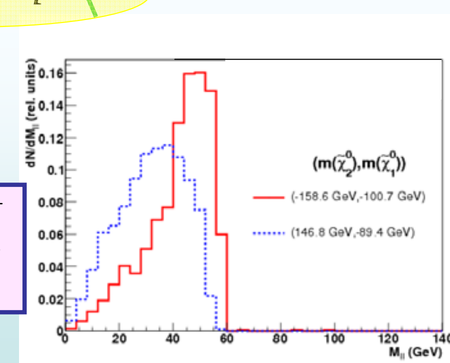
Dilepton Edge

$\tilde{\chi}_2^0$ can undergo chain two-body decay to $\tilde{\chi}_1^0$:

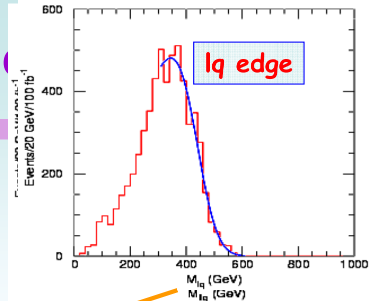


Sharp Same-Flavour Opposite-Sign (SFOS) dilepton invariant mass edge sensitive to sparticle mass differences

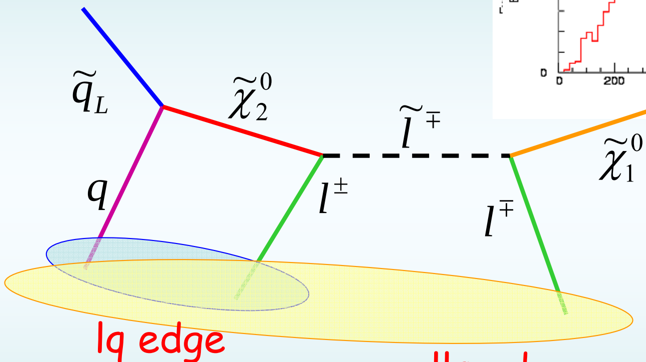
$$M_{ll}^{max} = M(\tilde{\chi}_2^0)\sqrt{1-\frac{M^2(\tilde{l}_R)}{M^2(\tilde{\chi}_2^0)}}\sqrt{1-\frac{M^2(\tilde{\chi}_1^0)}{M^2(\tilde{l}_R)}}$$



More Decay Chains (and ...



Decay chains originating from squarks:



Consider invariant mass combination of lepton and jets

Combine constraints from different decay chains to extract information of individual sparticle masses

Exclusive Channels – An ATLAS Example

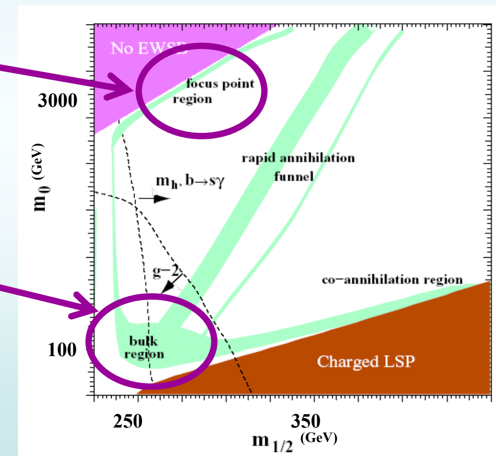
Trilepton signal (from direct chargino-neutralino production and decay) two different points in the mSUGRA parameter space

"SU2" — Focus Point

- Heavy scalars
- No decays through intermediate sleptons

"SU3" — Bulk Region

- "Typical" spectrum
- Decays through intermediate sleptons are allowed

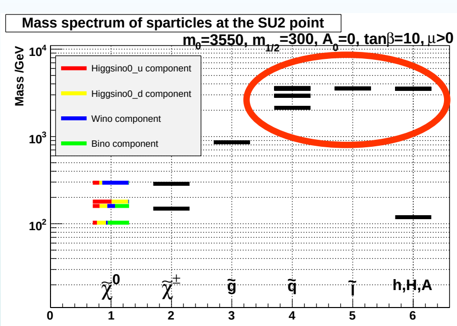


ATLAS Example – SU2 and SU3 Points

SU2

m_0 = 3550 GeV
$m_{1/2}$ = 300 GeV
A = 0
tanβ = 10
m > 0

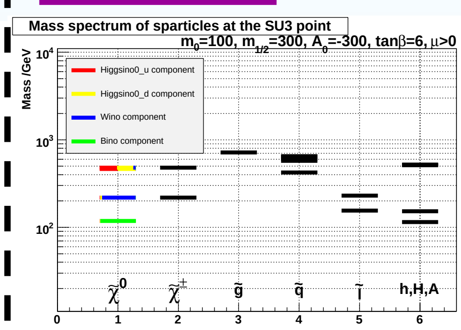
σ = 4.9 pb



SU3

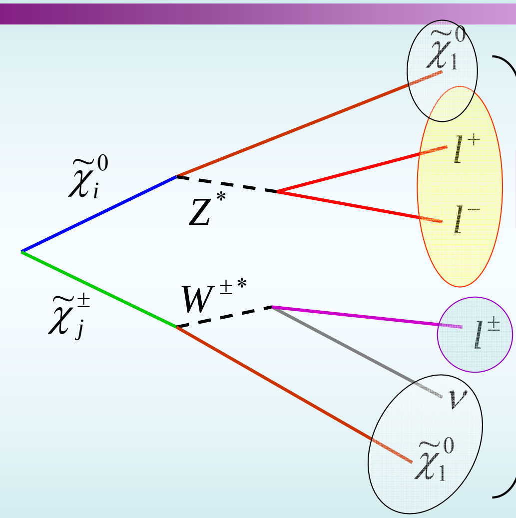
m_0 = 100 GeV
$m_{1/2}$ = 300 GeV
A = -300 GeV
tanβ = 6
m > 0

σ = 18.6 pb



Direct Gaugino Production – Focus Point (SU2)

SU2 – No intermediate sleptons



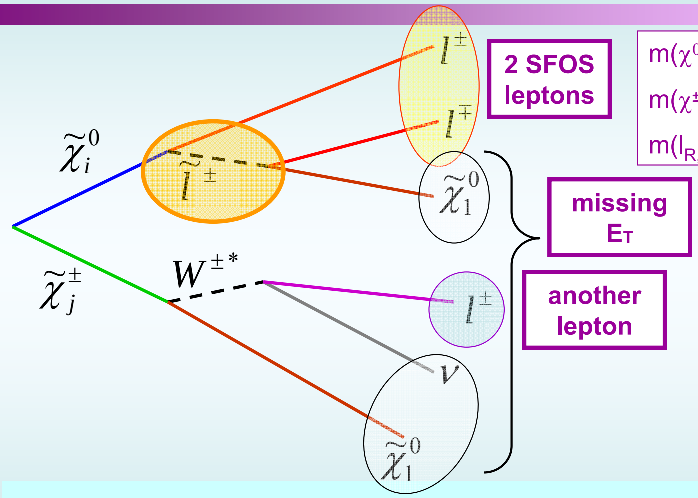
SM bkgd from ZW, ZZ, ttbar, Z/W+jets

$m(\chi^0)$ =103, 160, 180, 296 GeV
$m(\chi^{\pm})$ =149, 288 GeV

Relatively low-p_T leptons due to small mass differences

Preliminary results indicate discovery possible with few 100s fb^{-1}

Direct Gaugino Production – Bulk (SU3)



m(χ^0) =116, 224, 460, 478 GeV

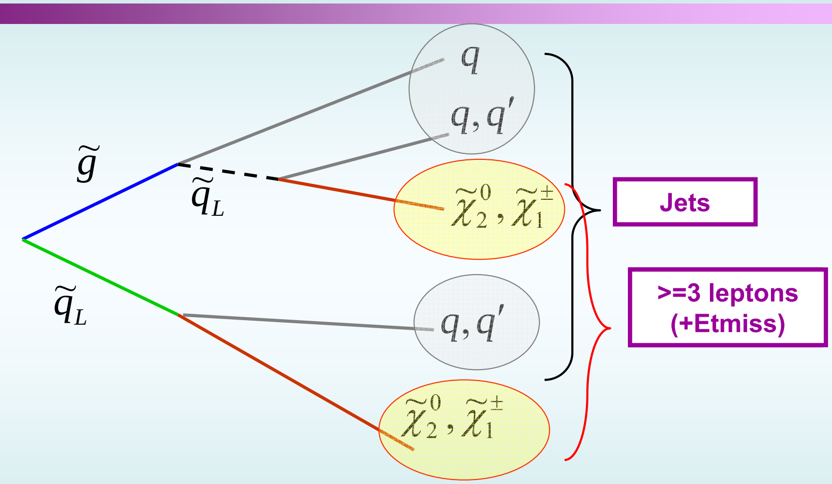
m($\chi^\pm$) =224, 476 GeV

m($l_{R,L}$) =152, 232 GeV

Decays through intermediate sleptons are now allowed

Preliminary results show that the statistics needed for discovery in this channel (SU3) would be prohibitive (1000s fb^{-1} !)

Trileptons +jets (+ Etmiss) signature



Relevant for "low-mass" SUSY (SU3, SU4), not in Focus Point region

An interesting channel for mass edges, but largest background is from SUSY itself → explore discovery potential of inclusive 3-lep search !

Trileptons +jets (Bulk region, SU3) – Inclusive

Signal = any decay originating from SUSY particles that gives

3 leptons (+ jets + Etmiss) in the final state

Simple cut flow:

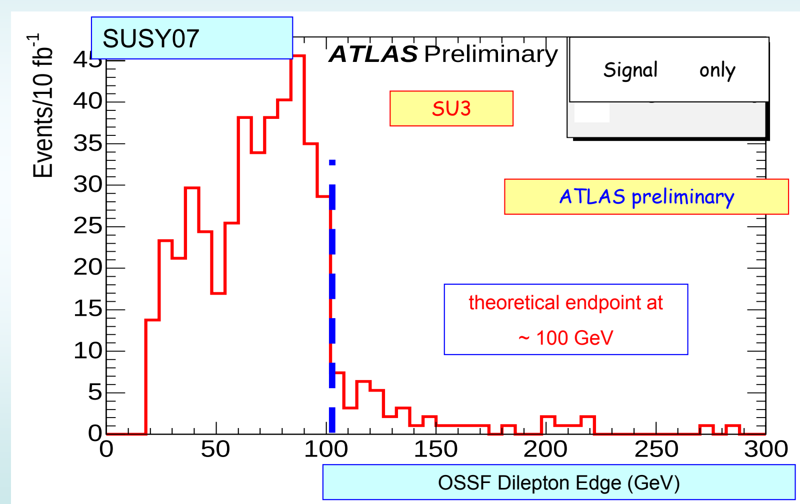
- 3 isolated leptons (including e,μ from taus) – not necessarily SFOS
- at least 1 high-pt jet (>200 GeV)
- high Etmiss requirement can help, but not crucial

Preliminary results for 5s discovery reach:

SU2 ("focus point") : **O(10-15 fb^{-1})**

SU3 ("bulk") : **O(1-2 fb^{-1})**

Trilepton Inclusive – SU3



BEYOND SUSY – EXTRA DIMENSIONS

Models of Extra Dimensions

Plenty of models on the market

cannot possibly discuss all of them in detail

Two "popular" examples:

ADD (Arkani-Hamed, Dimopoulos, Dvali)

[Phys Lett B429 (98)]

RS (Randall-Sundrum)

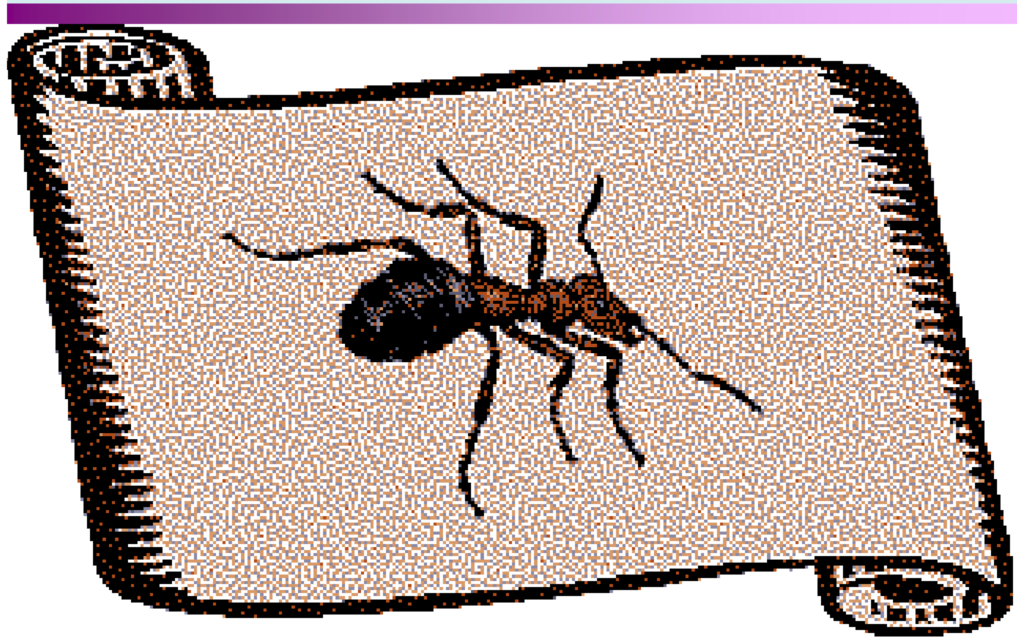
[Phys Rev Lett 83 (99)]

Motivations

The hierarchy problem (M_{EW} /M_{Planck}~10^{-17}), which we saw can be solved in the context of supersymmetry, could also be addressed by exploiting the geometry of space-time

The three spatial dimensions in which we live could be a three-spatial-dimensional "membrane" embedded in a much larger extra dimensional space

Motivations



Motivations

The hierarchy problem ($M_{EW}/M_{Planck} \sim 10^{-17}$), which we saw can be solved in the context of supersymmetry, could also be addressed by exploiting the geometry of space-time

The three spatial dimensions in which we live could be a three-spatial-dimensional "membrane" embedded in a much larger extra dimensional space

In this scenario, the hierarchy that we observe between the gravitational and the EW scale is generated by the geometry of the additional dimensions, rather than by an intrinsic smallness of the gravitational coupling constant

Such ideas have led to extra dimensional theories whose consequences can be verified at LHC energies

Motivations – Cont'd

Our knowledge of the weak and strong force extends down to scales of $\sim(100\text{ GeV})^{-1} \sim O(10^{-15}\text{ m})$

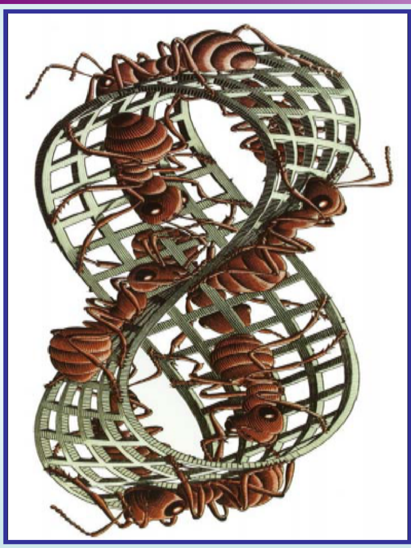
Our knowledge of the gravitational force (based on mechanically limited torsion-balance experiments, e.g. Cavendish expt), is limited to distances not smaller than ~1 mm

It is hence conceivable that gravity may diverge from Newton's law at small distances

$$V(r) = \frac{1}{M_{Pl}^2}\frac{m_1 m_2}{r} \rightarrow \frac{1}{\left(M_{Pl}^{[3+n]}\right)^{n+2}}\frac{m_1 m_2}{r^{n+1}}$$

Matter and non-gravitational forces may be "confined" to our 3-dim space ("brane"), while gravity may propagate throughout the full n+3 spatial volume of a higher dimensional (D=3+n+1) volume, the "bulk"

Compactification



Mobius Strip II (Escher, 1963) Relativity (Escher, 1953)

ADD Model

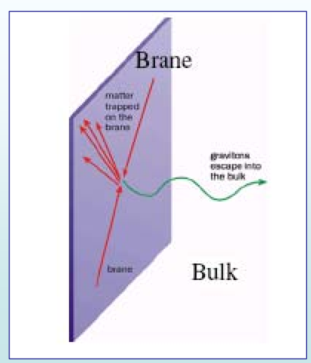
Modified Newton's law ruled out for large ED, but not excluded for sufficiently small, compactified ED of size R <<r :

$$V(r) \propto \frac{1}{\left(M_{Pl}^{[3+n]}\right)^{n+2}}\frac{m_1 m_2}{R^n r} \quad \text{for } r >> R$$

$M_{Pl}^{[3+n]} =$ effective Planck scale for n extra dim.

Intrinsically strong gravitational force diluted by bulk volume

$$\left(M_{Pl}^{[3+n]}\right)^{n+2} \propto M_{Pl}^2 / R^n$$

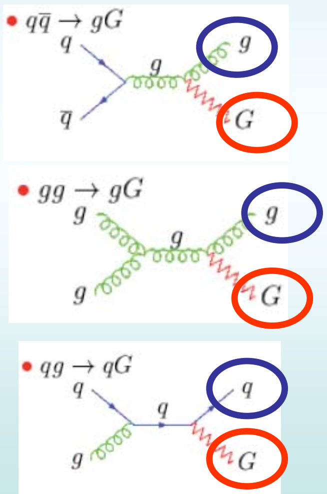


For n>1, fundamental Planck scale could be as low as 1 TeV (n=2 disfavoured by cosmological arguments):

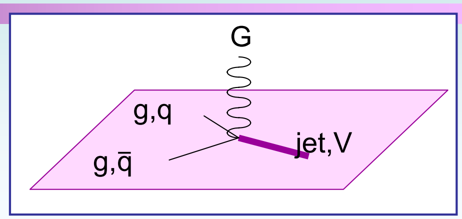
$$R = \frac{1}{2\sqrt{\pi}\, M_{Pl}^{[3+n]}}\left(\frac{M_{Pl}}{M_{Pl}^{[3+n]}}\right)^{2/n} \propto \begin{cases} 8\times 10^{12}\ m, & n=1 \\ 0.7\ mm, & n=2 \\ 3\ nm, & n=3 \\ 6\times 10^{-12}\ m, & n=4 \end{cases}$$

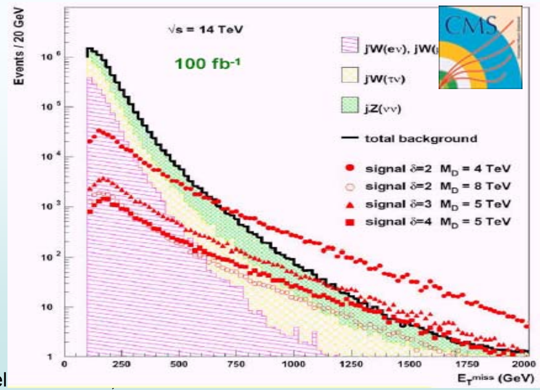
ADD Collider Signatures – Real Graviton Emission

Graviton emitted in association with jet or gauge boson

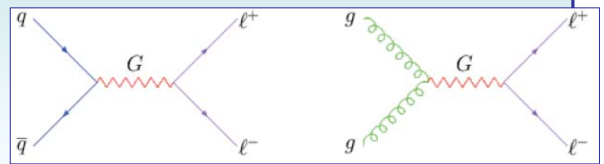


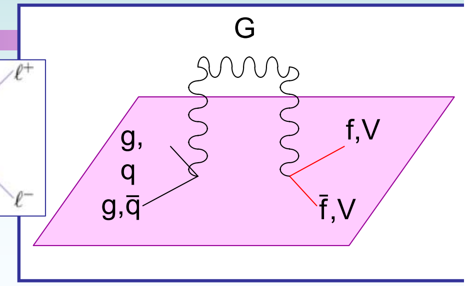
Jet + Etmiss



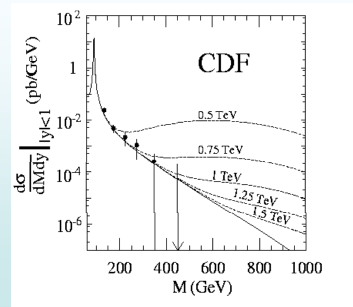


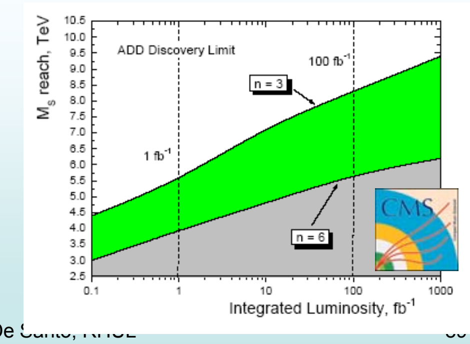
ADD Collider Signatures – Virtual Graviton Emission



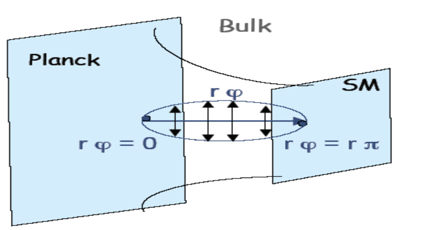


Excess over dilepton continuum from SM processes such as q-qbar, gg→ l^+l^-





RS Models

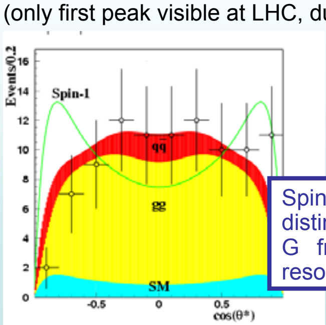


A small, highly curved ("warped") extra dimension connects the SM brane (at O(TeV)) to the Planck scale brane

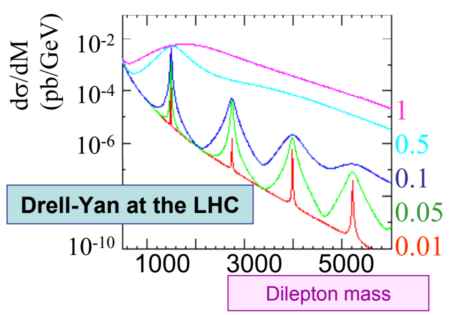
Gravity small in our space because warped dimension decreases exponentially between the two branes

Series of narrow, high-mass resonances:
(only first peak visible at LHC, due to PDFs)

$$q\bar{q}, gg \to G_{KK} \to \ell^+\ell^-, \gamma\gamma, j+j$$



Spin analysis to distinguish spin-2 G from spin-1 Z' resonance



… AND A LOT MORE…

More Physics at the LHC

Standard Model

B-physics

Heavy Ions

Diffractive physics

More Physics at the LHC

Standard Model

B-physics

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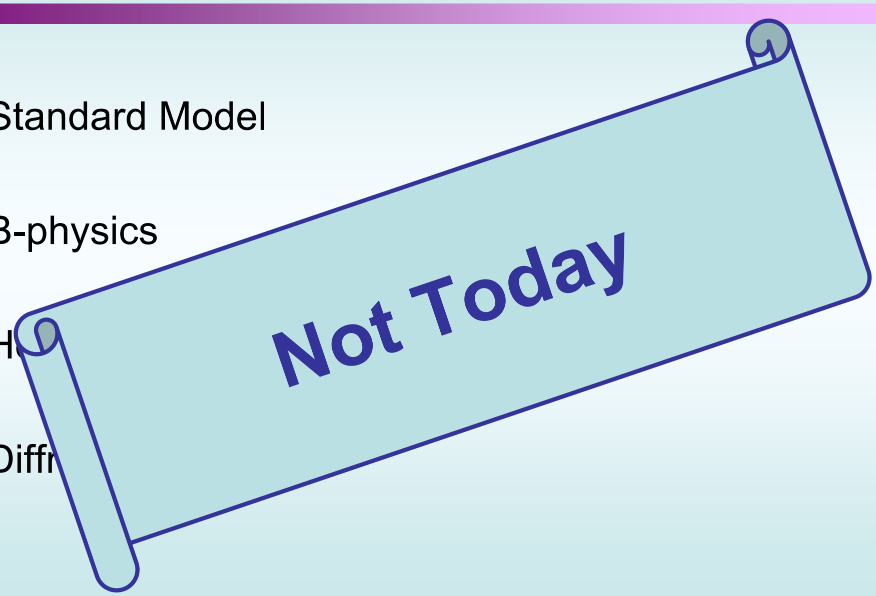
Diffr



CONCLUSIONS

With the LHC turn on, physics at the TeV scale will become accessible experimentally at an accelerator for the first time

High expectations to be able to shed light on the origin of mass and the mechanism for EW symmetry breaking

Serious possibility to observe “dark matter in a laboratory”, and even to test gravity

A new golden age for particle physics may be ahead of us!