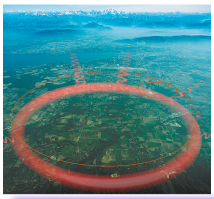
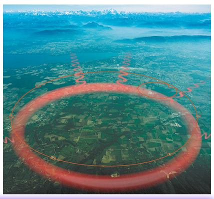
The Search for New Physics at the LHC



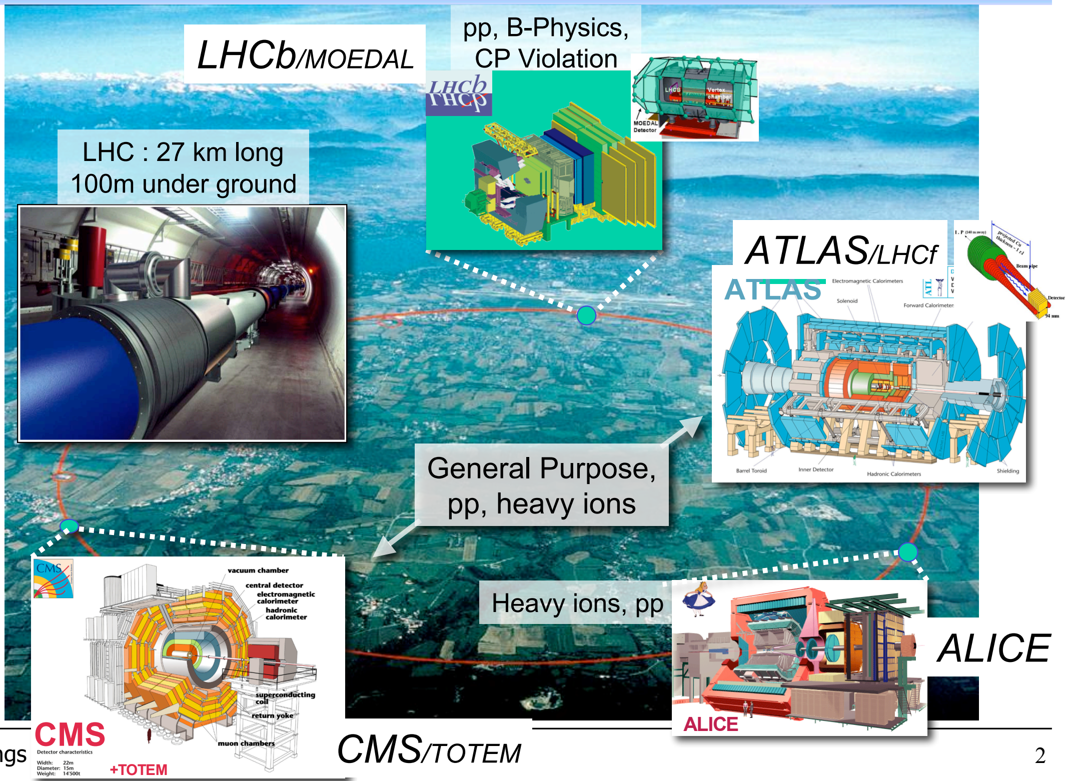
Oliver Buchmüller
CERN



- *The "LHC Environment"*
  - a real challenge
- *Physics Commissioning*
  - rediscovery of the SM
- *Search for New Physics in the Early Days*
  - focus on illustrative examples from ATLAS/CMS

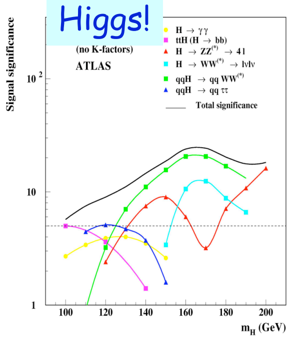
Strings 2008 18/08/2008

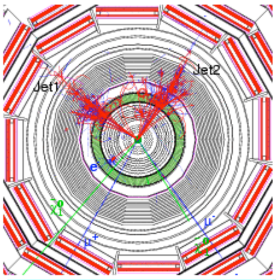
The Large Hardon Collider at CERN



A Glimpse at the LHC Physics Program

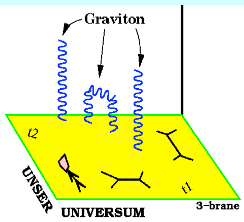
Higgs!



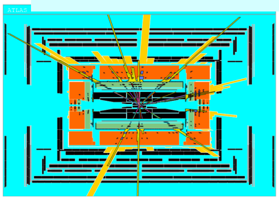


Supersymmetry?

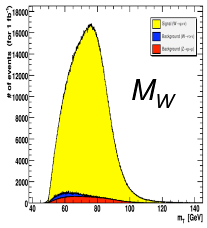
Extra Dimensions??

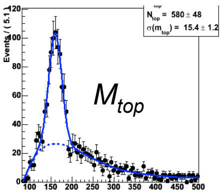


Black Holes???

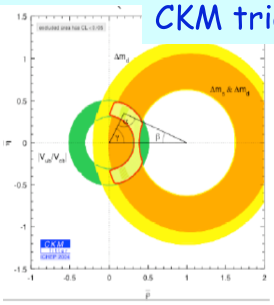


Precision Electroweak!

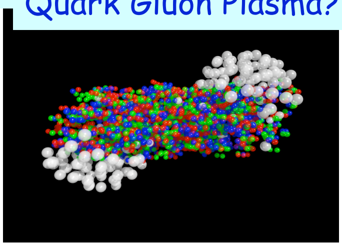




CKM triangle!



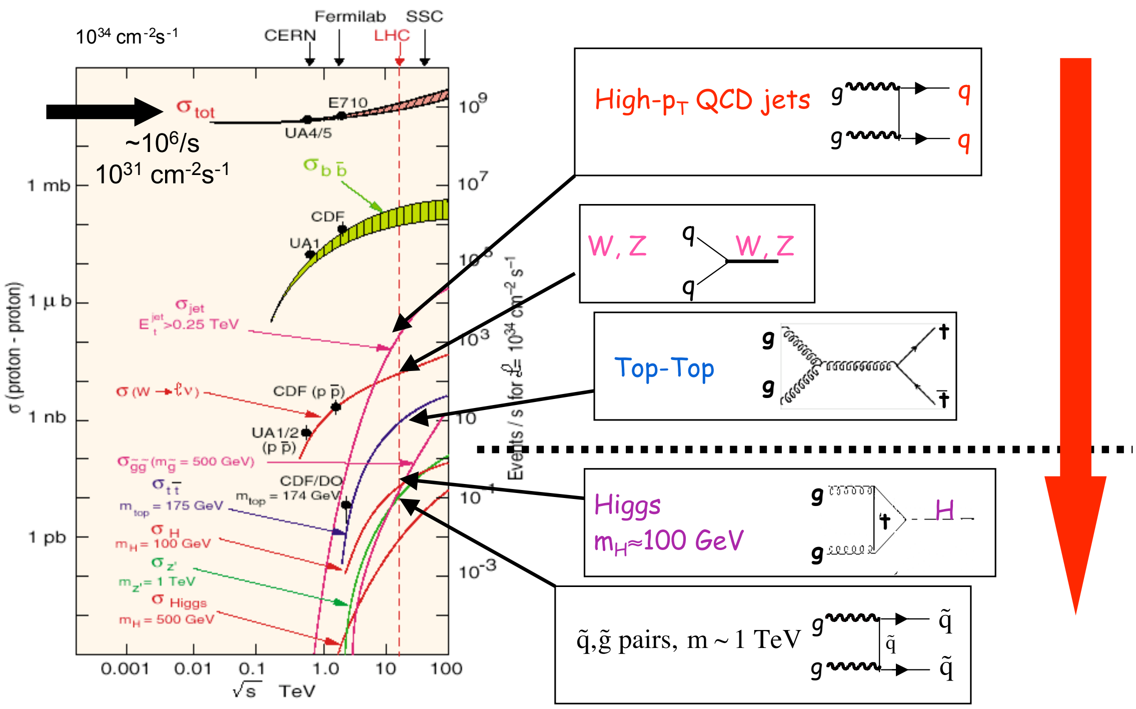
Quark Gluon Plasma?



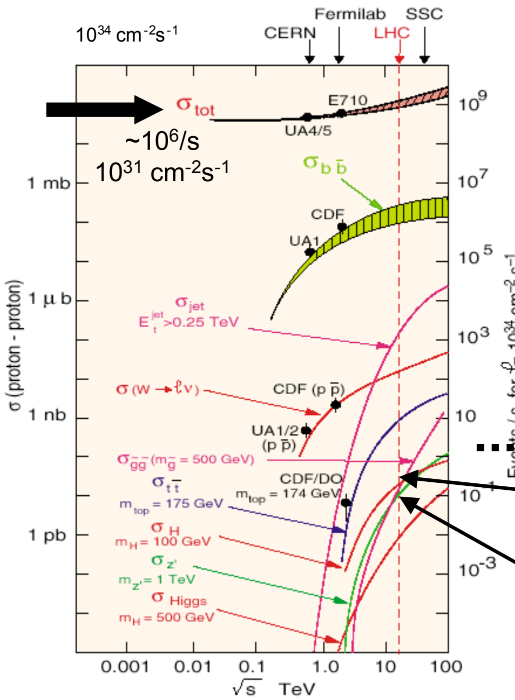
Physics at a new energy frontier!

The LHC Environment

Background and Signal



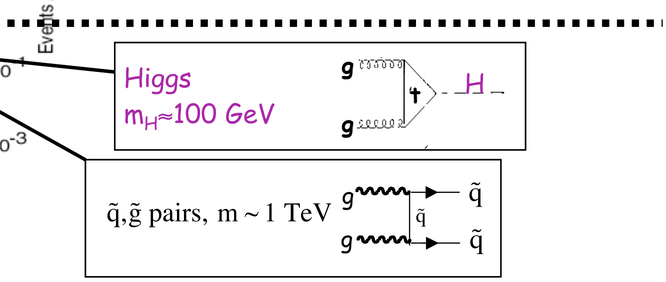
Background and Signal



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

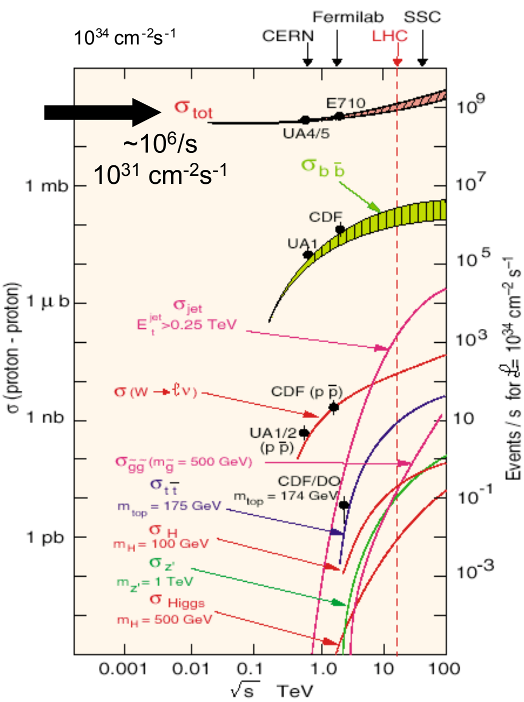
σ_{tot}	≈ 100mb
Jets w. E_T>100 GeV	≈ 1μb
ttar	≈ 800pb

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)



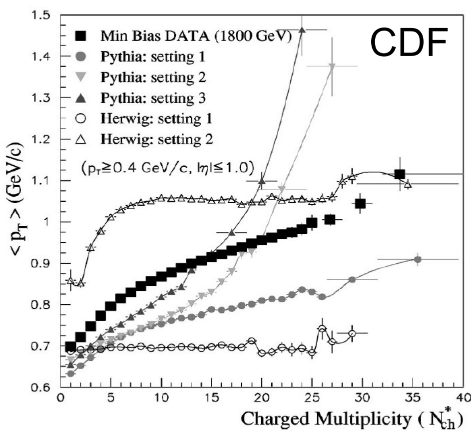
Physics Commissioning with the first collision data

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.

1 March 2009??

Probably one of the first papers:
not Higgs, not SUSY,
but rather "boring bread-and-butter" stuff

Charged particle multiplicity in pp collisions at $\sqrt{s}$ = 10 TeV

CMS collaboration

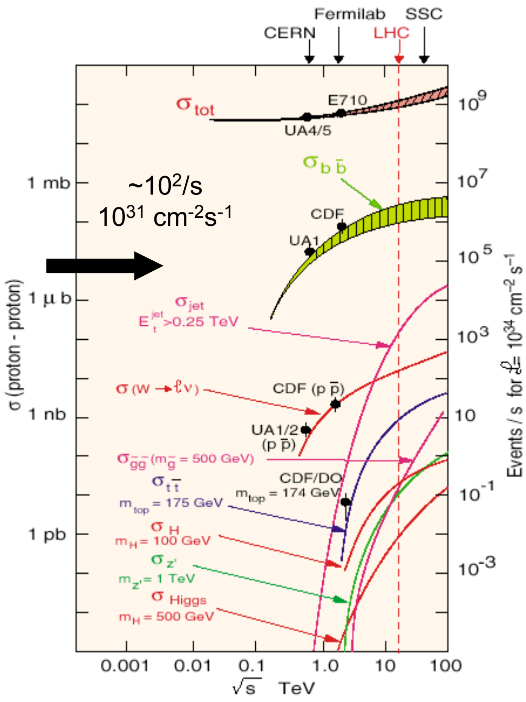
Abstract

We report on a measurement of the mean charged particle multiplicity in minimum bias events, produced in the central region $|\eta| < 1$, at the LHC in pp collisions with $\sqrt{s}$ = 14 TeV, and recorded in the CMS experiment at CERN. The events have been selected by a minimum bias trigger, the charged tracks reconstructed in the silicon tracker and in the muon chambers. The track density is compared to the results of Monte Carlo programs and it is observed that all models fail dramatically to describe the data.

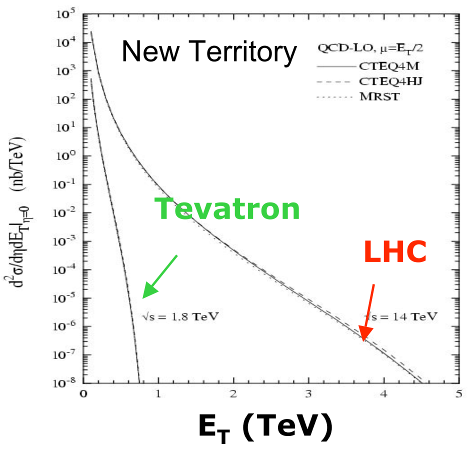
Submitted to *European Journal of Physics*

Second Phase

Measure Jet Cross Section

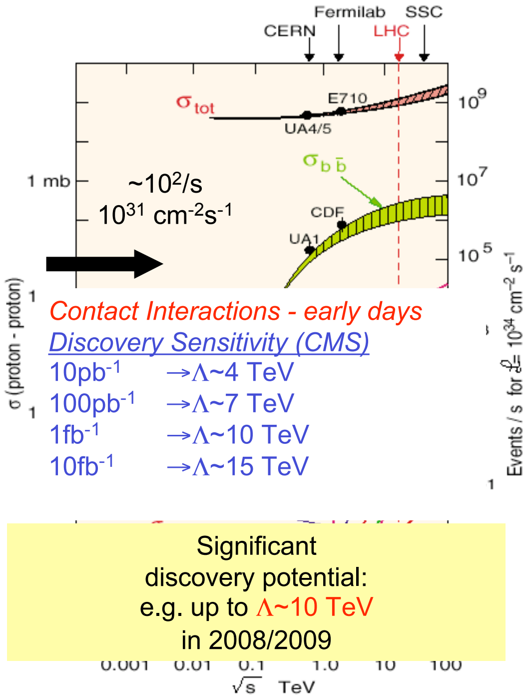


- E_T^{Jet} > 500 GeV after a few weeks at 10^{31}cm^{-2}s^{-1}
- Going fast beyond the reach of the Tevatron
- Early sensitivity to compositeness requires understanding of the jet energy scale, PDF's, …



Second Phase

Measure Jet Cross Section



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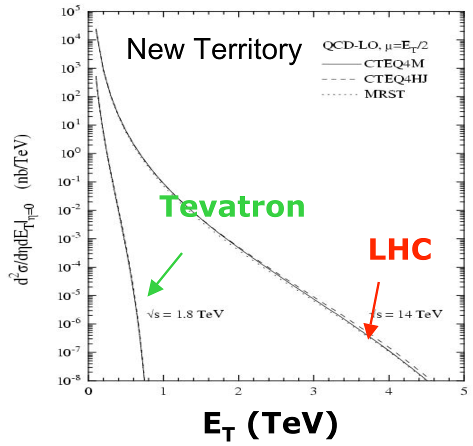
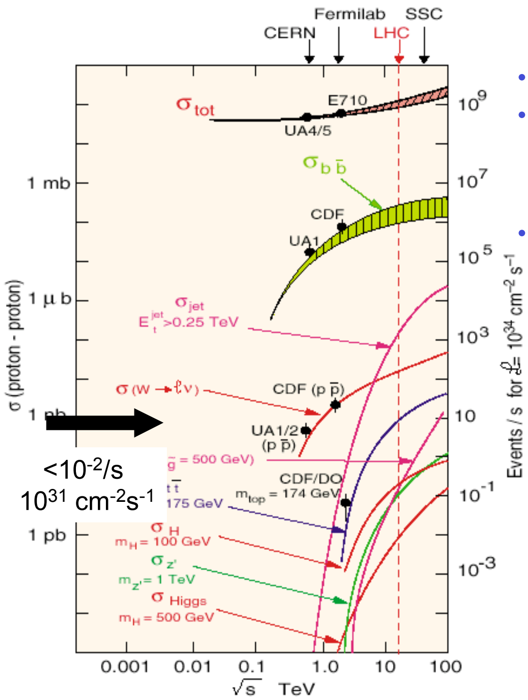


Third Phase



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

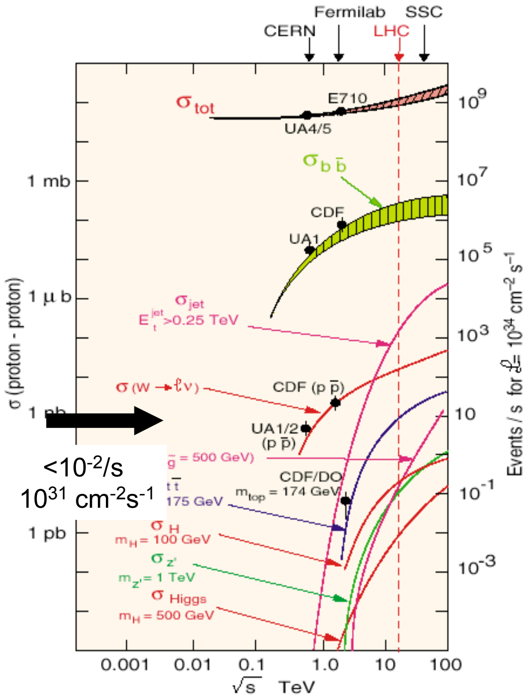
THE path to new physics! 14 TeV

At Luminosity $10^{31}cm^{-2}s^{-1}$

bb production:	→ 10^3 Hz
W→ ℓ ν:	→0.1 Hz
Z→ ℓ ℓ:	→0.01 Hz
t t production:	→0.01 Hz
SM Higgs	→0.0001 Hz

At this stage the LHC becomes a real SM Factory!

Third Phase



Rediscover the SM

For L=10/pb @ 10 TeV

W→ ℓ ν:	→300K Events
Z→ ℓ ℓ:	→30K Events
t t production:	→10K Events

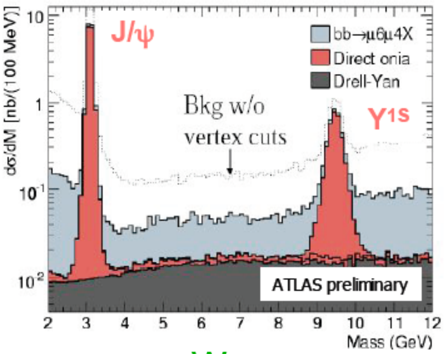
Rather large data samples already expected for 2008!

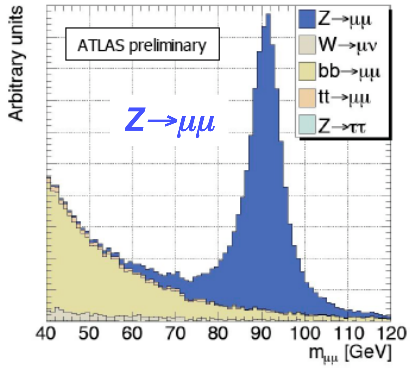
Production Rate: 10 vs.14 TeV:
- W/Z ~70%
- ttbar ~50%
- Higgs (200) ~50%

"Rediscovery" of the Standard Model @ 14 TeV (10 TeV)

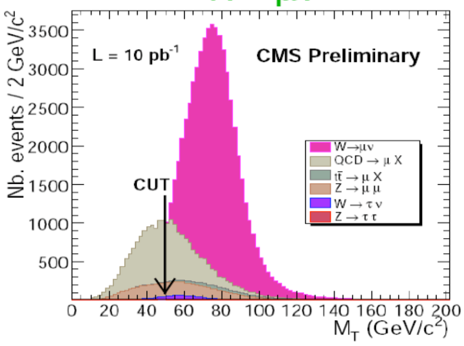
Rediscovery of the SM

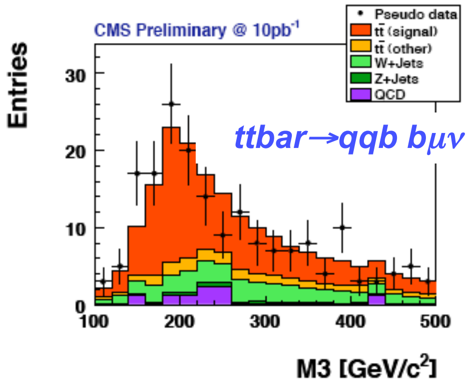
J/ϕ→μμ and Υ→μμ





W→μν



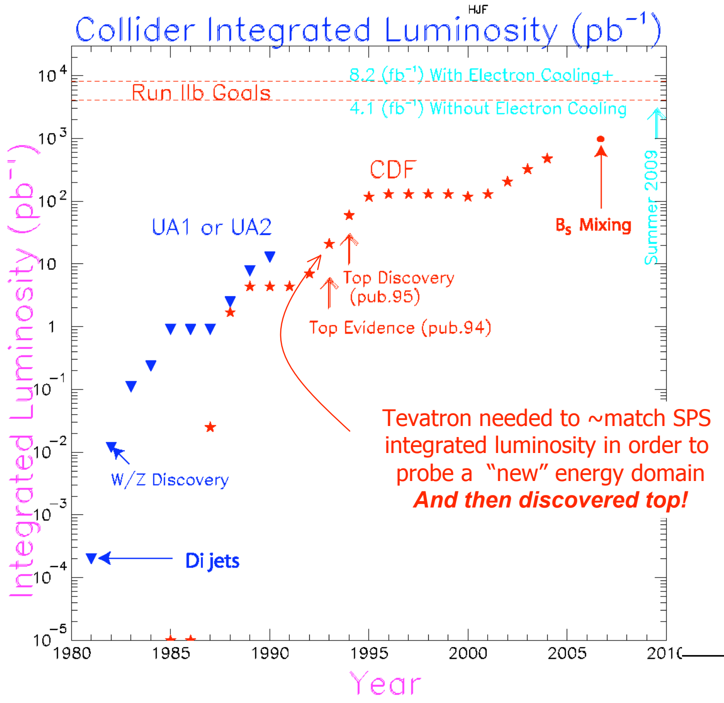


New Physics
What to expect?

Good Things Come Early … and Late

J. Incandela

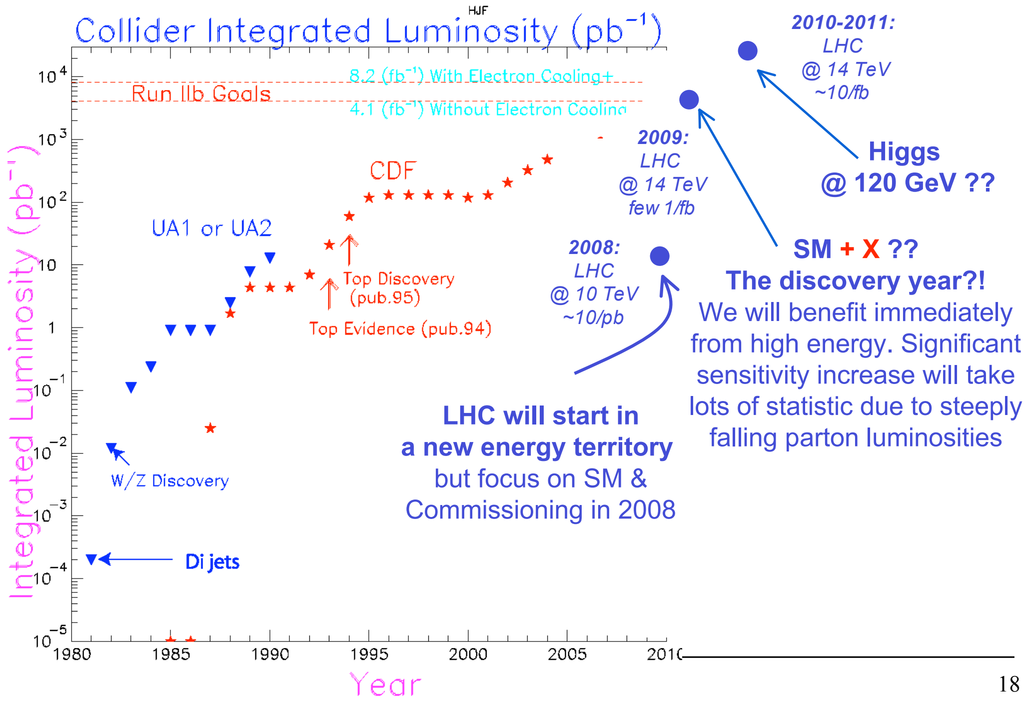
Hadron Collider History



Good Things Come Early … and Late

J. Incandela

Hadron Collider History … and its potential Future



Another Way to Look at It …

Many people now ask:

Will the LHC discover the Higgs boson?

My answer is …

Another Way to Look at It …

Many people now ask:

Will the LHC discover the Higgs boson?

My answer is …

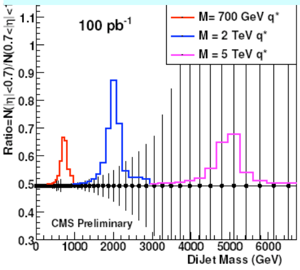
By the time the LHC discovers the Higgs boson, that discovery will no longer be considered interesting.

M.E. Peskin - Tools 2008

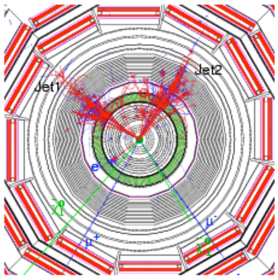
SM + X: New Physics Potential of the LHC

What could make a Higgs discovery "uninteresting"?

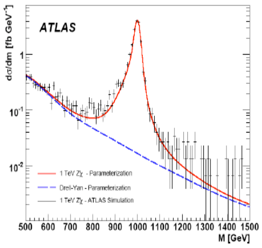
Contact Interaction /Excited Quarks?



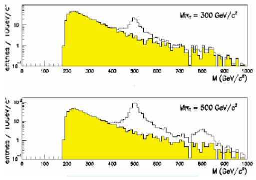
Supersymmetry?



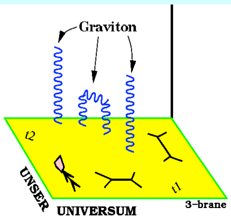
New Gauge Bosons?



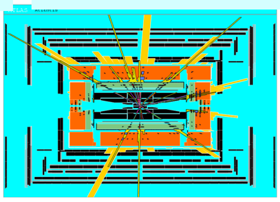
Technicolor?



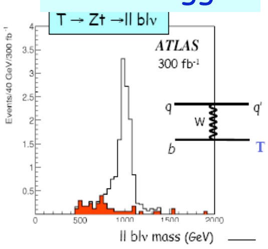
Extra Dimensions?



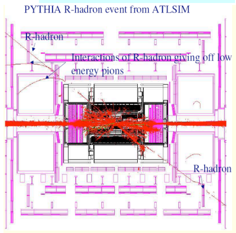
Black Holes???



Little Higgs?



Split Susy?



New Physics Potential - Early Days

Model	Mass reach	Luminosity (fb^{-1})	Early Systematic Challenges
Contact Interaction	Λ < 3 TeV	0.01	Jet Eff., Energy Scale
Z' W'	M ~ 1 TeV M ~ 1 TeV	0.01-0.1 0.01	Alignment Alignment/MET
Black Holes	M_D~ 2.0 TeV	0.01	MET/ Jet Energy Scale
Excited Quark	M ~0.7 – 3.6 TeV	0.1	Jet Energy Scale
Axigluon or Colouron	M ~0.7 – 3.5 TeV	0.1	Jet Energy Scale
E6 diquarks	M ~0.7 – 4.0 TeV	0.1	Jet Energy Scale
Technirho	M ~0.7 – 2.4 TeV	0.1	Jet Energy Scale
ADD Virtual G_{KK}	M_D~ 4.3 - 3 TeV, n = 3-6 M_D~ 5 - 4 TeV, n = 3-6	0.1 1	Alignment
ADD Direct G_{KK}	M_D~ 1.5-1.0 TeV, n = 3-6	0.1	MET, Jet/photon Scale
SUSY Jet+MET+0 lepton Jet+MET+1 lepton	M ~1.5 – 1.8 TeV M ~0.5 TeV M ~0.5 TeV	1 0.01 0.1	MET, Jet Energy Scale, Multi-Jet backgrounds, Standard Model backg.
mUED	M ~0.3 TeV M ~ 0.6 TeV	0.01 1	Lepton ID
HSCP	M ~ 0.3 TeV M ~ 1.0 TeV	0.1 1	TOF, dE/Dx
RS1 di-jets di-muons	 M_{G1}~0.7- 0.8 TeV, c=0.1 M_{G1}~0.8- 2.3 TeV, c=0.01-0.1	 0.1 1	 Jet Energy Scale Alignment

Not an exhaustive list!!

Understood data - of course!

Courtesy of R. Cavanaugh

New Physics Potential - Early Days

Model	Mass reach	Luminosity (fb^{-1})	Early Systematic Challenges
Contact Interaction	Λ < 3 TeV	0.01	Jet Eff., Energy Scale
Z'	M ~ 1 TeV	0.01-0.1	Alignment
W'	M ~ 1 TeV	0.01	Alignment/MET
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SUSY Jet+MET+0 lepton	M ~1.5 – 1.8 TeV M ~0.5 TeV	1 0.01	MET, Jet Energy Scale, Multi-Jet backgrounds, Standard Model backg.
Jet+MET+1 lepton	M ~0.5 TeV	0.1	
mUED	M ~0.3 TeV M ~ 0.6 TeV	0.01 1	Lepton ID

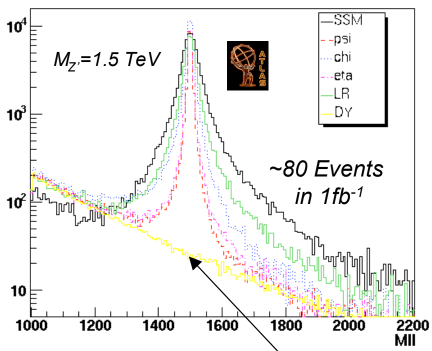
Not an exhaustive list!!

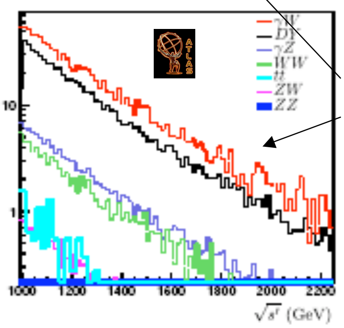
Rather than presenting the generic reach plots for each scenario (we have seen them so many times already), I will discuss a few illustrative examples in more detail.

Courtesy of R. Cavanaugh

Di-lepton Resonances (Example Z')

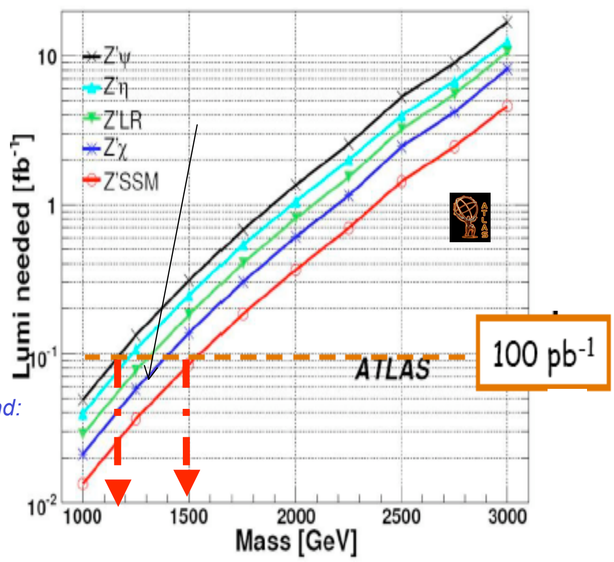
has always been the subject of (clean) searches …





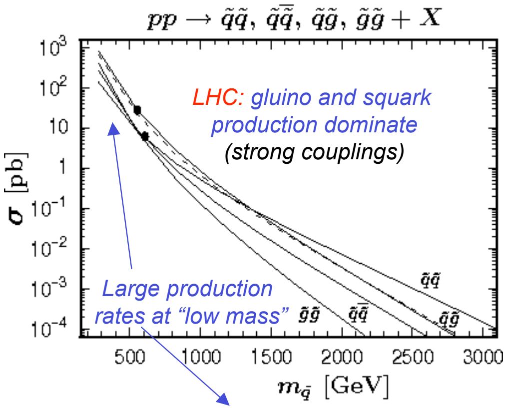
Main background: Drell-Yan: <1 event for M>1.5 TeV in 1fb^{-1}

Z'→e⁺e⁻ Discovery Potential



Very early discovery potential with clean signatures!

SUSY Searches @ LHC

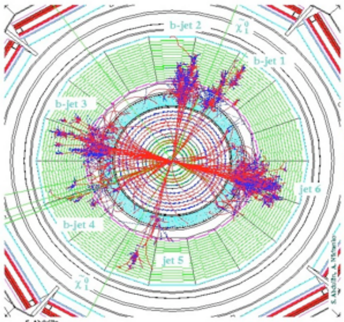


M_{sp}(GeV)	σ (pb)	Evts/yr
500	100	10^6-10^7
1000	1	10^4-10^5
2000	0.01	10^2-10^3

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

Huge number of theoretical models

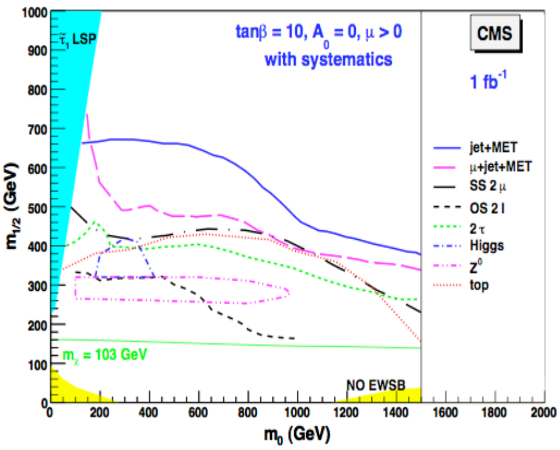
- Very complex analysis; MSSM >100 parameter
- To reduce complexity we have to choose some "reasonable", "typical" models; use a theory of dynamical SUSY breaking
  - mSUGRA (main model)
  - GMSB (studied in less detail)
  - AMSB (studied in less detail)
- Use models to study different SUSY signatures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

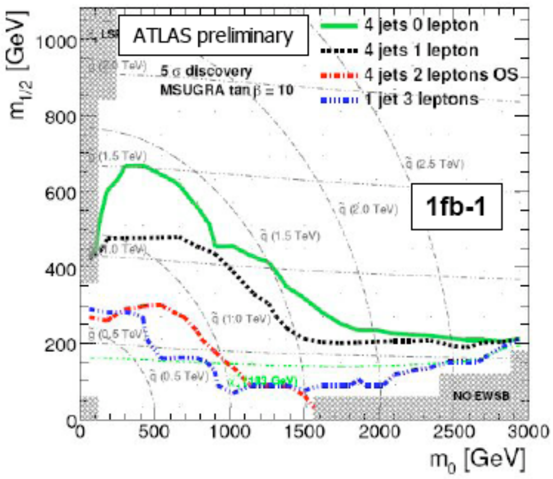


Clear signatures of large missing energy, hard jets and many leptons!
(assume R-Parity)

Could be very spectacular!

SUSY Discovery Potential - CMSSM

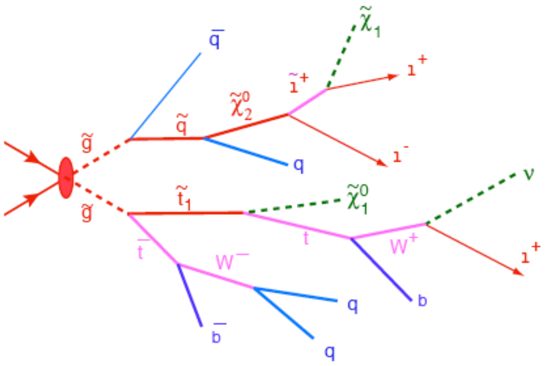




Discover Potential for "muli-jet, multi-lepton and missing energy search" is described in the CMSSM.
Both ATLAS and CMS have very similar performance (as expected).

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*

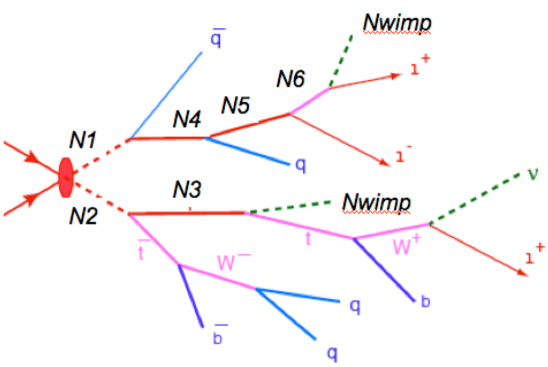
Multi-Jet:
- *from cascade decay (gaugino)*

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.

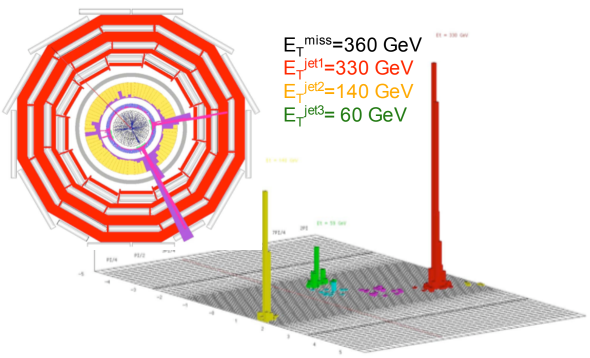
"SUSY Searches" - What are we searching for?

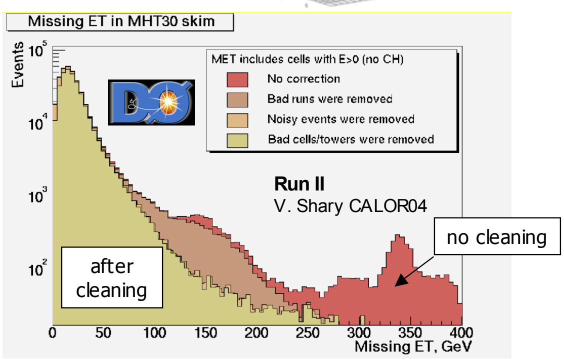
- Pair-produced new particles N with a colour charge and a mass of O(TeV/2)
- N decays via a cascade into other new particles as well as SM particles like bosons, leptons and quarks
- At the end of the cascade decay is a weakly interacting new particle - i.e. a dark matter candidate

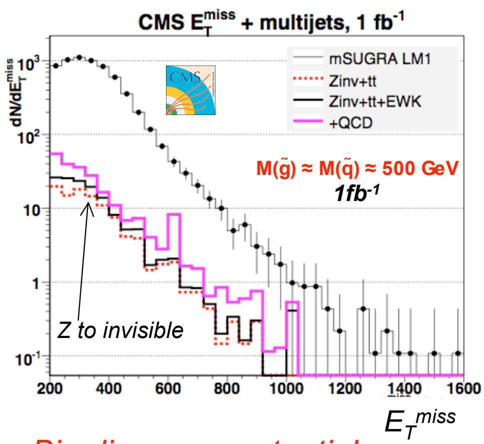
In other words, a "SUSY search" is a search for a weakly interacting (stable) particle that was produced in the cascade decay of a heavy new particle.

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

Jets + E_T^{miss} - Inclusive Search







Big discovery potential

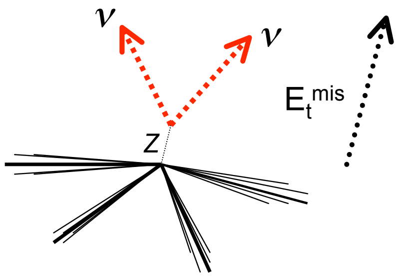
But requires a very good detector understanding and background control:

Analysis Strategy:

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

Data Driven Background Estimations

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

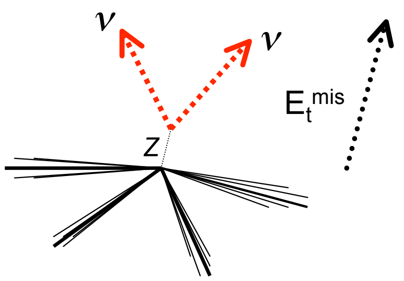


Data-driven strategy:

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

Data Driven Background Estimations

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



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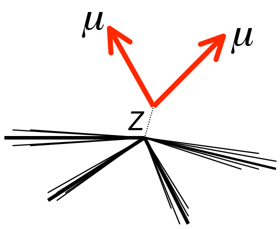

$Z \rightarrow \mu\mu$+jets

Strength:
- *very clean, easy to select*

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

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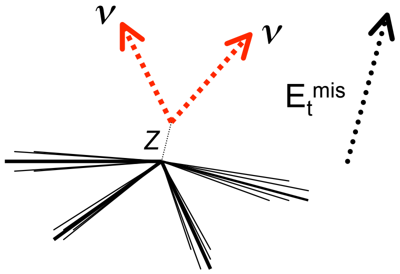

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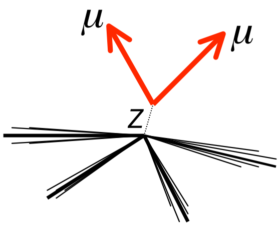

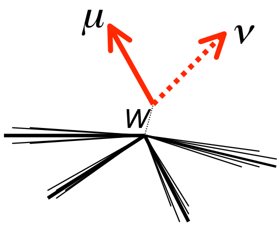

$Z \rightarrow \mu\mu$+jets

Strength:
- *very clean, easy to select*

Weakness:
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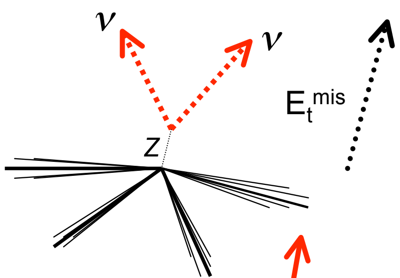
$W \rightarrow \mu\nu$+jets

Strength:
- *larger statistic*

Weakness:
- *not so clean, SM and signal contamination*

Data Driven Background Estimations

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



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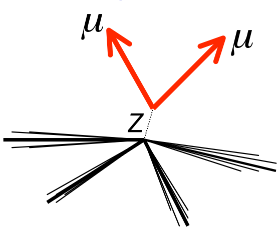
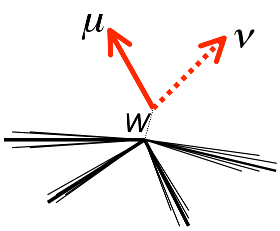
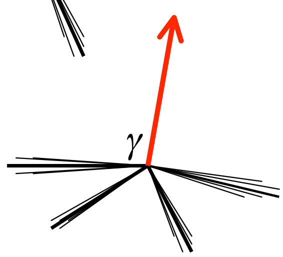






$Z \rightarrow ll$+jets

Strength:
- *very clean, easy to select*

Weakness:
- *low statistic: factor 6 suppressed wrt. to $Z \rightarrow \nu\nu$*

$W \rightarrow l\nu$+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

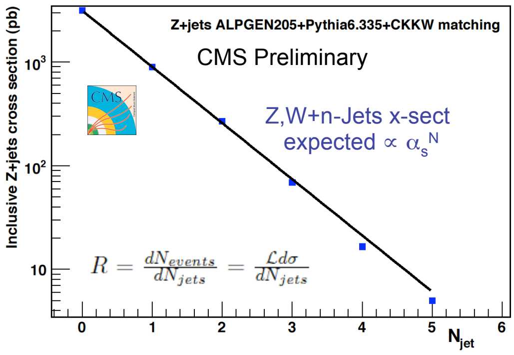
Measure from ≥ 2 Jets from Data:

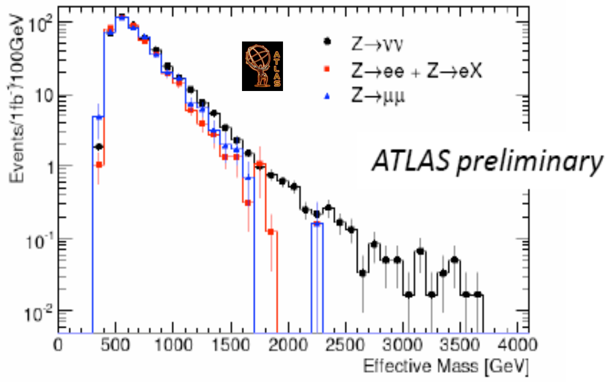
Use:

- $Z(\rightarrow\mu\mu)$ + ≥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

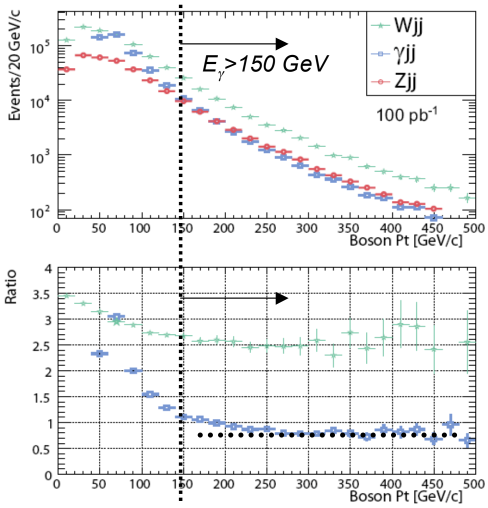
γ+jets: Estimate Z to invisible

γ+jets selection & properties:

- E_γ>150 GeV

→ clean sample: S/B>20

→ ratio σ(Z+jet)/σ(γ+jet) constant

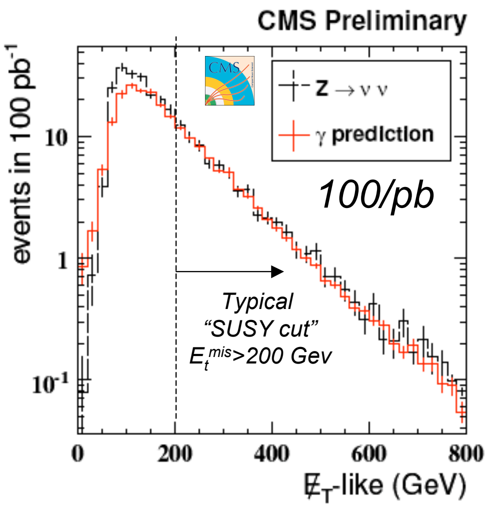


γ+jets: Strategy:

- remove γ from the event:

→ γ becomes E_T^{mis}

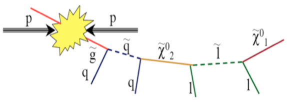
- take σ(Z+jet)/σ(γ+jet) for E_γ>200 GeV from MC or measure in data



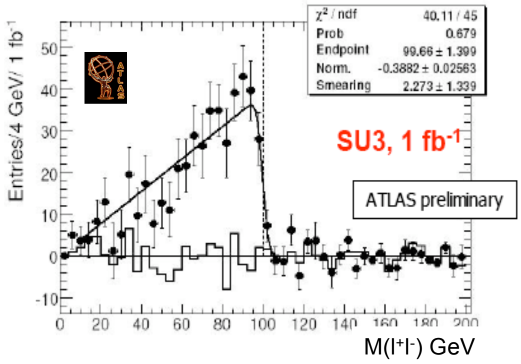
First Kinematic Measurements

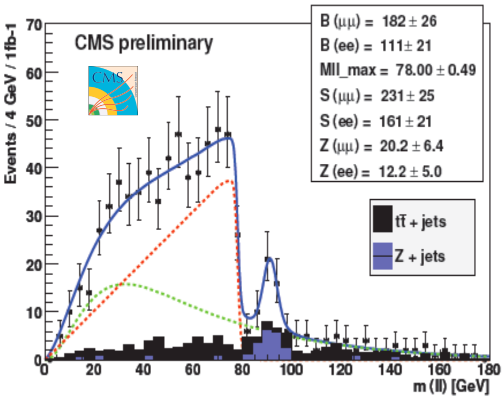
. . .and if we are a bit lucky we might see such spectacular signals already in the early days!

Look for generic signatures of cascade decays:



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



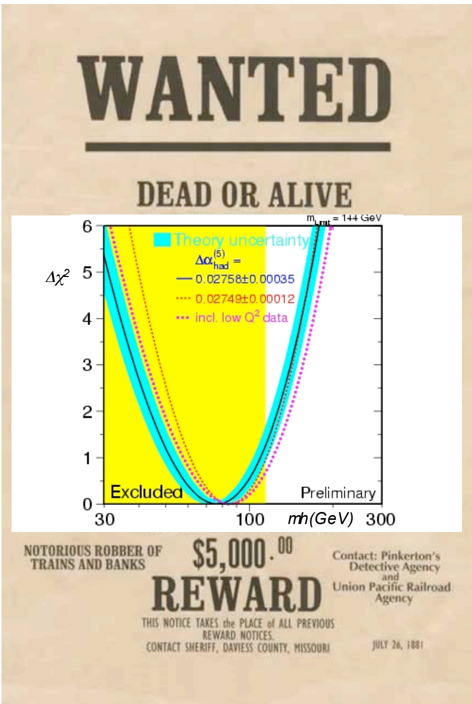


Extract: $M_{\ell\ell}^{max} = M(\tilde{\chi}_2^0)\sqrt{1-\frac{M^2(\tilde{\ell}_R)}{M^2(\tilde{\chi}_2^0)}}\sqrt{1-\frac{M^2(\tilde{\chi}_1^0)}{M^2(\tilde{\ell}_R)}}$

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.

SM-like Higgs Boson



Good things come early … and late(r)

Although it may come "late" and therefore may not be the first major discovery of the LHC - we still need to find it (or exclude it).

No reason to discount it … it will be a major event for the LHC & Particle Physics in any case!

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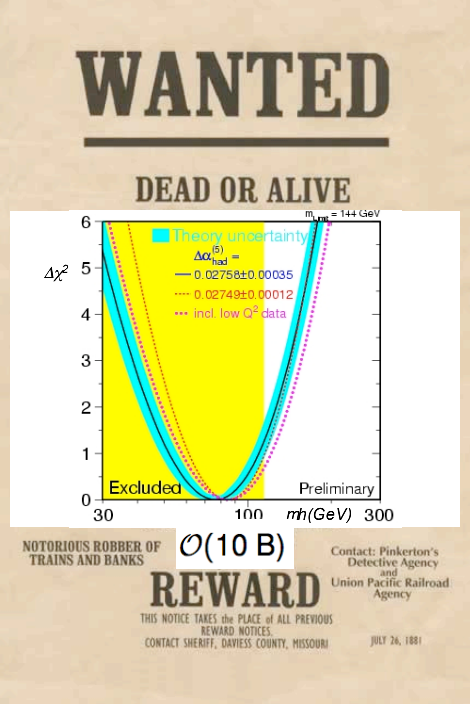

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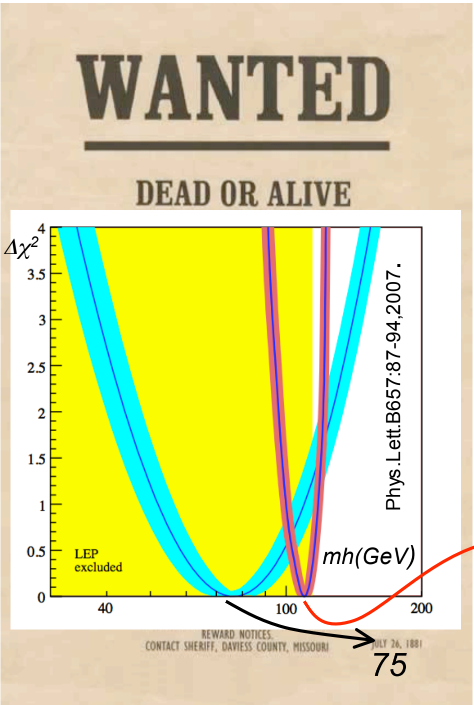
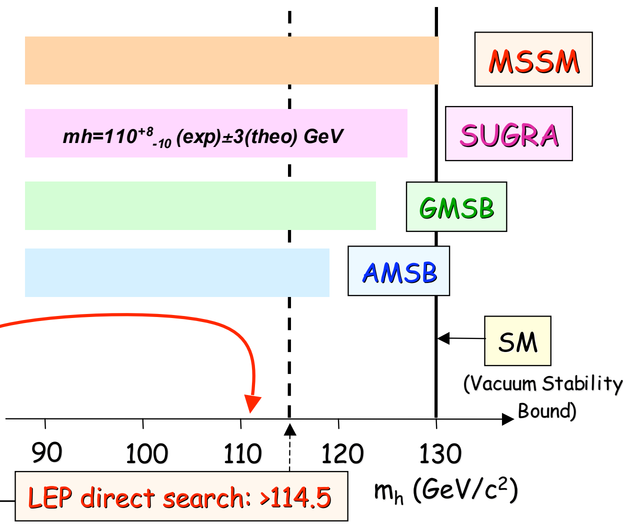


SM: Constrained Phase Space

mh(SM)=76$^{+33}_{-24}$ GeV

mh(SM)<144 GeV @ 95% CL

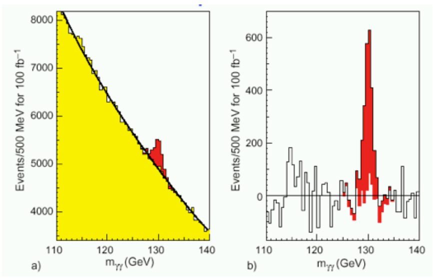
SUSY: Accessible Phase Space

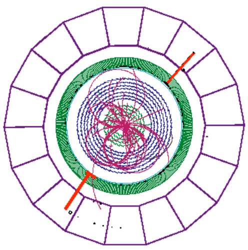


Higgs Mass below 200 GeV

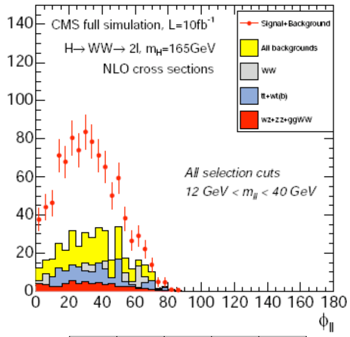
Low M_H < 140 GeV | $2M_w$ < M_h < $2M_Z$ | 130 < M_H < ~600 GeV

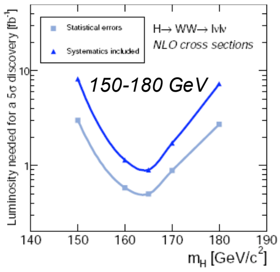
$H \to \gamma\gamma$



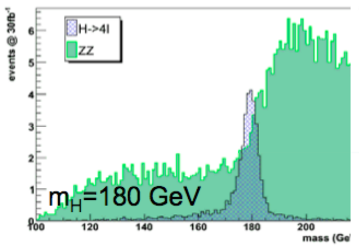


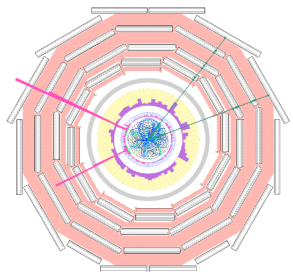
$H \to WW^{(*)} \to 2l$



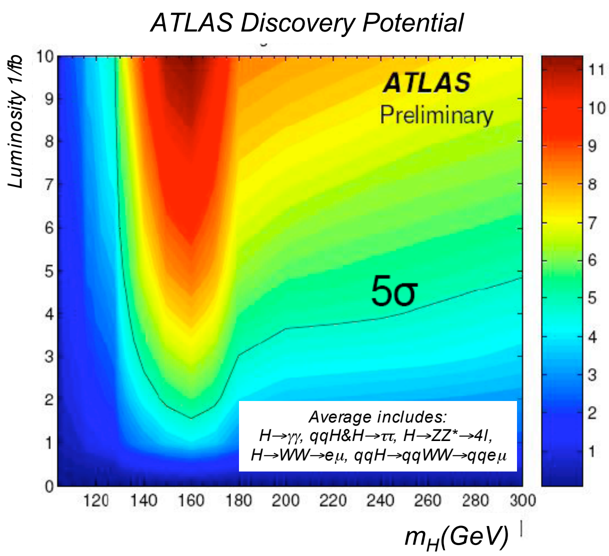


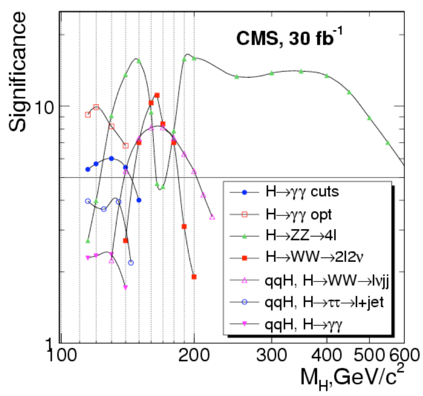
$H \to ZZ^{(*)} \to 4l$





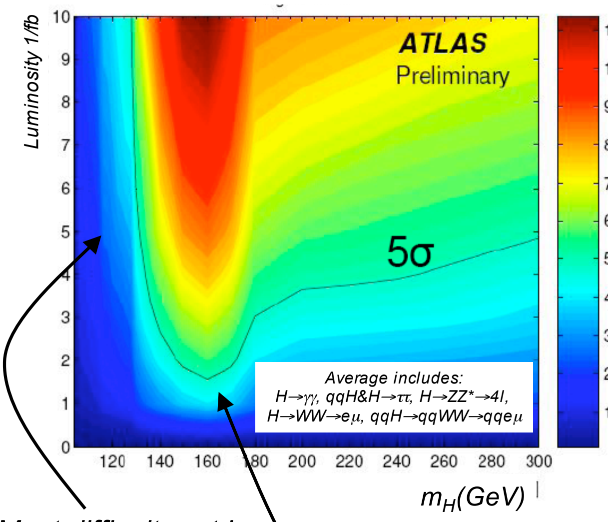
SM Higgs Reach

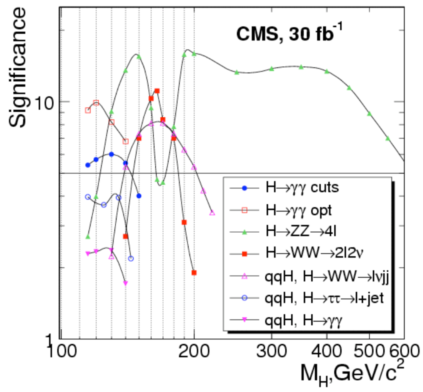




SM Higgs Reach

ATLAS Discovery Potential





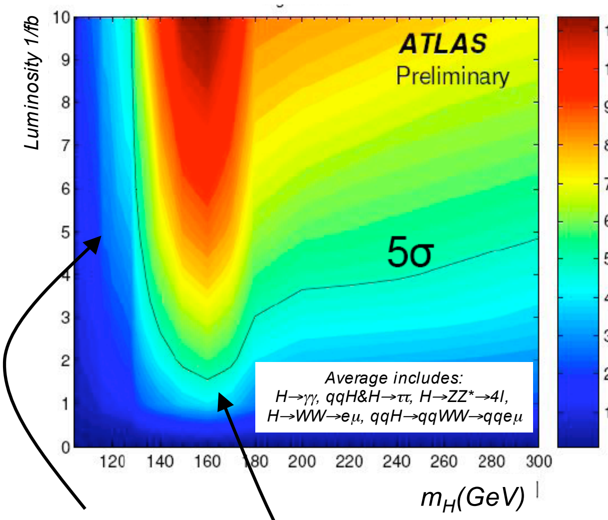
Most difficult part is M_h~115 to 120 GeV

ttH→ttbb more difficult than originally expected

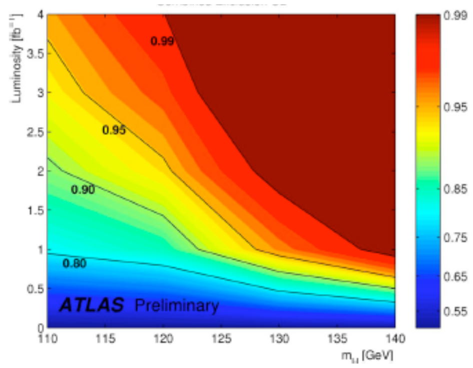
Early discovery already possible with $1fb^{-1}$ $H \rightarrow WW^{(*)} \rightarrow 2l$

SM Higgs Reach

ATLAS Discovery Potential



ATLAS 95% CL Exclusion



Most difficult part is M_h~115 to 120 GeV

ttH→ttbb more difficult than originally expected

Early discovery already possible with $1fb^{-1}$ $H \rightarrow WW^{(*)} \rightarrow 2l$

With $1fb^{-1}$ of understood data:

- *potential to exclude a very large mass range*
- *potential to discover higgs with m_h~165 GeV (m_h~170 GeV recently excluded by Tevatron)*

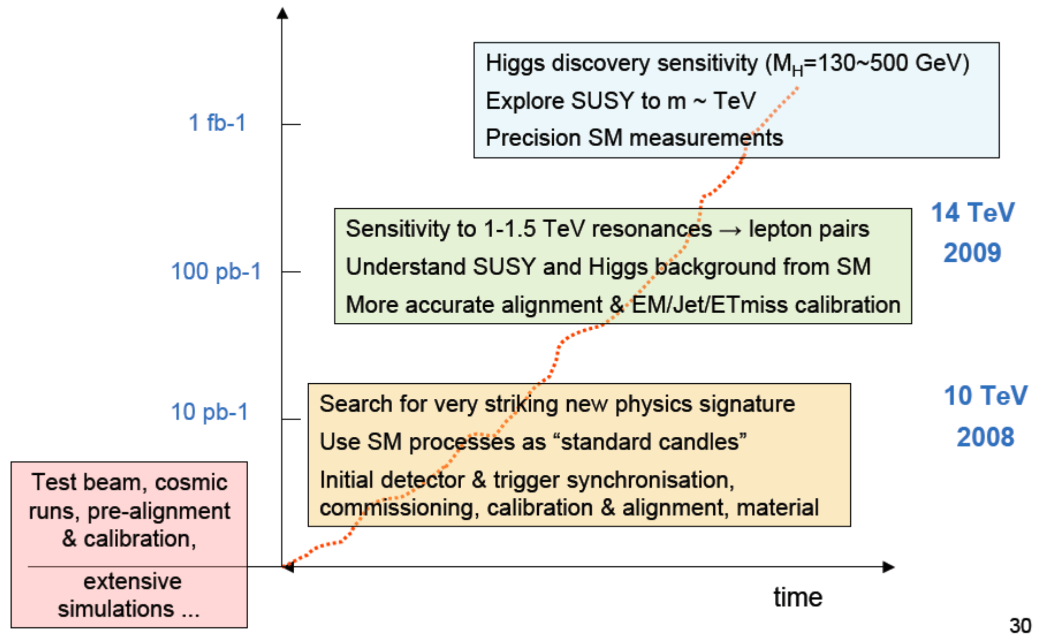
LHC will give us an answer!

Summary

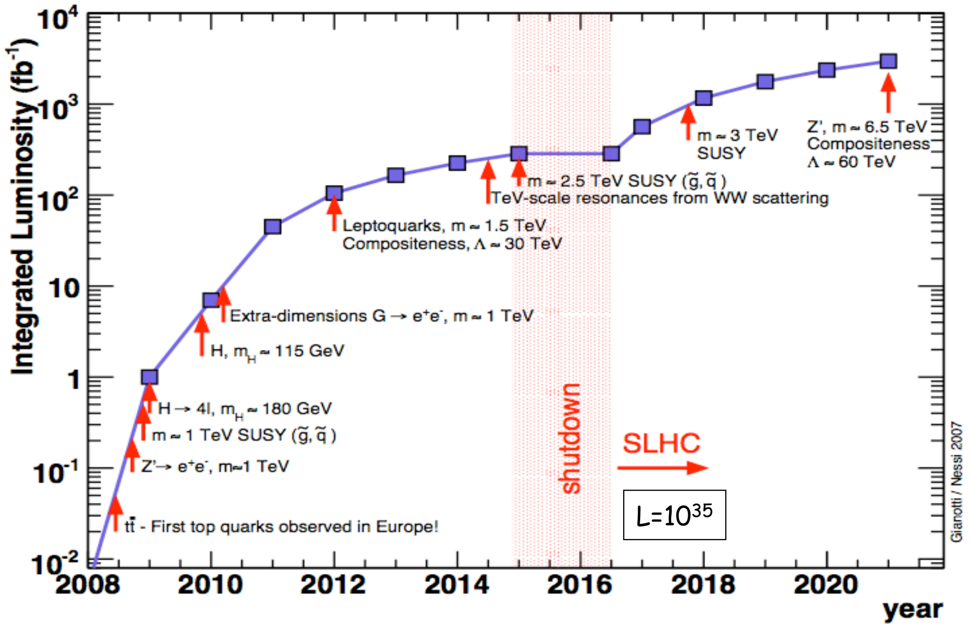
- 2008 will be the year of machine, detector, and physics analysis commissioning - i.e. intense preparation for the physics year 2009.
  - Challenge: commissioning of machine and detectors of unprecedented complexity, technology, and performance
  - Re-discover the Standard Model at 10 TeV, understand the “LHC environment”
- The LHC will discover (or exclude) the Higgs by ~2010-2011 [~10/fb].
  - We will get an answer!
  - Large phase space can already be excluded with only ~1fb^{-1} (i.e. 2009)
- The LHC will discover low energy SUSY (if it exists).
  - 2009 could become the year of “SUSY” but it could also take more time and ingenuity before we can claim a discovery
  - First signals might emerge already in the first data but do we understand them?!
- The LHC will cover a new physics scale of 1-3 TeV.
  - Many new physics models; Black hole, Extra Dimensions,Little Higgs, Split Susy, New Bosons, Technicolour, etc …

In other words; the next years will be a very exciting time for particle physics . . .

Timeline: Near-term Prediction



Timeline: Long-term Guess



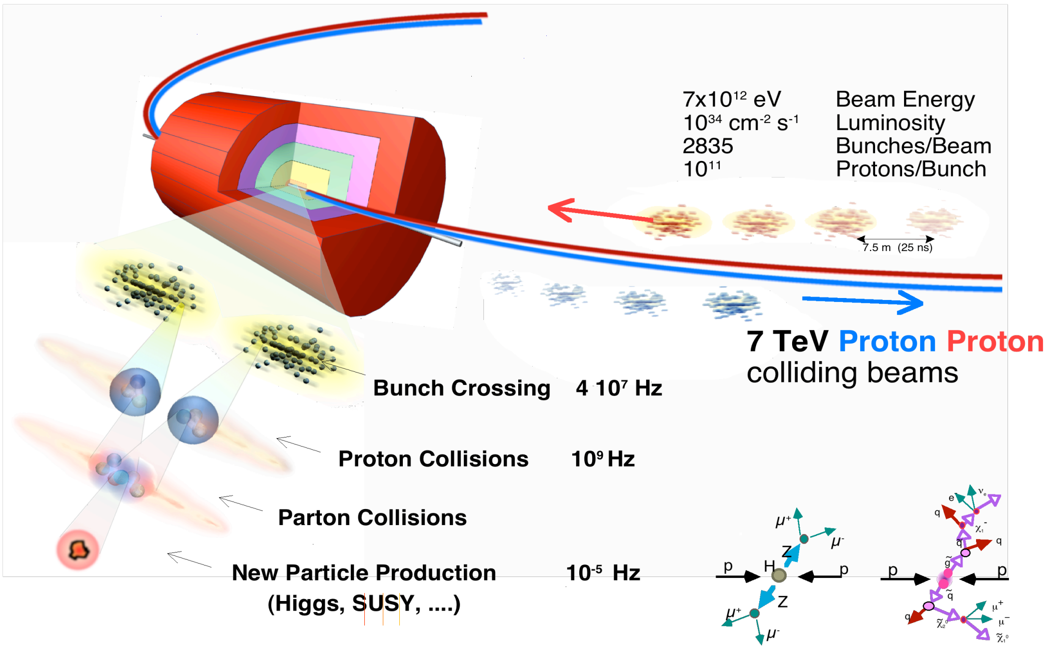
Many Thanks to:

A. De Roeck, F. Gianotti, G. Giudice, J. Incandela, K.Jakobs
and many others …

Backup

The LHC Environment

Collisions at the LHC



Selection of 1 event in 10,000,000,000,000

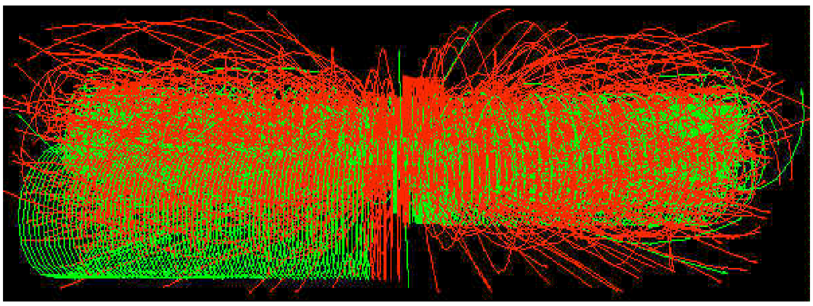
pp collisions at 14 TeV at 10^{34} cm^{-2}s^{-1}

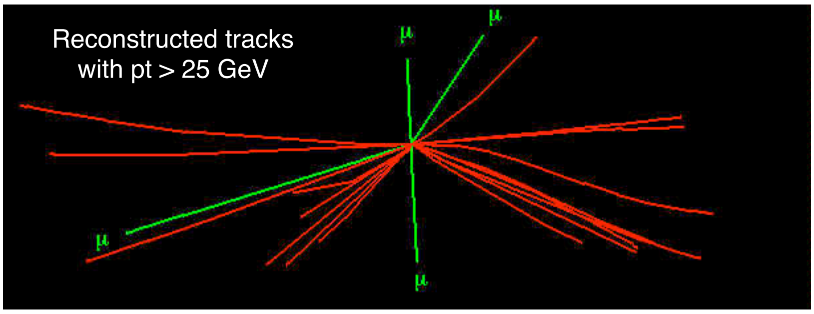
A very difficult environment …

20 min bias events overlap & H→ZZ with Z → 2 muons

: H→ 4 muons: the cleanest ("golden") signature

And this (not the H though…) repeats every 25 ns…

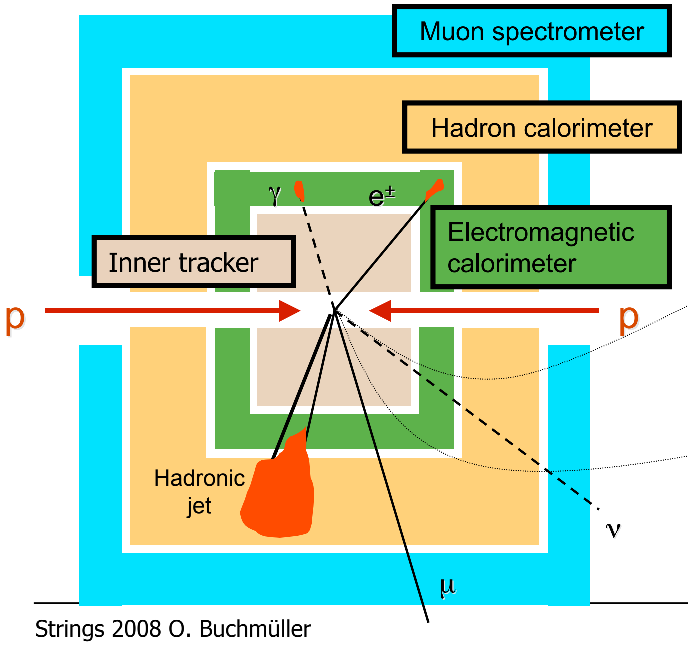




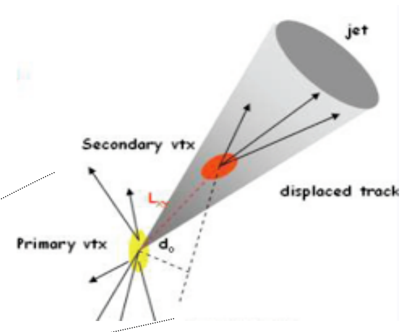
High Performance Detectors

We don't know how New Physics will manifest itself

→ detectors must be able to detect as many particles and signatures as possible: e, μ, τ, ν, γ, jets, b-quarks, ….

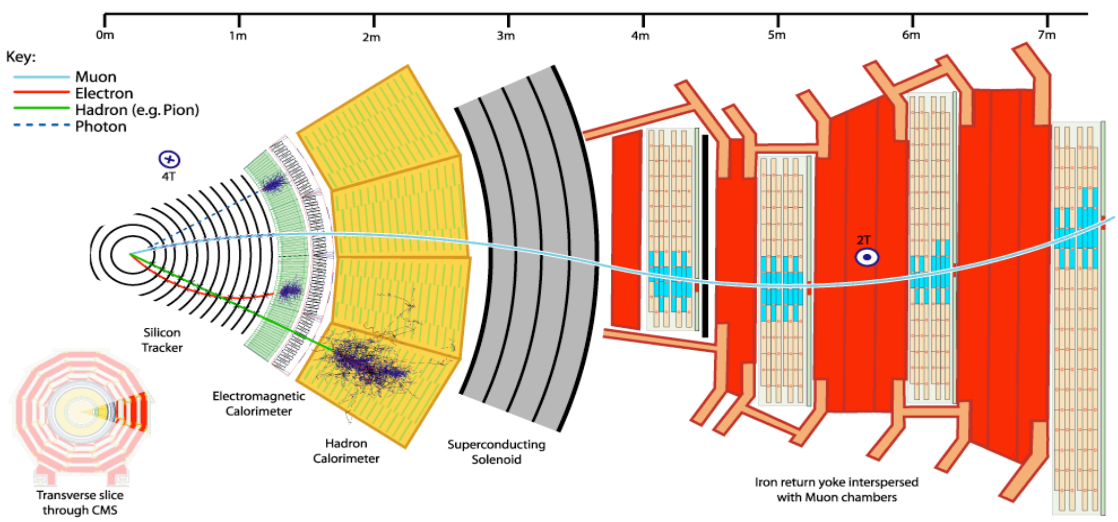


Very precise vertex reconstruction of secondary particle decays (e.g. b quarks)



Excellent performance over unprecedented energy range : **few GeV → few TeV**

High Performance Detectors

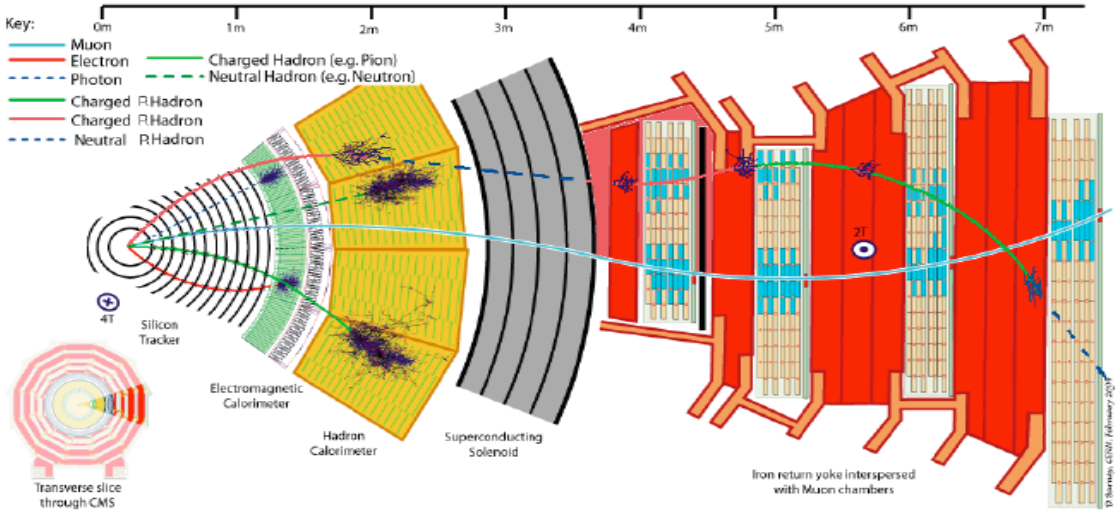


We don't know how New Physics will manifest itself.

→ Detectors must be able to detect as many particles and signatures as possible: e, μ, τ, ν, γ, jets, b-quarks, ….

High Performance Detectors

Even for exotic particles like R-Hadrons (if they exist)



We don't know how New Physics will manifest itself.

→ Detectors must be able to detect as many particles and signatures as possible: e, μ, τ, ν, γ, jets, b-quarks, ….

LHC Startup

Slide from Mike Lamont

- 1 to N to 43 to 156 bunches per beam
- N bunches displaced in one beam for LHCb
- Pushing gradually one or all of:
  - Bunches per beam
  - Squeeze
  - Bunch intensity

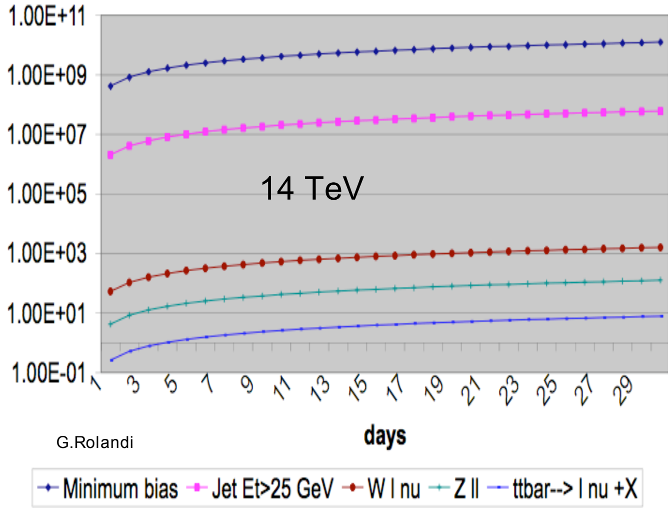
After initial commissioning phase 156x156 running of another month could yield O(10pb^{-1}) @ 10 TeV in 2008

IP 1 & 5

Bunches	β^*	I_b	Luminosity	Event rate
1 x 1	11	10^{10}	~10^{27}	Low
43 x 43	11	3 x 10^{10}	6 x 10^{29}	0.05
43 x 43	4	3 x 10^{10}	1.7 x 10^{30}	0.21
43 x 43	2	4 x 10^{10}	6.1 x 10^{30}	0.76
156 x 156	4	4 x 10^{10}	1.1 x 10^{31}	0.38
156 x 156	4	9 x 10^{10}	5.6 x10^{31}	1.9
156 x 156	2	9 x 10^{10}	1.1 x10^{32}	3.9

Produced Events in the very First Days

30 days at 3x10^29 with efficiency 20% =0 .15 pb^-1



Assumed Efficiencies

$\varepsilon(W) = 0.3$ $\varepsilon(Z) = 0.5$ $\varepsilon(ttbar) = 0.02$

Events after one Month

Min Bias : $\sim 10^{10}$

$Jet_{Et>25}$: $\sim 10^{8}$

$W \to \ell\nu$: $\sim 10^{3}$

$Z \to \ell\ell$: $\sim 10^{2}$

$tt \to \ell\nu + X$: $\sim 10^{1}$

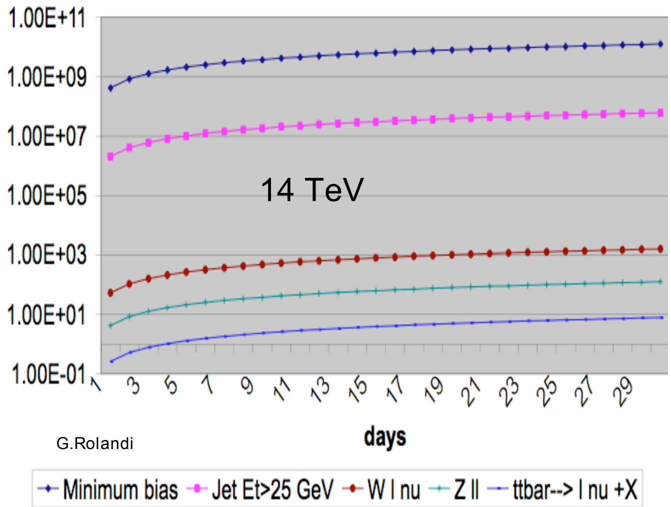
14 TeV

Mainly used for general commissioning and detector alignment & calibration.

Produced Events in the very First Days

Production Rate: 10 vs.14 TeV:
- W/Z ~70%
- ttbar ~50%
- Higgs (200) ~50%

30 days at 3x10^29 with efficiency 20% =0 .15 pb^-1



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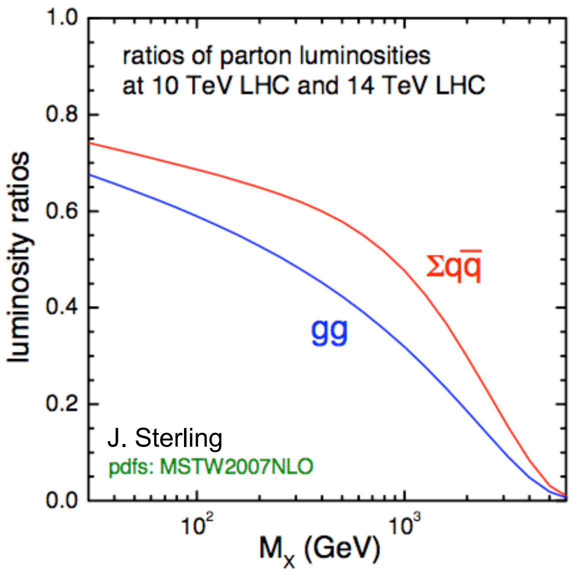
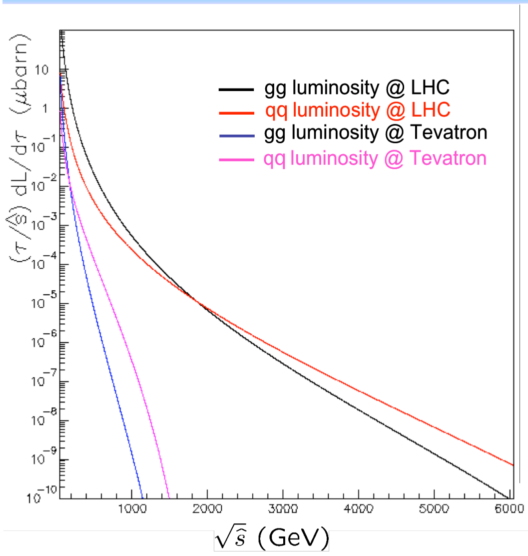
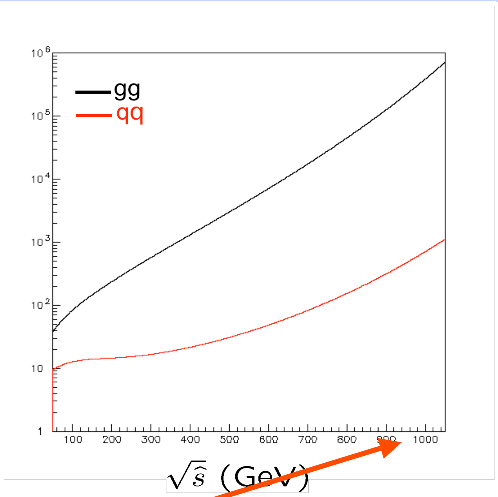
Production Rates: 14 TeV vs. 10 TeV



Production Rate wrt 14 TeV:
- W/Z ~70%
- ttbar ~50%
- Higgs (200) ~50%

LHC will startup in new territory





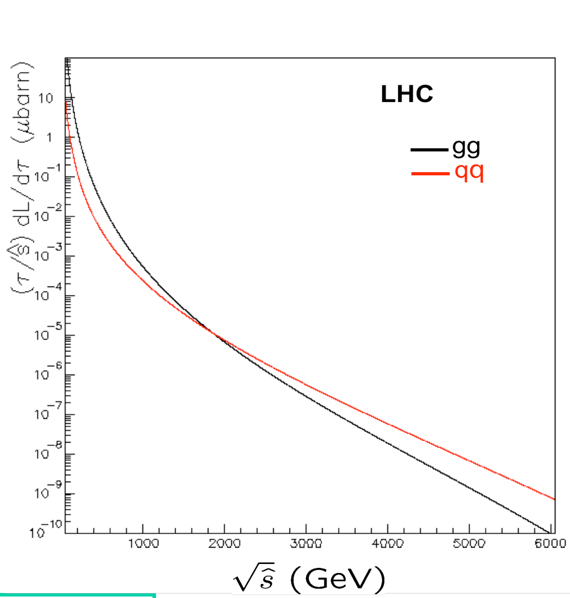
At 1 TeV constituent com energy

→ ***gg: 1 fb^{-1} at Tevatron is like 1 nb^{-1} at LHC***

→ ***qq: 1 fb^{-1} at Tevatron is like 1 pb^{-1} at LHC***

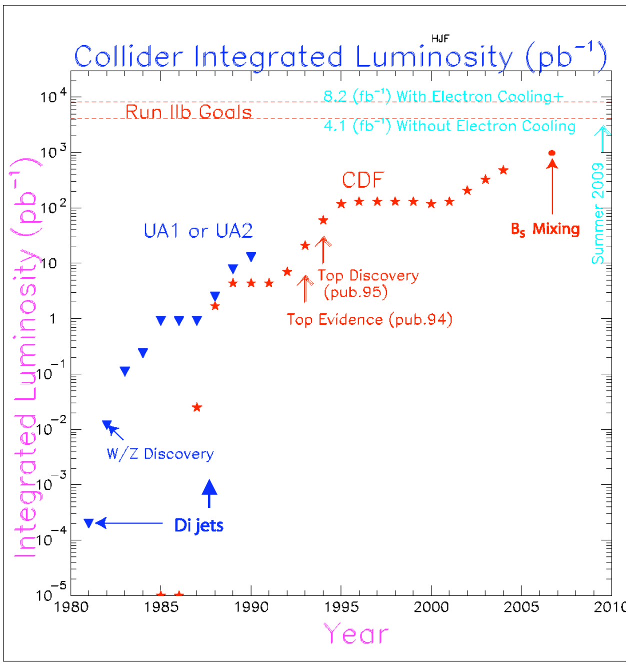
Early and Late

- Parton Luminosity falls steeply
  - In multi-TeV region, ~ by factor 10 every 600 GeV
- New states produced near threshold
  - Suppose you have a limit on some pair-produced object, M > 1 TeV. How does your sensitivity improve with more data?
    - *By ~ (600/2)=300 GeV = 30% for 10 times more integrated luminosity*



Improving sensitivity is tough....
but you can turn evidence into an observation

Good stuff comes early…and late.



- SPS
  - 683 GeV com and ~100 GeV mean com partons
- Tevatron I
  - 1800 GeV com and ~270 GeV mean com partons
- SPS & Tevatron Discoveries
  - SPS turn-on led to quick major discoveries
  - Not true at the Tevatron
- SPS had a lot of data
  - Already probed quite a bit higher than the mean constituent com energy (~100 GeV)
  - Tevatron needed to ~match SPS integrated luminosity to in order to probe a "new" energy domain
    - *And then discovered top!*
- Early discoveries have been followed by other important results at hadron colliders – but these have generally come late

“Re-discovery” of the Standard Model @ 14 TeV (10 TeV)

W/Z Production

Expected rate uncertainties:

W	ATLAS 50/pb	ATLAS 1/fb	CMS 1/fb
Statistical:	0.2%	0.04%	0.04%
Systematic:	3.1% – 5.2%	2.4%	3.3%

Experimental systematic error dominated by missing energy determination

Z	ATLAS 50/pb	ATLAS 1/fb	CMS 1/fb
Statistical:	0.8%	0.2%	0.13%
Systematic:	3.2% – 3.6%	1.3%	2.3%

W/Z theoretical systematic error dominated by PDFs (1-2%) and boson Pt

Luminosity uncertainty: 10% (at startup), 5% (long-term)

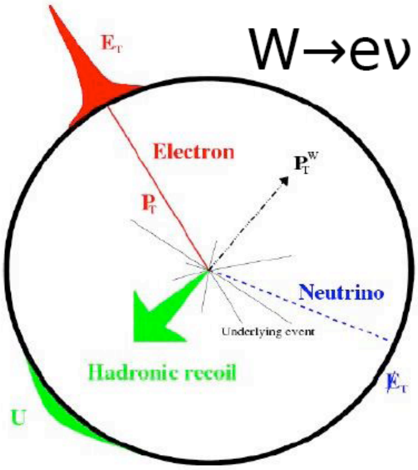
Use W (Z) production as luminosity reaction:

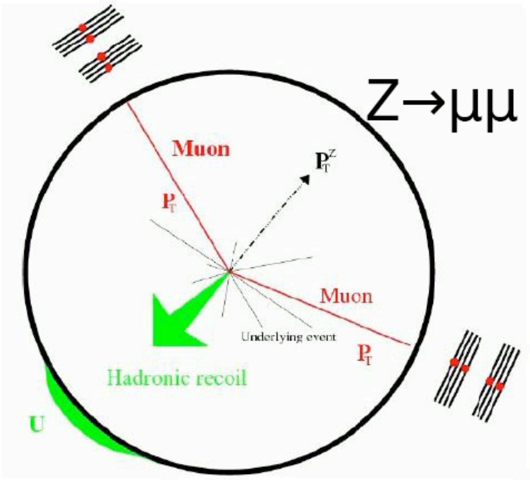
High Q^2 – similar to other reactions (tT, SUSY, ...)
PDF effects cancel to a large extend in ratio of rates

W/Z Production

Inclusive W→lν:

- Single high-energy lepton (e, μ)
- Missing (transverse) energy (ν)
- Hadronic recoil, possibly jet(s)





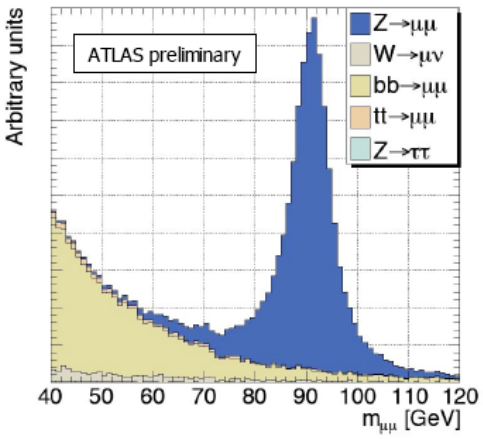
Inclusive $Z \to l^+l^-$:

- Pair of high-energy leptons of opposite electric charge
- No missing transverse energy
- Hadronic recoil, possibly jet(s)

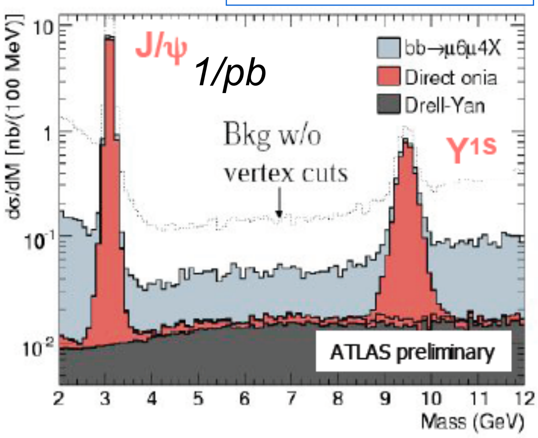
8

Example: J/ϕ, Υ and Z

Z→μμ
26K Z and 0.1K backg. @ 50/pb
~200/day ***Z→μμ*** @ 10^{31}



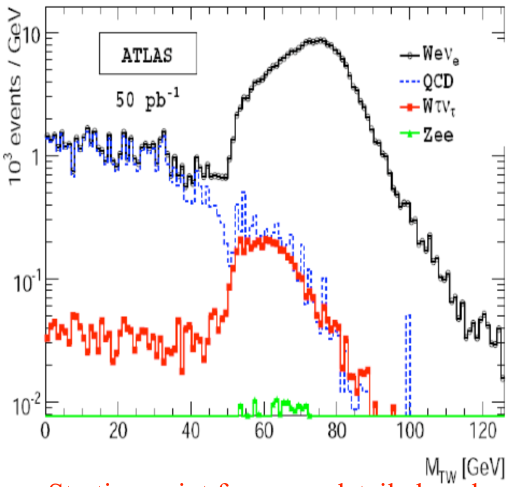
J/ϕ→μμ and Υ→μμ
5000/day J/ϕ and
800/day Υ @ 10^{31}



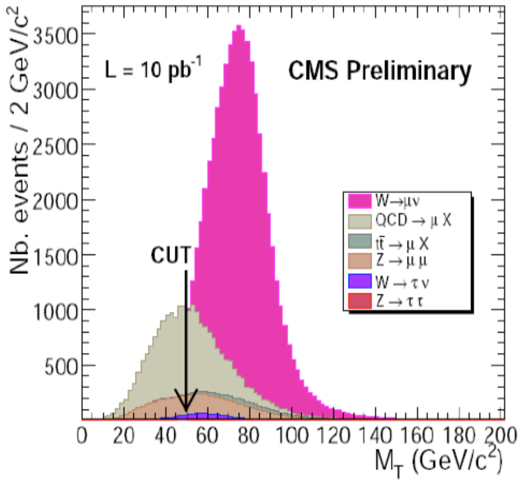
Crucial data samples for the commissioning of the experiments (alignment, momentum scale, efficiencies, etc) but also for physics.

Example: W Production

W→eν



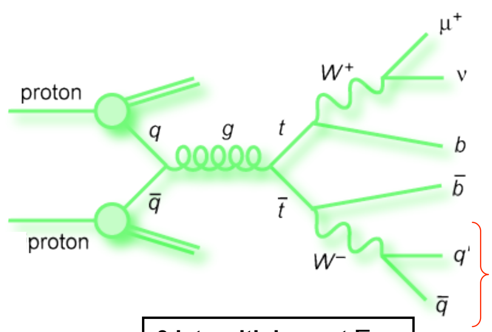
W→μν



Starting point for many detailed analyses:
- p_T boson spectrum
- W(and Z) + multi-jets (important for searches)
- Asymmetries
- W mass and width
- Calibration candles (in particular Z)
- etc

Very rich program of work starting already at day one. Very relevant for searches!

Ttbar re-discovery & Ttbar as a tool



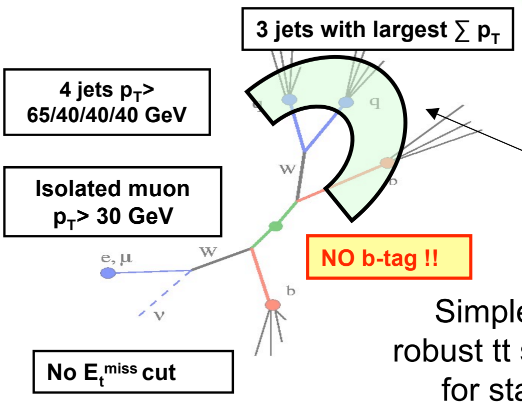
Tag and Lepton study tool

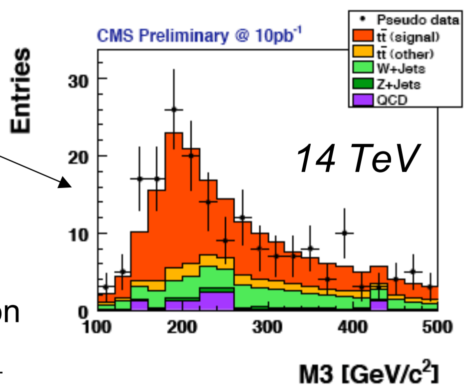
Missing E_T study tool

B tag study tool

Light quark jet energy scale from M_W constraint

b quark jet energy scale from M_{top} constraint

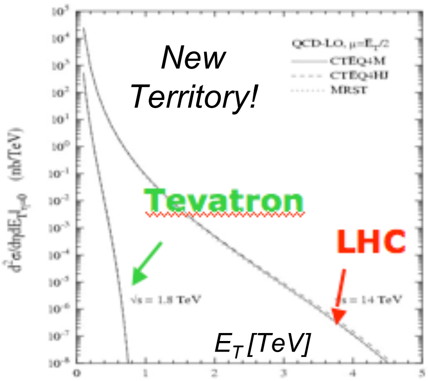




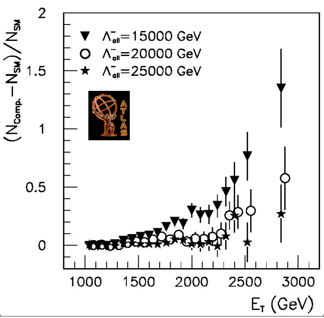
Simple and robust tt selection for start-up

New Physics

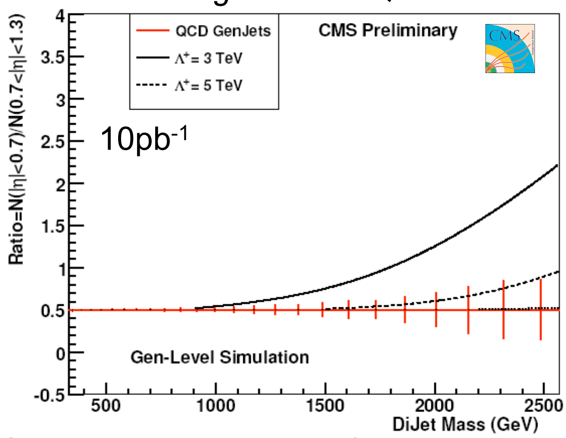
Contact Interactions with Di-jets



ATLAS:
Probe Λ>20 TeV already with 30fb-1



Signal "over QCD"



Small systematic due to use of ratio:
Di-jet Ratio = N(|h|<0.5) / N(0.5<|h|<1)

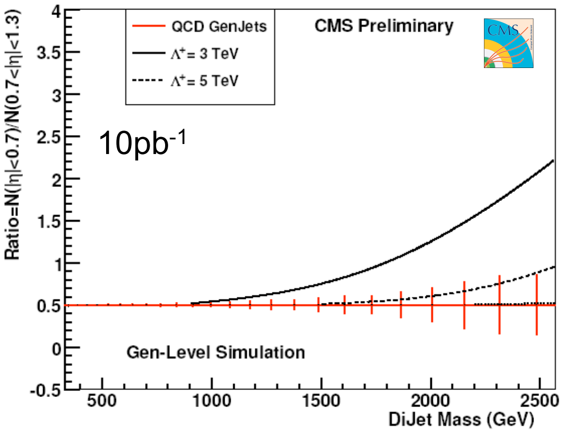
Discovery Sensitivity (CMS)

- $10pb^{-1}$ →Λ~4 TeV
- $100pb^{-1}$ →Λ~7 TeV
- $1fb^{-1}$ →Λ~10 TeV
- $10fb^{-1}$ →Λ~15 TeV

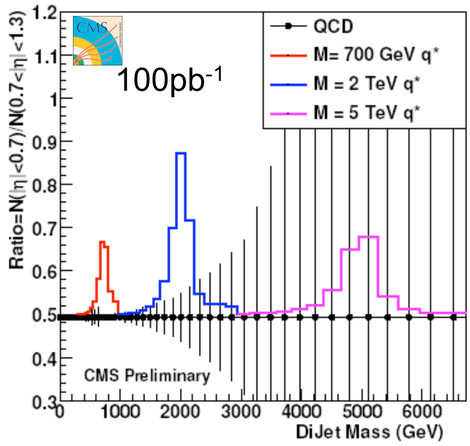
Significant discovery potential: e.g. up to Λ~10 TeV in 2008/2009

New Physics Search with Di-jets

Contact Interaction



Exited Quarks



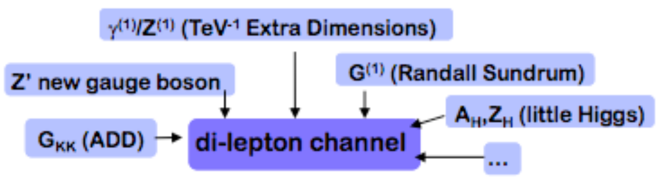
Small systematic due to use of ratio:
Di-jet Ratio = N(|η|<0.7) / N(0.7<|η|<1.3)

	Excluded Λ (TeV)			Discovered Λ (TeV)		
	$10\ pb^{-1}$	$100\ pb^{-1}$	$1\ fb^{-1}$	$10\ pb^{-1}$	$100\ pb^{-1}$	$1\ fb^{-1}$
DØ and PTDR η cuts	< 3.8	< 6.8	< 12.2	< 2.8	< 4.9	< 9.1
Optimized η cuts	< 5.3	< 8.3	< 12.5	< 4.1	< 6.8	< 9.9

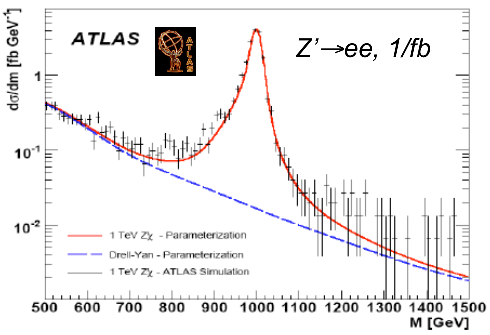
Significant discovery potential: e.g. up to Λ~10 TeV in 2008/2009

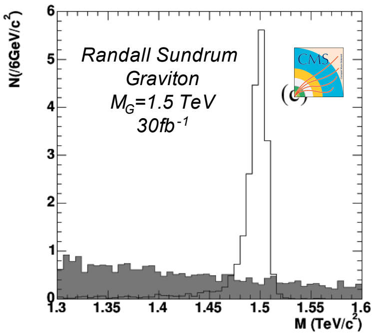
Di-lepton Resonances

Because of their clear signature di-lepton resonances have always been the subject of new physics searches.
At the LHC they are predicted to arise in many BSM models:



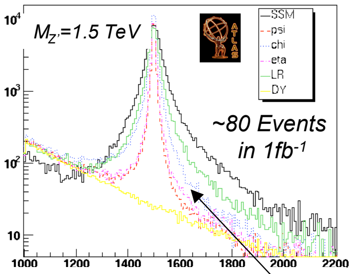
Clear signatures: $\mu^+\mu^-$ *and* e^+e^- *final state*

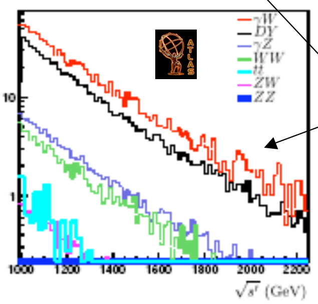




Di-lepton Resonances (Example Z')

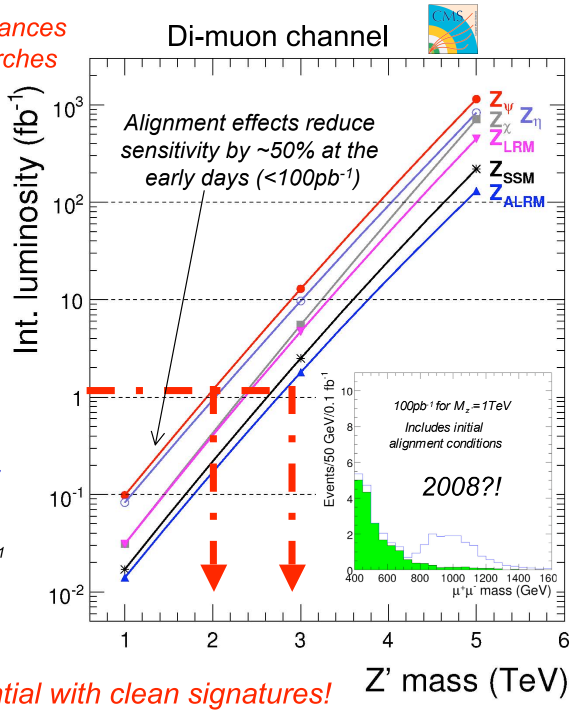
Because of their clear signature di-lepton resonances have always been subject of new physics searches





Main background:
Drell-Yan:
<1 event for M>1.5 TeV in 1fb^{-1}

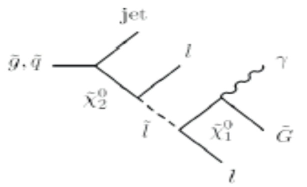
Di-muon channel

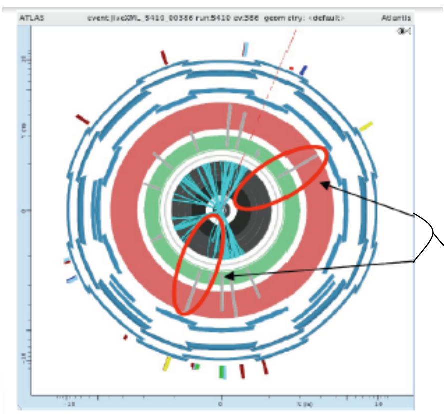


Very early discovery potential with clean signatures!

SUSY: GMSB

SUSY breaking mediated via gauge interactions:

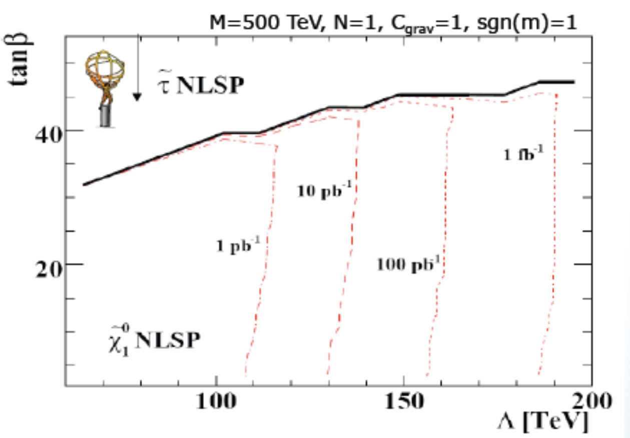




Experimental Signature:

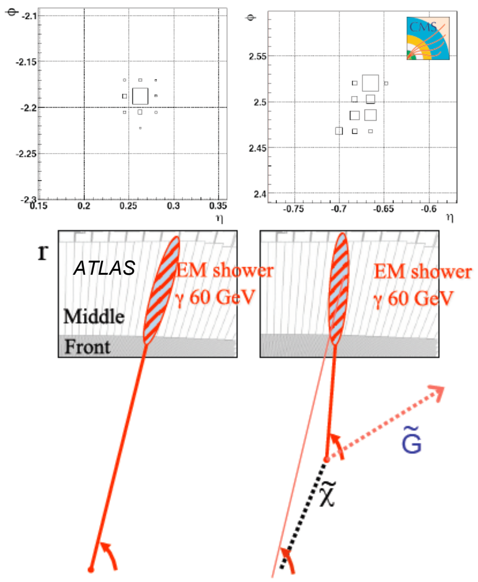
- *lepton and jets*
- *missing energy from gravition*
- *hard photons pointing or non-pointing or long lived staus*

Example:
2 Photons & "Standard" SUSY cuts

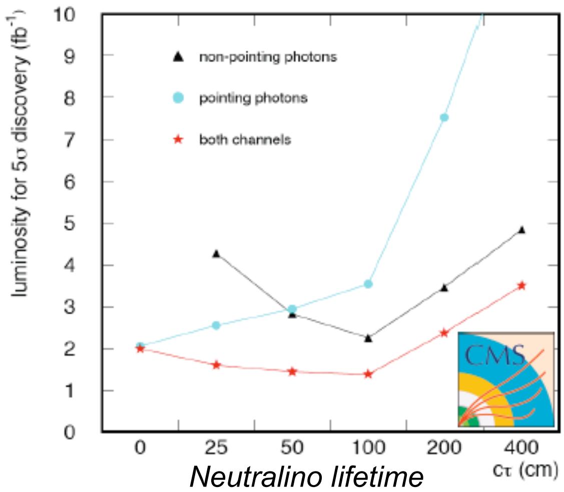


SUSY: GMSB

Separate pointing from non-pointing photons by looking at the ECAL cluster shape



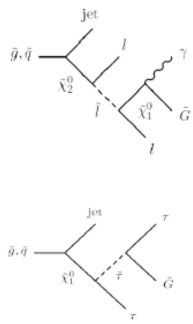
Discovery potential already with 1/fb

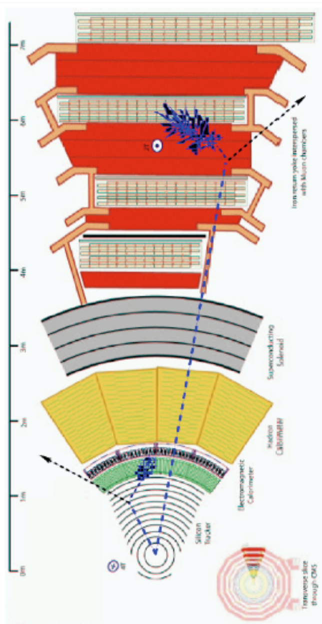


Neutralino lifetime

GMSB

- Theoretical framework
  - renormalizable local supersymmetry including gravity
  - SUSY breaking mediated via gauge interactions
  - depends on 6 parameters
  - spin 3/2 gravitino superpartner of the graviton
- Phenomenological consequences
  - production as in MSSM
    - can have large cross section (squarks and gluinos produced)
  - decay chains
  - LSP: gravitino, mass<KeV
  - neutralino or stau NLSP decaying to a gravitino ($\chi_1^0 \rightarrow G\gamma$)
    - decay time can be long
- Final states:
  - leptons and jets
  - MET from gravitino
  - hard photons (pointing or not-pointing) or
  - long lived stau

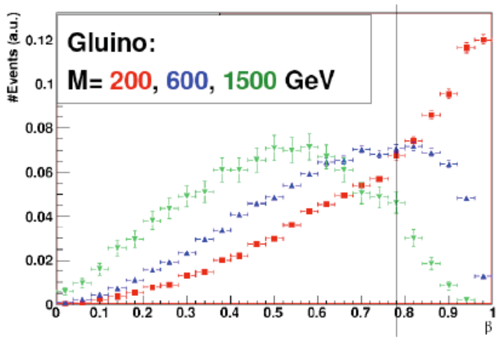


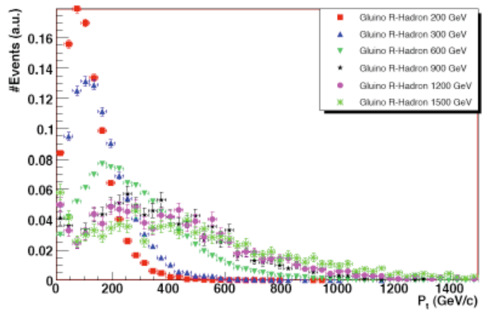


Heavy Stable (Charged) Particles

- Heavy:
  - hundreds of GeV
  - $\beta < 1$
- Stable:
  - $c\tau$ few meters
  - can decay in the detector or can cross it
  - we show results about particles crossing the detector
- Charged:
  - electrical or colour charge

- Models:
  - lepton like particles:
    - GMSB staus
    - Kaluza-Klein tau resonances in UED
  - R-hadrons:
    - long lived stops in SUSY
    - long lived gluino in Split-SUSY
- Many model considered, but model independent analysis
  - no assumption, just observation of a heavy object crossing the detector





Heavy Stable Particles: GMSB

Gauge Mediated Supersymmetry Breaking. Models for SUSY breaking, alternative to mSUGRA

SUSY breaking transmitted from Hidden sector to visible sector via gauge interactions ("messengers")

Lightest supersymmetric particle (LSP) is the Gravitino (m≤keV)
light, stable and weakly interacting, possible candidate for Dark Matter

Par.	Description
Λ	SUSY breaking scale
M_m	Messenger mass scale
tanβ	Ratio of Higgs vev
N_m	Number of SU(5) messenger multiplets
sign(μ)	μ from Higgs sector
C_{grav}	Sets NLSP lifetime

τ mass	156	247
N_m	3	3
Λ(TeV)	50	80
M_m(TeV)	100	160
Tanβ	10	10
sign(μ)	1	1
C_{grav}	10^4	10^4

If N_m>3 NLSP is the stau
quasi-stable due to the smallness of the coupling constant

- production: ISASUGRA 7.69
  - 2 points from SPS line 7
    - stau(156): N=3, Λ=50 TeV, M = 100 TeV, tanβ=10, sgn(μ)=1, C_{grav}=10000
    - stau(247): N=3, Λ=80 TeV, M = 160 TeV, tanβ=10, sgn(μ)=1, C_{grav}=10000
  - for both points:
    - larger squark and gluino cross section than direct stau production
    - $c\tau$ ~ 200 m
- Generation: PYTHIA 6.409

Table 2: Summary of the slepton NLSP sample. $N_5 = 3, \tan\beta = 5, \mathrm{sgn}(\mu) = +$, and no decay of slepton is assumed.

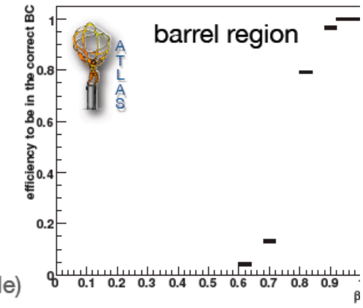
name	NLO (LO) σ [pb]	Λ [TeV]	M_m [TeV]	$M_{\tilde{\tau}_1}$ [GeV]
GMSB5	21.0 (15.5)	30	250	102.3

Heavy Stable Particles

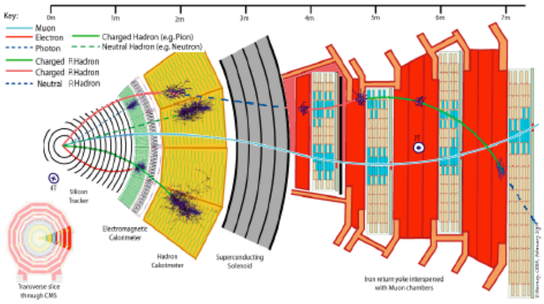
- Muon-like signature but:
  - due to particle slowness, trigger and data acquisition efficiency may be affected:

if β<<1 the event may be associated with the wrong bunch crossing

Efficiency in the correct bunch-crossing



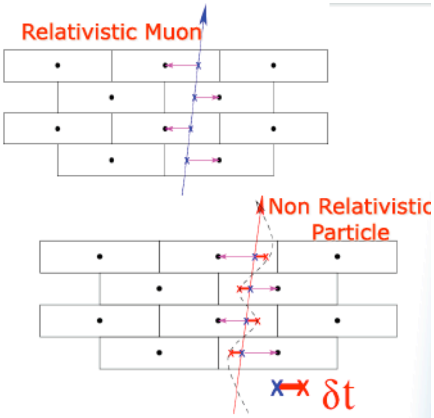
- R-hadrons most demanding case
  - direct pair production → must relies on the two R-hadrons only
  - both particles can be slow
  - charge flipping (trajectory modified and neutral R-hadrons not visible)

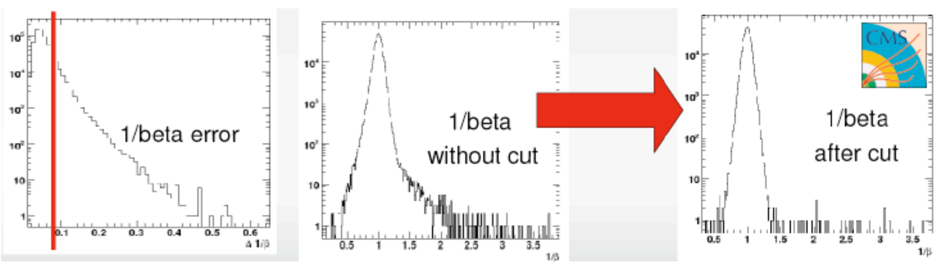


	HLT Trigger Path Efficiencies [%]				
	MU	MET	∑ET	JET	Total
$\tilde{\tau}$ 150-250 GeV	~97	~80	~90	~70	>99
$\tilde{g}$ 200-1500 GeV	~15	~30-60	~40-95	~10-50	~60-95
$\tilde{t}$ 130-800 GeV	~20	~20-40	~20-60	~4-20	~40-70

Heavy Stable Particles: beta

- Drift tubes time resolution (~1 ns in ATLAS and CMS) allows the distinction of relativistic and non-relativistic particles
  - drift time as parameter of the fit
  - realignment of the hits to give an estimate of the delay
- Main bkg:
  - tails in true muons
    - will be estimated with real data using Z→μμ
  - cosmics
    - strongly suppressed if DT combined with tracker





Heavy Stable Charged Particles

Predicted by several models:

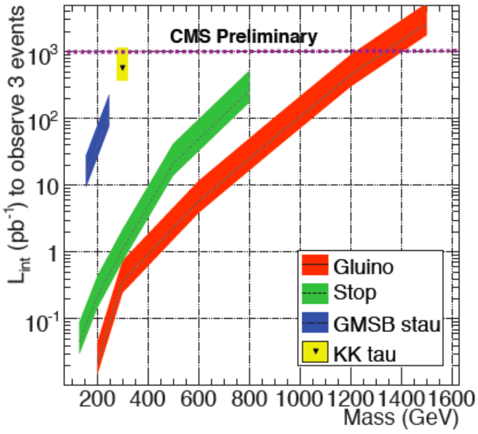
- *lepton like*
  - *•GMSB staus*
  - *•Kaluza-Klein tau's in UED*
- *R-Hadrons*
  - *•long lived stop in SUSY*
  - *•long lived gluino in split-susy*

Properties:

•O(100 GeV), β<1

•$c\tau$ few meters

•electrical or colour charge

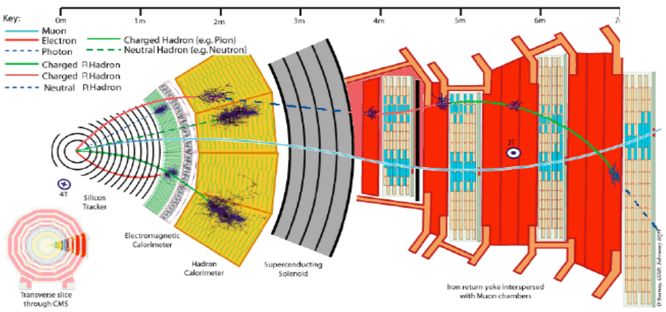


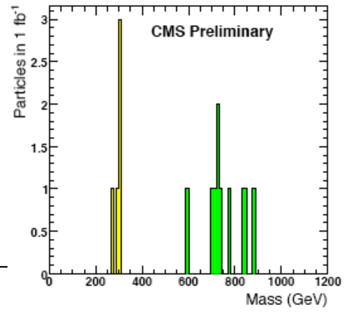
Measurement

• momentum in Tracker&Muon

•β TOF in Muon DT & dE/dx in Tracker

ATLAS similar





Strings 2008 O. Buchmüller

Heavy Stable Charged Particles

Predicted by several models:

- *lepton like*
  - *•GMSB staus*
  - *•Kaluza-Klein tau's in UED*
- *R-Hadrons*
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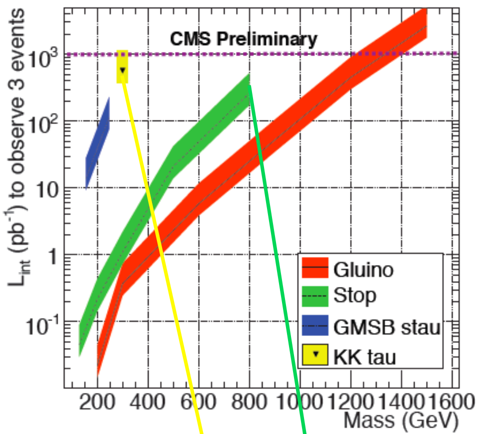

Measurement

• momentum in Tracker&Muon

•β TOF in Muon DT & dE/dx in Tracker

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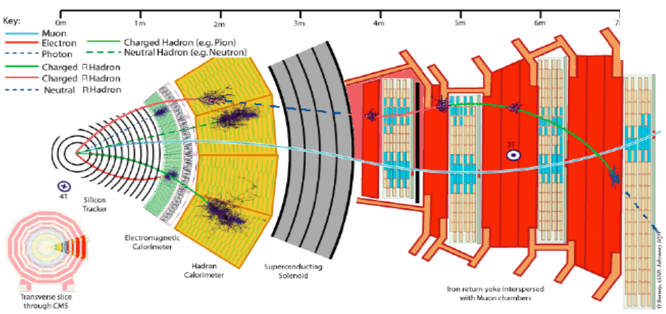

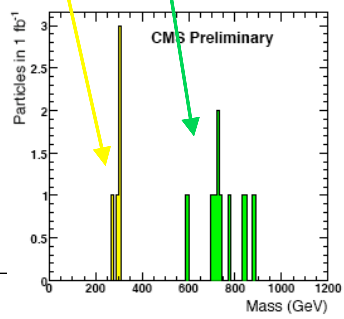

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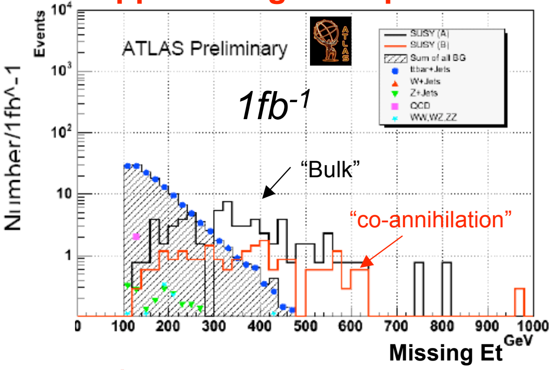
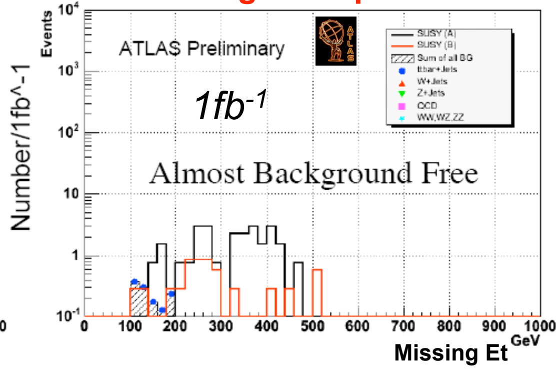
Jets+E_t^{miss}+(1,2) l - Inclusive Search

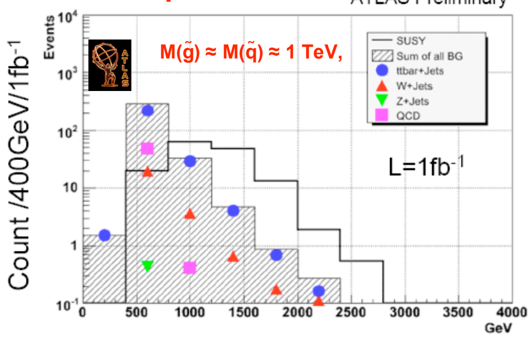
Opposite sign di-leptons



Same sign di-leptons



1 Lepton



Good discovery potential

Lower statistic but cleaner than "0 lepton".

Analysis Strategy:

- Still worry about ttbar, W/Z jets and QCD
- Use data control samples
- get lepton reconstruction/selection under control

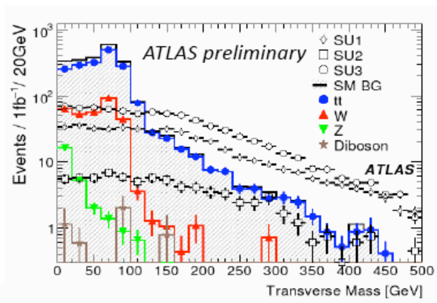
SM Background: Jets+MET+(1Lepton)

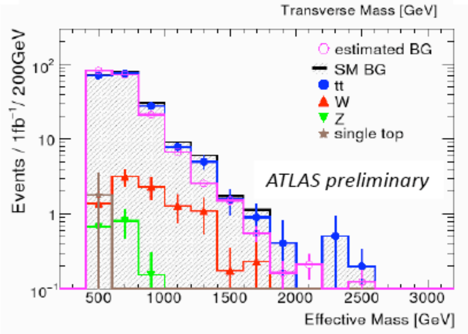
jets + 0 and 1 lepton channel

Estimate top and W background from data

ATLAS:
control region with M_T < 100 GeV
Here we have more SM events than new physics signal

effective mass distribution in control region can be used to predict distribution in signal region (M_T > 100 GeV)

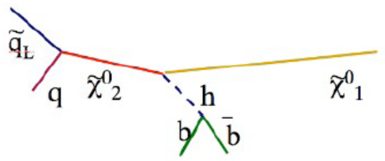




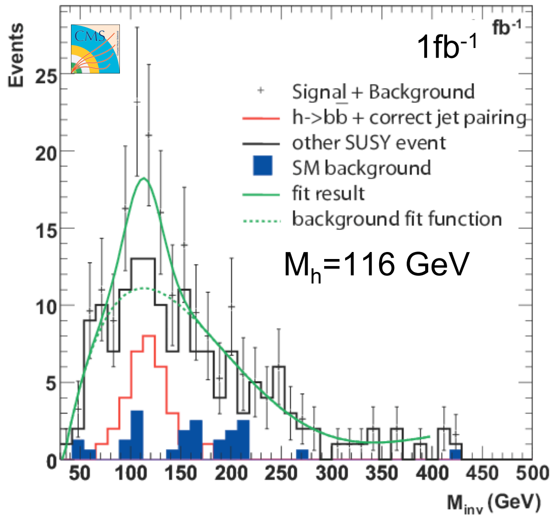
ICHEP08

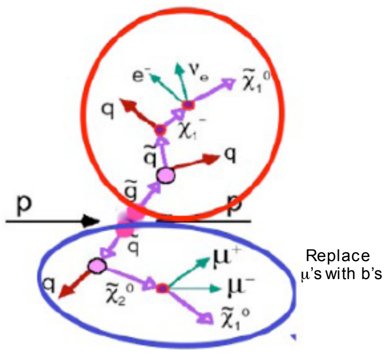
Sascha Caron 11

"Low Mass M_h" in SUSY Decays



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

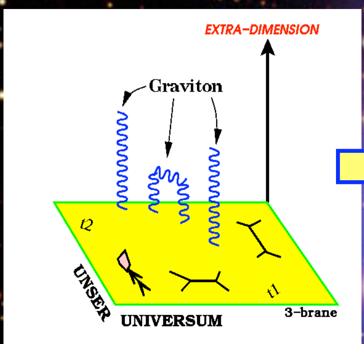


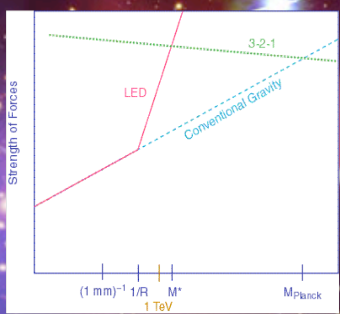


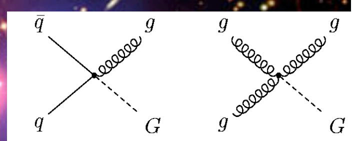
- Separate cascade decay chain in two hemispheres and require two b's in one.
- 5σ Signal (M_h=115 GeV) already with~2fb^{-1}

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

Extra space dimensions?







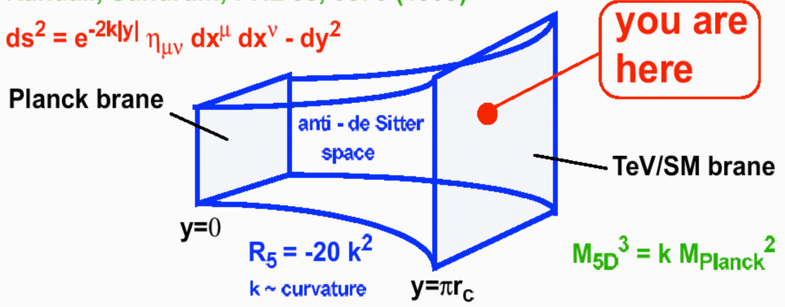
Signatures
Eg monojet events
monophoton event
Z' like resonances
KK excitations
…

The Gravity force becomes strong!

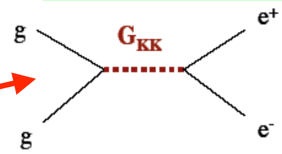
Curved Space: RS Extra Dimensions

Randall, Sundrum, PRL 83, 3370 (1999)

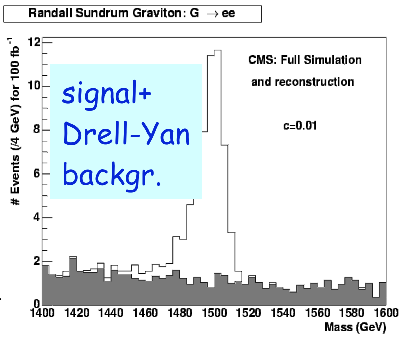
$ds^2 = e^{-2k|y|}\,\eta_{\mu\nu}\,dx^\mu\,dx^\nu - dy^2$

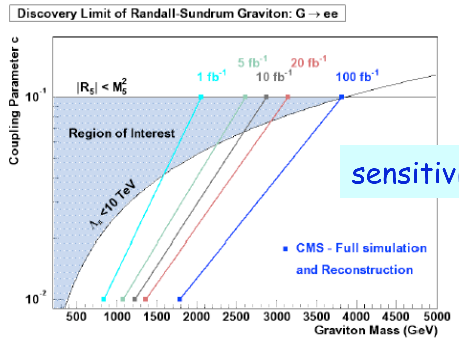


phenomenology



Study the channel pp→Graviton→ e+e-





Quantum Black Holes at the LHC?

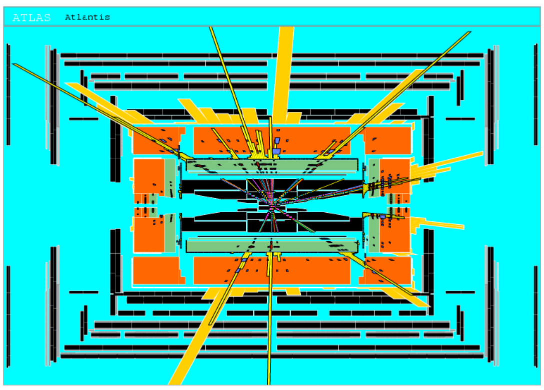
Black Holes are a direct prediction of Einstein's general theory on relativity

If the Planck scale is in ~TeV region: can expect Quantum Black Hole production

4 dim. : R_s → « 10^{-35} m

4+n dim. : R_s → ~ 10^{-19} m

R_S = schwartzschild radius



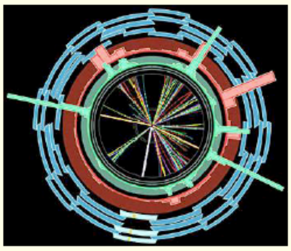
Simulation of a Quantum Black Hole event

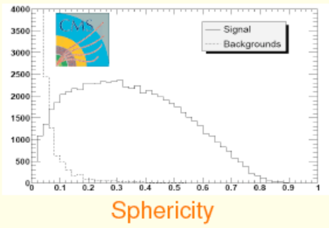
Quantum Black Holes are harmless for the environment: they will decay within less than 10^{-27} seconds

Quantum Black Holes open the exciting perspective to study Quantum Gravity in the lab!

Black Holes at LHC:

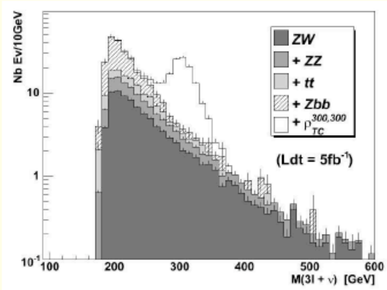
- With Large Extra Dimensions micro Black Holes (BH) could be produced at LHC energy scale, *in (4+n) dimensional spacetime*
  - Schwarzschild radius $r_{s(4+n)}$ function of the reduced Plank scale M_D
- BH is formed if the p-p impact parameter is less than $r_{s(4+n)}$
  - from semiclassical approach $\sigma(M_{BH}) = \pi r^2_{s(4+n)}$
  - In case of $M_D \sim$ TeV then $\sigma(M_{BH}) \sim$ pb
- Could be discovered with 1 fb^{-1} if $M_D < 5$ TeV
- BH with short life time, of the order of 10^{-12} fs
- BH is expected to evaporate by emission of all particle types
  - source of new particles
  - possibility to probe quantum gravity in lab
- Signature
  - High track multiplicity, hadrons:leptons = 5:1
  - spherical event





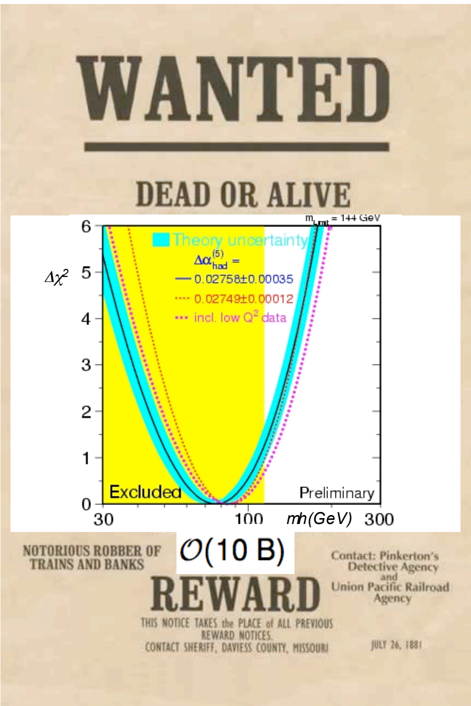
Technicolors: $\rho^+_{TC} \rightarrow W+Z \rightarrow 3l+\nu$

- Dynamical Electroweak Symmetry Breaking
  - QCDlike force which acts on technifermions at a scale of ~ 250 GeV
  - Mediated by technimesons
  - π_{TC} (s = 0), ρ_{TC} and ω_{TC} (S = 1)
  - *No need* for the Higgs boson
- Most promising channel is $\rho_{TC} \rightarrow W+Z \rightarrow 3l+\nu$
  - isolated high p_T leptons + missing E_T
  - W and Z kinematics as signature
  - Background from VV (V=Z,W), Z bb, tt



Higgs

SM-like Higgs Boson

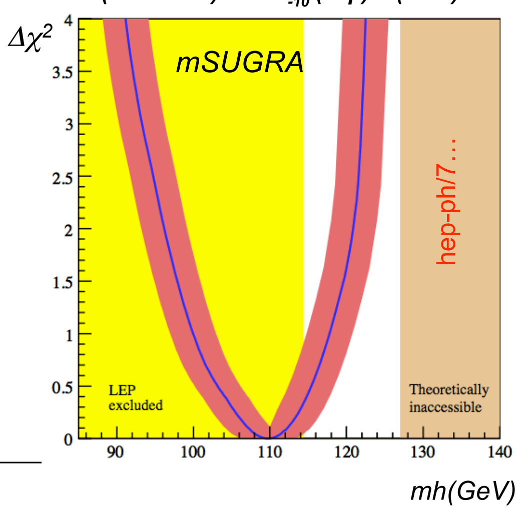


Precision electroweak data tightly constrain the allowed region of m_h in the SM.

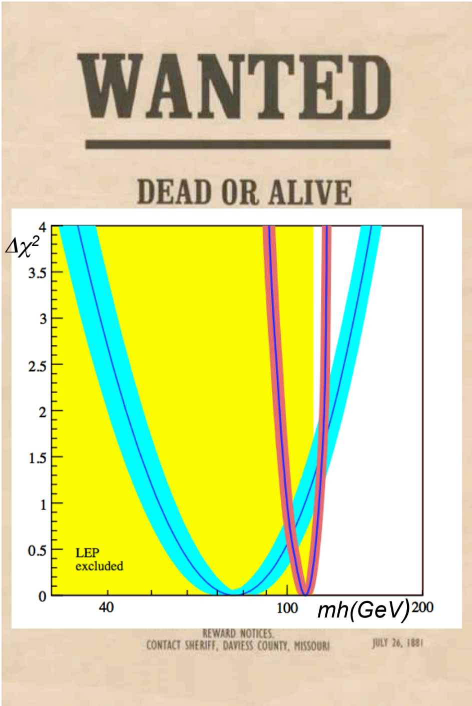
Yet, also other important models like mSUGRA are constrained by these data:

mSUGRA fit to flavour, electroweak and cosmology data:

$mh(mSUGRA)=110^{+8}_{-10}$ (exp)±3(theo) GeV



SM-like Higgs Boson



Many of the popular models (e.g SM or MSSM) require the lightest higgs boson mass to be significantly below 200 GeV.

If the higgs boson really exist, it is probably just around the corner!

Concentrate on SM-like higgs search for mh<200 GeV but the LHC covers full phase space up to 1 TeV.

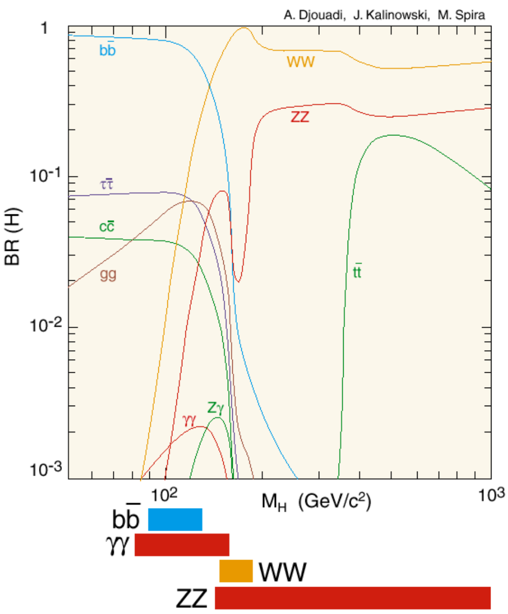
⇒ We will get an answer!

Not covered in this talk:
Search for heavy higgs (e.g. MSSM)

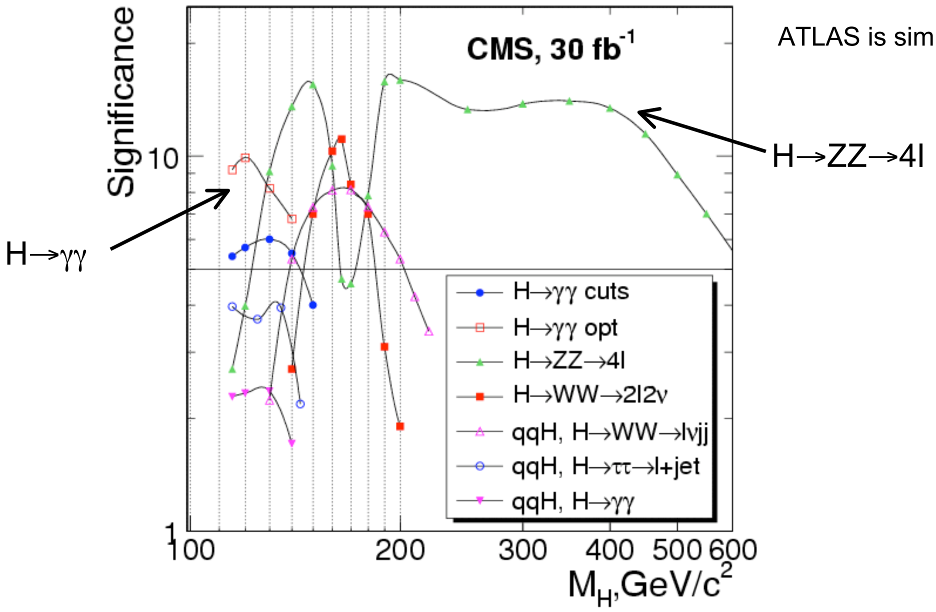
SM Higgs (or lightest Higgs)

Higgs Decay channels

- Higgs couples to m_f^2
  - *Heaviest available fermion (b quark) always dominates*
  - *Until WW, ZZ thresholds open*
- Low mass: b quarks→ jets; resolution ~ 15%
  - *Only chance is EM energy (use γ decay mode)*
- Once M_H>$2M_Z$, use this
  - *W decays to jets or lepton+neutrino (E_T^{miss})*



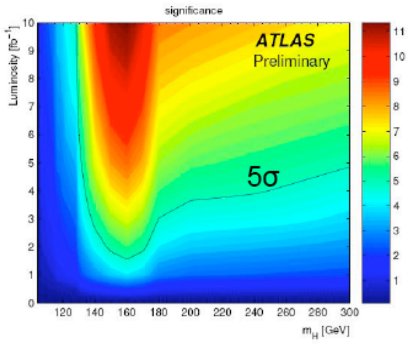
CMS: Higgs Discovery Potential



ATLAS is similar

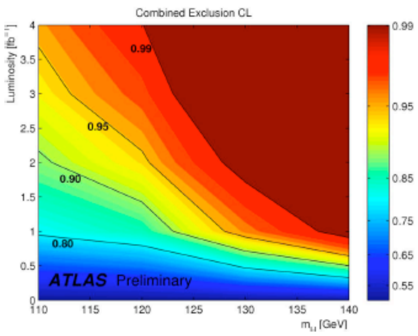
Bottom line: We will find the Higgs (or exclude it)!

SM Higgs Reach - New ATLAS update



For 5σ discovery, one needs

- ~20 fb^{-1} to probe down to m_H=115 GeV
- 10 fb^{-1} for m_H range 127 – 440 GeV
- 3.3 fb^{-1} for m_H range 136 – 190 GeV
- Just under 2 fb^{-1} for $m_H \approx 2m_W$



For 95% CL exclusion, one needs

- 2.8 fb^{-1} for m_H = 115 GeV/c^2
- 2 fb^{-1} for m_H range 121– 460 GeV
- Less than 2 fb^{-1} to exclude $m_H \approx 2m_W$

Important Higgs Channels

- **$H \to ZZ^* \to 4l$**
- **$H \to WW^* \to l\nu l\nu$**

} "early" discovery channels
measure Higgs properties (mass, width, xsec)
already with 30 fb^{-1} !!

- **$H \to WW^* \to jjl\nu$ / $l\nu l\nu$ in VBF**
- **$H \to \tau\tau$ in VBF**

} significance > 5(3) with 30 fb^{-1}
but good comprehension of detector needed
(jet, MET, τ in lept. and hadr. decay)

- **$H \to \gamma\gamma$** very difficult analysis with still quite unpredictable background
- **$ttH \to ttbb$** at least 60 fb^{-1} (many jets also with low p_T (<30 GeV) → bad reso/eff)
- other channels (mainly **associated production**) can help EXCLUDING Higgs (e.g. $WH \to WWW^* \to Wl\nu l\nu$)

	channel	XS	studied M_H
	$H \to ZZ^* \to 4l$	5-100 fb	130-500 GeV
	$H \to WW^* \to l\nu l\nu$	0.5-2.5 pb	120-200 GeV
VBF	$H \to WW^* \to jjl\nu$	200-900 fb	120-250 GeV
VBF	$H \to WW^* \to l\nu l\nu$	50-250 fb	120-200 GeV
VBF	$H \to \tau\tau$	50-150 fb	115-145 GeV
	$H \to \gamma\gamma$	50-100 fb	115-150 GeV

❑ **Analysis focusing on**

- improvement of the reconstruction
- backgr. and syst. from data

$H \to \gamma\gamma$

❑ Photon conversions are important, due to material balance in inner detectors

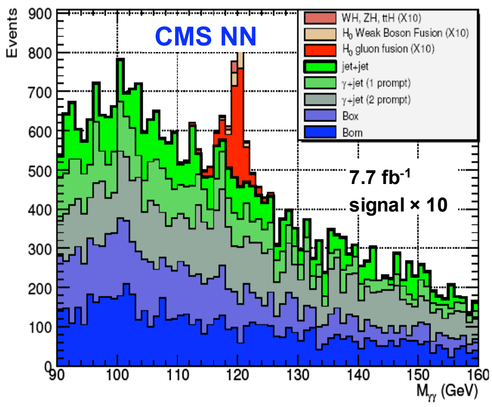
- **42%** in the barrel, **59.5%** in the endcap

❑ Energy Resolution

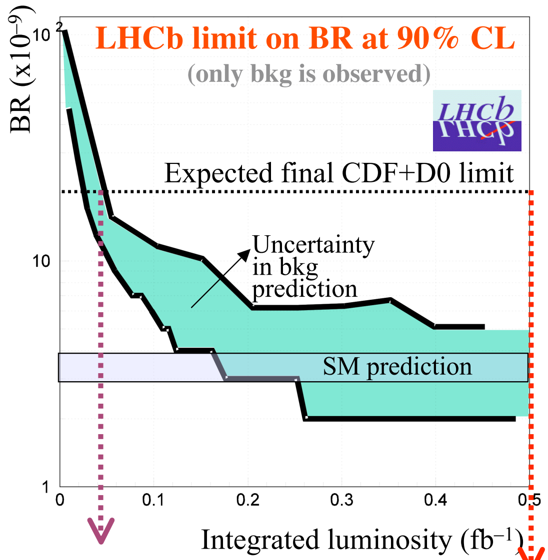
- **0.3%** in the barrel, **1%** in the endcap

❑ Associated production allows to improve s/b ratio. Both ATLAS and CMS are studying several channels

❑ "Advanced" analyses (NN, Likelihood, categories) allow to improve results with low statistics



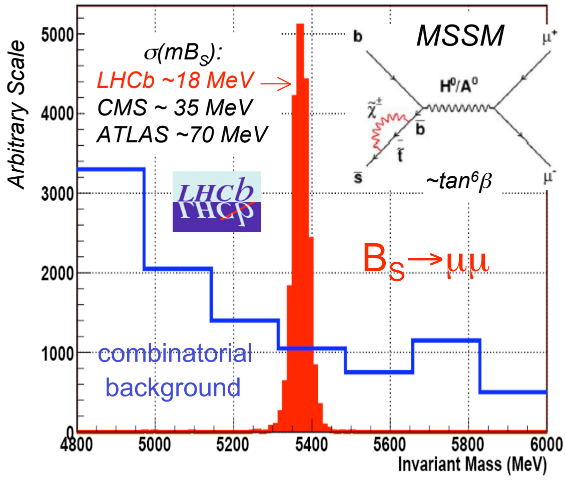
Indirect NP Search: $B_S \to \mu\mu$



$0.05fb^{-1}$ to overtake CDF&D0

$0.5fb^{-1}$ for 90% exclusion at SM value

Early discovery possible!



Integral LHC Luminosity	Signal ev. after cuts	BG ev. after cuts	ATLAS upper limit at 90% CL	CDF&D0 upper limit at 90% CL
100 pb^{-1}	~ 0	~ 0.2	6.4×10^{-8}	8×10^{-8}
10 fb^{-1}	~ 7	~ 20	7.0×10^{-9}	
30 fb^{-1}	~ 21	~ 60	6.6×10^{-9}	

CMS comparable sensitivity (or even a bit better)

LHC & Strings

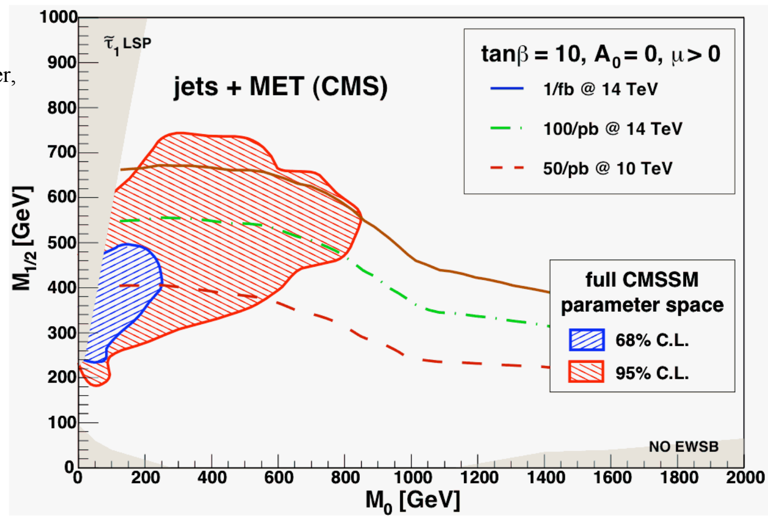
String Theory ⇔ LHC

- ## The LHC can discover
  - Supersymmetry in Nature
  - Extra dimensions at the Terascale
  - Black holes → Study quantum gravity in the lab
- ## Recent developments
  - String theory inspired models to predict SUSY phenomenology at the LHC
    - → *G2-MSSM models ⇒unusual signatures* *(B Acharya, G. Kane et al)*
    - → *String/M theory vacua with a visible MSSM sector (Kane, Kumar and Shao arXiv:0709.4259)*
  - New models inspired from string theoretical observations e.g. hidden valley models
  - AdS/CFT correspondence to calculate properties in heavy ion collisions
  - Pomeron as a messenger from the string world?

Preferred CMSSM Parameter Space

"LHC Weather Forecast"

OB, R.Cavanaugh, A.De Roeck, J.R.Ellis, H.~Flaecher, S.~Heinemeyer, G.Isidor, K.A.Olive, P.Paradisi, F.J.Ronga, G.Weiglein



Simultaneous fit of CMSSM parameters m_0, $m_{1/2}$, A_0, tanβ (μ>0) to more than 30 collider and cosmology data (e.g. M_W, M_{top}, g-2, BR(B→Xγ), relic density)

"CMSSM fit clearly favors low-mass SUSY - Evidence that a signal might show up very early?!"