Physics at the Large Hadron Collider

And the ATLAS Physics Programme

Astbury Symposium
TRIUMF
16 April 2000

- Physics Motivation
- The Large Hadron Collider
- The LHC Experiments
- Highlights from the ATLAS Physics Programme
  - Search for the Higgs Boson
  - Search for Supersymmetry
  - More Searches
  - Standard Model Physics
- Conclusions

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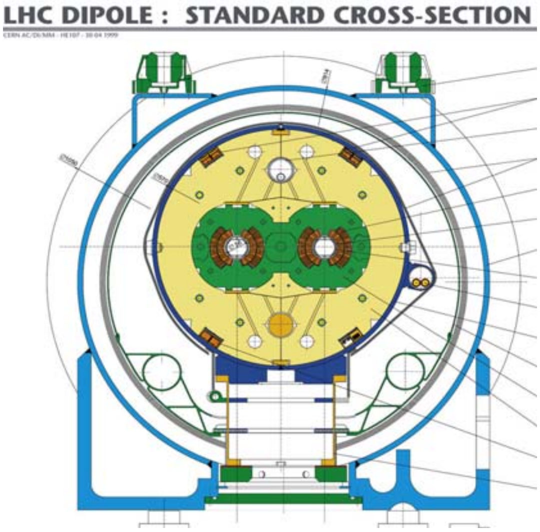
Physics Motivation

The LHC will allow to explore
the structure of matter at
the energy frontier
and at the energy density frontier

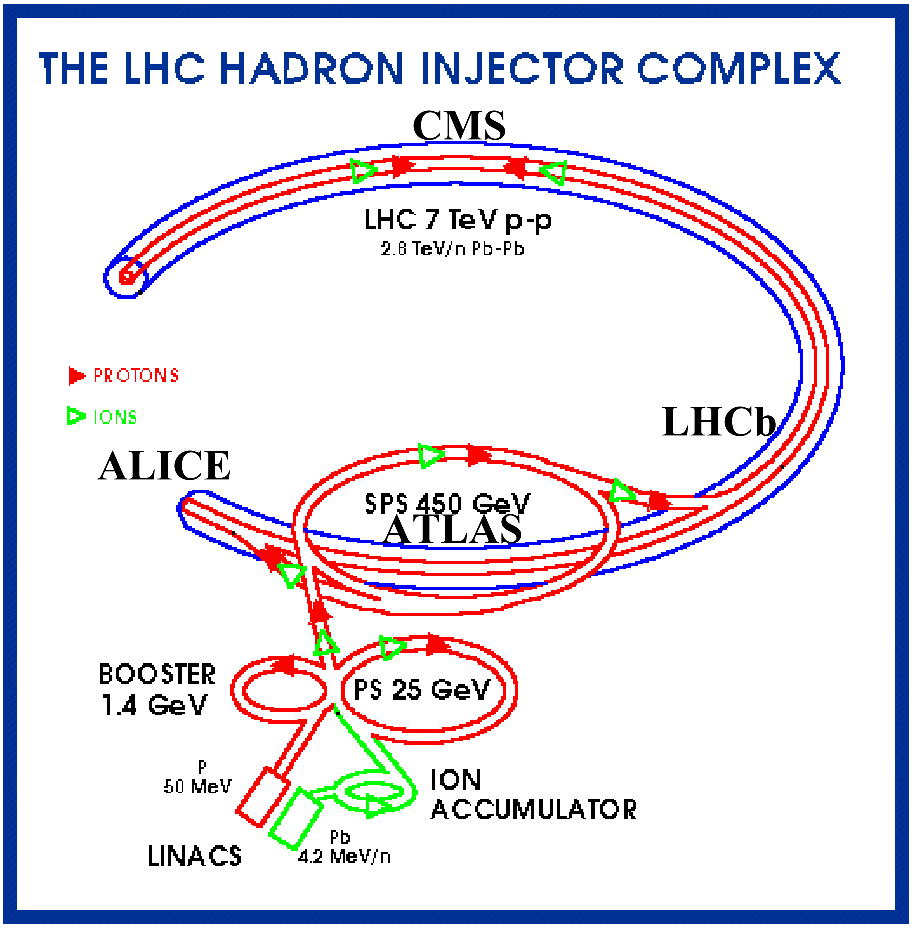
- **The physical origin of electroweak symmetry breaking and the origin of mass**
  - **Higgs boson**
- **The physical origin of CP violation**
  - **Unitary triangle**
- **Searches beyond the standard model**
  - **supersymmetry, new gauge bosons, compositeness,...**
- **Precision measurements of Standard Model parameters**
  - **top, beauty, tau, QCD, ...**
- **The physics of strongly interacting matter at extreme energy densities**
  - **quark-gluon plasma**

The Large Hadron Collider



Dipole field: 8.33 T

2.8 TeV/n Pb-Pb



p-p collisions at $\sqrt{s} = 14\ \mathrm{TeV}$ starting in 2005

bunch spacing: 24.95 ns **stored energy per beam**: 350 MJ

initial luminosity: $10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

$$\int L\,dt = 10\ \mathrm{fb}^{-1}$$ per year (over 3 years)

high luminosity: $10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

$$\int L\,dt = 100\ \mathrm{fb}^{-1}$$ per year

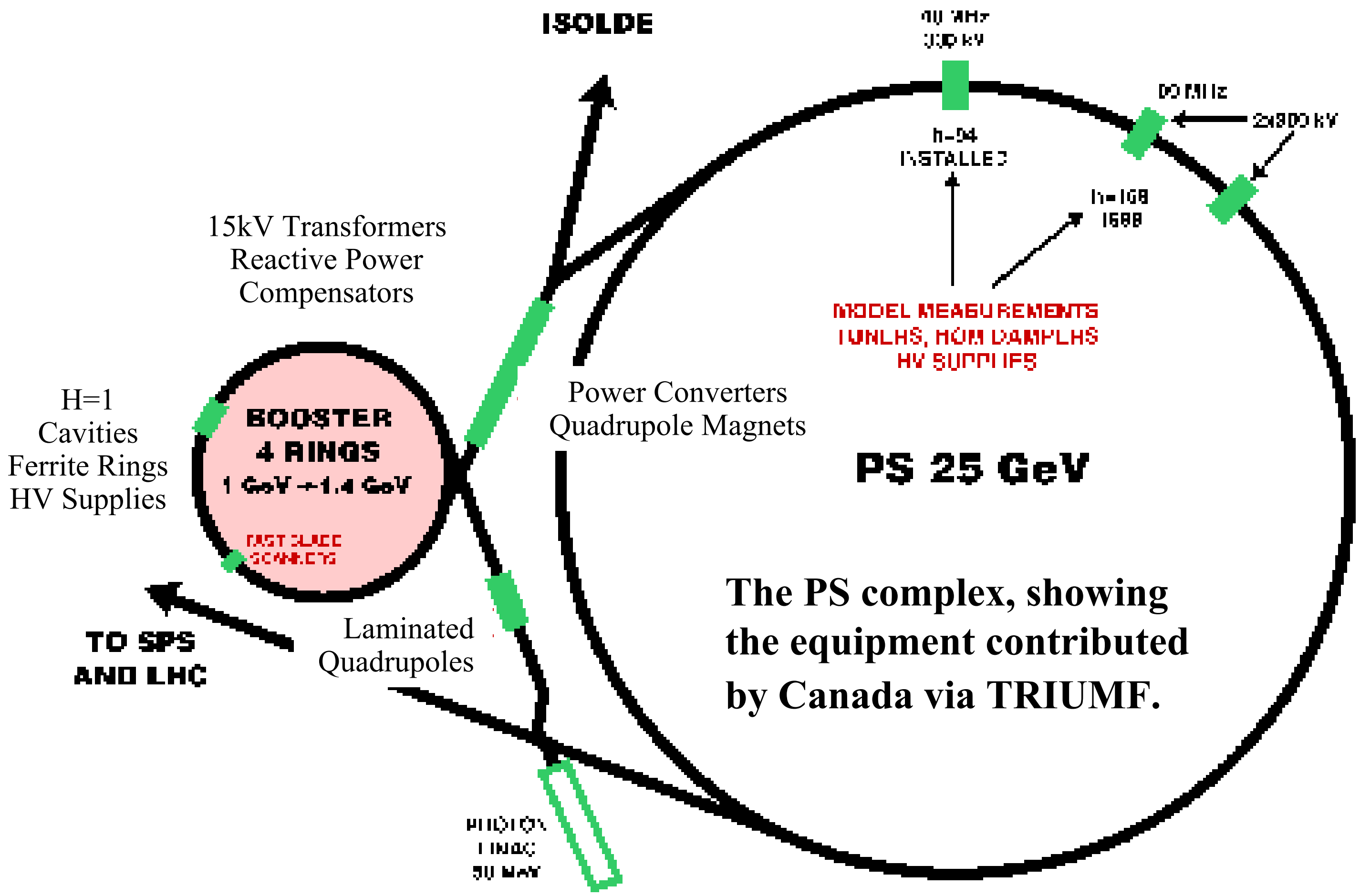
ultimate reach:

$$\int L\,dt = 300\ \mathrm{fb}^{-1}$$ < 10 years

The Large Hadron Collider

Canadian Contributions via TRIUMF

The PS and PS Booster: modifications to deliver proton beams with much higher brightness, more strictly controlled emittance and a different bunch spacing



15kV Transformers
Reactive Power
Compensators

H=1
Cavities
Ferrite Rings
HV Supplies

Power Converters
Quadrupole Magnets

Laminated
Quadrupoles

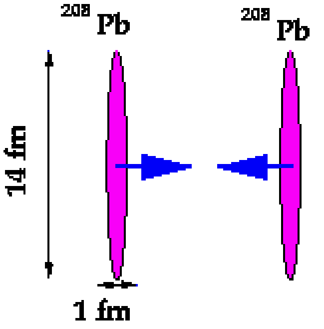
The PS complex, showing the equipment contributed by Canada via TRIUMF.

Electronics for the SPS: calibrator modules for the orbit monitor upgrade

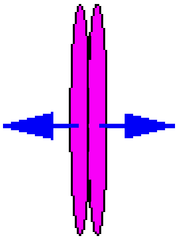
Components for the LHC: injection kickers, cleaning-insertion quadrupoles, current calibration equipment

LHC Experiments

ALICE

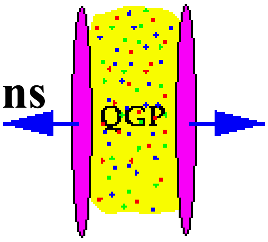


Dedicated heavy ion experiment $\sqrt{s} \approx 5.5\text{TeV/n}$

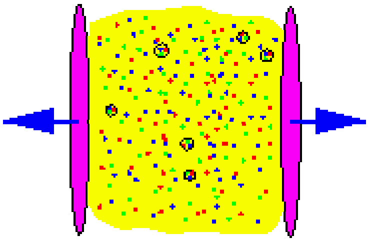


Study quark gluon plasma: key issues in QCD for the understanding of confinement and chiral-symmetry restoration

Expect $\frac{dN_{ch}}{dy} \le 8000$ detail study of hadrons, electrons,muons and photons



$T \le 1000\text{MeV} \approx 10^{13}\text{K}$ for Pb - Pb



LHCb

Second generation dedicated CP violation experiment

10^4 increase statistics wrt BaBar and Belle

Sensitive to all species of B hadrons, including Bs

Low luminosity (de-tuned beams: 2. 10^{32} cm^{-2}s^{-1}, $N_{bb}=10^{12}$/y)

Optimised detector

- forward geometry
- efficient trigger for hadrons and leptons
- good proper time resolution (~40 fs)
- hadron ID (RICH, 1 < p < 150 GeV 5σ k-π separation)

LHC Experiments

ATLAS **CMS**

General purpose detectors for p-p at $\sqrt{s} = 14\ \mathrm{TeV}$

Designed to operate at high luminosity
$10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$, 23 inelastic pp-collisions per bunch crossing
about 700 charged particles with $P_T > 150$ MeV
and at initial lower luminosities

Designed to be sensitive to many signatures

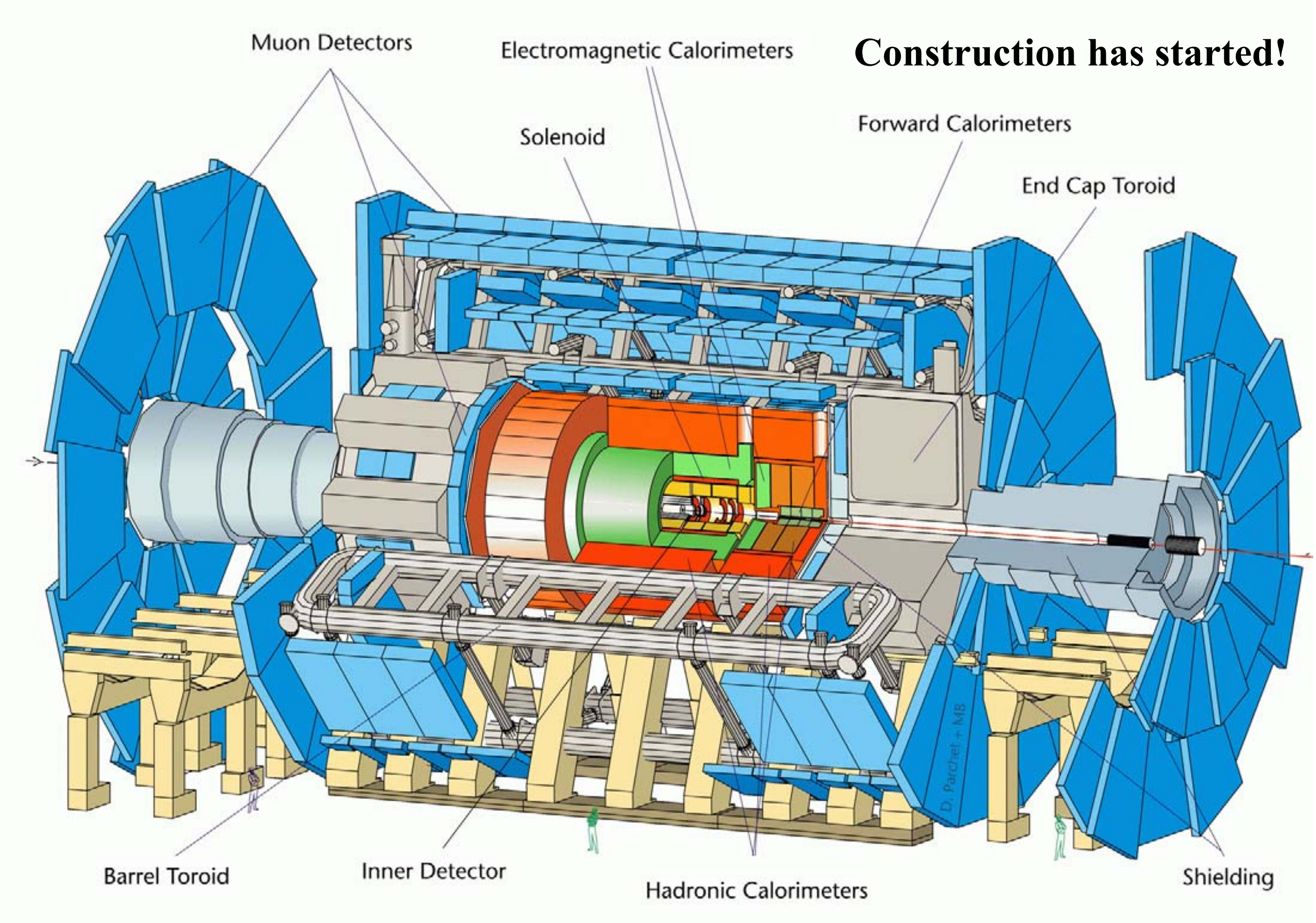
$$e, \gamma, \mu, \mathrm{jet}, E_T^{\mathrm{miss}}, b-\mathrm{tagging}, \ldots$$

and to more complex signatures
tau and heavy flavour from secondary vertices

CMS plans to cover several aspects of the heavy ion programme

- Good mesurement of leptons and photons
  - from a few GeV $(b \to l\nu)$ to a few TeV $(W' \to l\nu)$
- Good measurement of missing transverse energy
  - calorimeter coverage down to $|\eta| < 5.0$
- Efficient b-tagging
- Fast detectors (bunch crossing every 25 ns)
- Radiation hard detectors and electronics

The ATLAS Detector



Construction has started!

ATLAS and Canada

Activities focused on LAr Calorimetry

4 Major Projects Funded by a Major Installation Grant

- **Endcap Hadronic Calorimeter**
- **Forward Hadronic Calorimeter**
- **Front-End-Board Electronics**
- **Endcap Signal Cryogenics Feedthroughs**

Important Activities

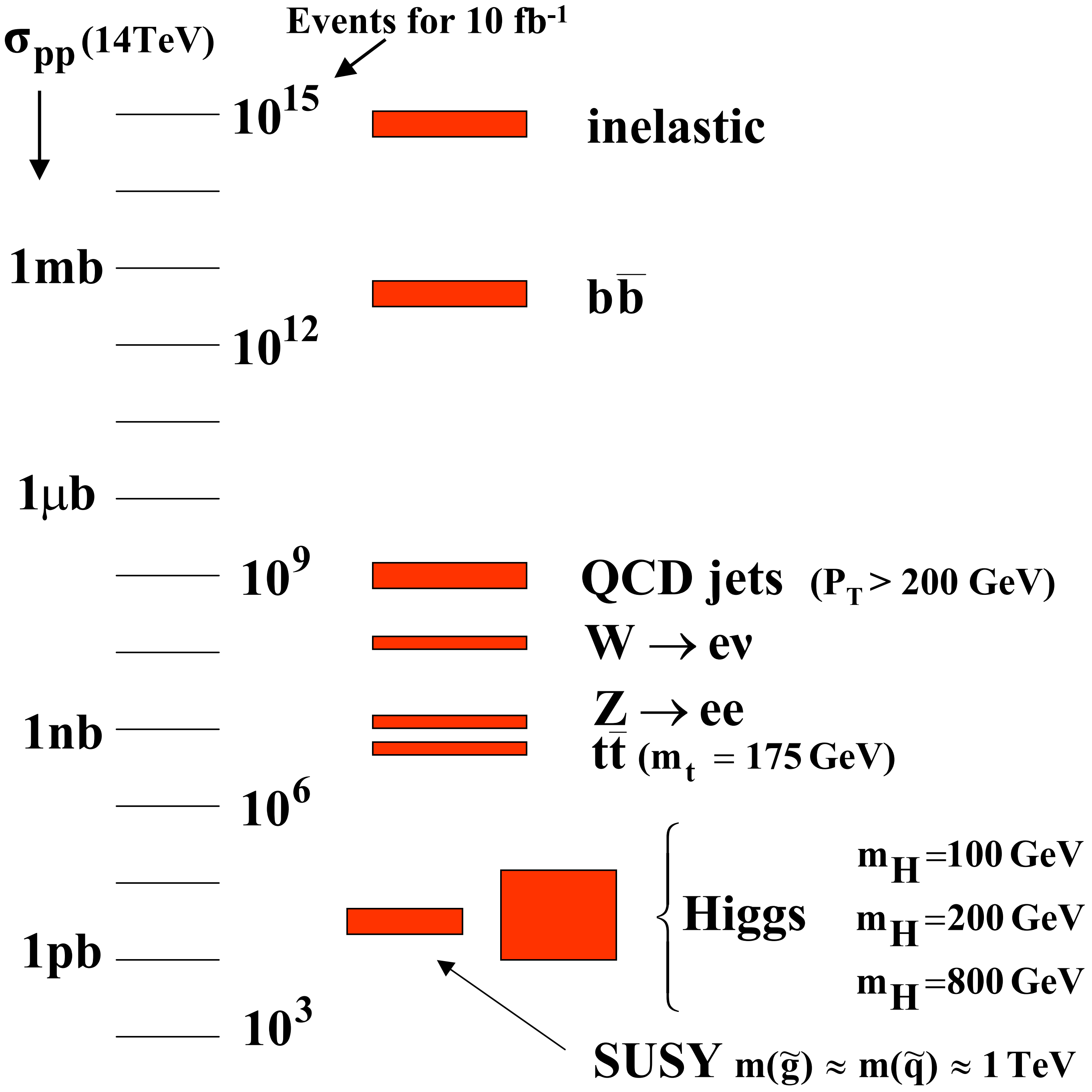
- **Radiation Hardness Studies**
- **Physics Studies**

New Initiatives

- **National Computing and OO Software**
- **Pixel Detector Contribution**

Alberta
Carleton
CRPP
Montréal
Toronto
TRIUMF
UBC
Victoria
York

PP Cross Section



- Large production rates
  - LHC is a top, b, W, Z factory
- Mass reach for new particles up to TeV range
- Precision measurements dominated by systematics

ATLAS Physics Programme

Highlights:

- **Higgs Boson**

  SM Higgs searches

  MSSM Higgs searches

- **Supersymmetry**

  squarks and gluinos

  SUGRA, gauge mediated SUSY breaking and R-parity breaking models

- **More Searches**

  new gauge bosons, extra dimensions, monopoles, technicolour, excited quarks, leptoquarks, compositeness...

- **Standard Model Physics**

  QCD processes: hard diffractive, jets, photons, heavy flavours

  Electroweak gauge bosons: W mass, gauge boson pair production

  B physics: CP violation, Bs oscillation, rare decays, B hadrons

  Heavy quarks and leptons: top, electroweak single top quark production, 4th generation quarks

Standard Model Higgs Boson

Mass without mass

Can we remove mass from the basic equations of physics ?

The bulk of the mass of ordinary matter comes from the mass of protons and neutrons:

energy associated with quark motion and gluon fields

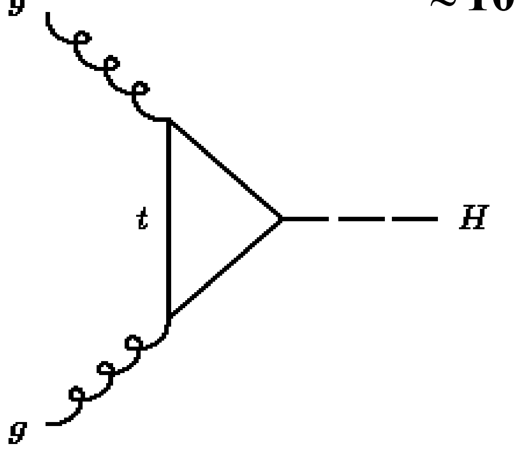
massless QCD predicts nucleon masses to 10%!

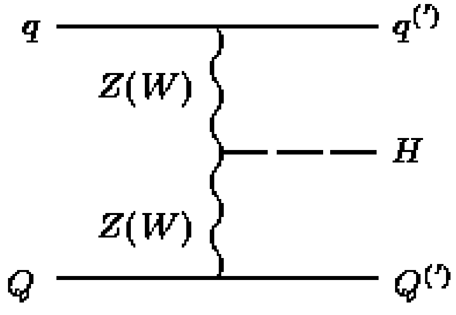
***Mass without mass* is not necessary in QCD, but it is indispensable in the electroweak sector:**

chiral gauge symmetry
Higgs mechanism → generates all particle masses
→ Higgs boson

The SM Higgs properties are well predicted, except its mass!

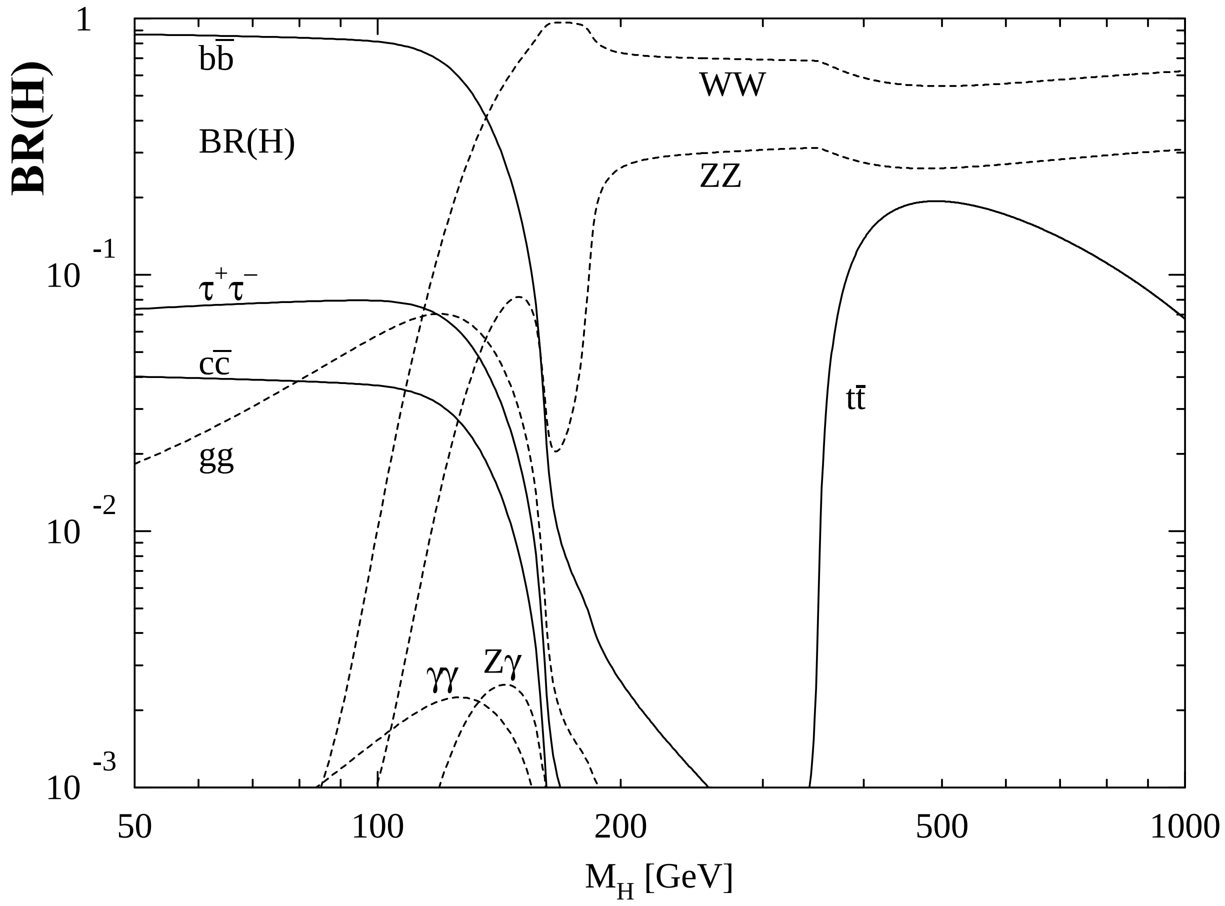
$$\begin{aligned} \sigma(pp \rightarrow H + X) &\approx 30\,\mathrm{pb} \quad m_H = 100\,\mathrm{GeV} \\ &\approx 100\,\mathrm{fb} \quad m_H = 1\,\mathrm{TeV} \end{aligned}$$





LEP direct searches: $m_H > 107.7$ GeV
LEP EWWG fit: $m_H < 188$ GeV 95% C.L.

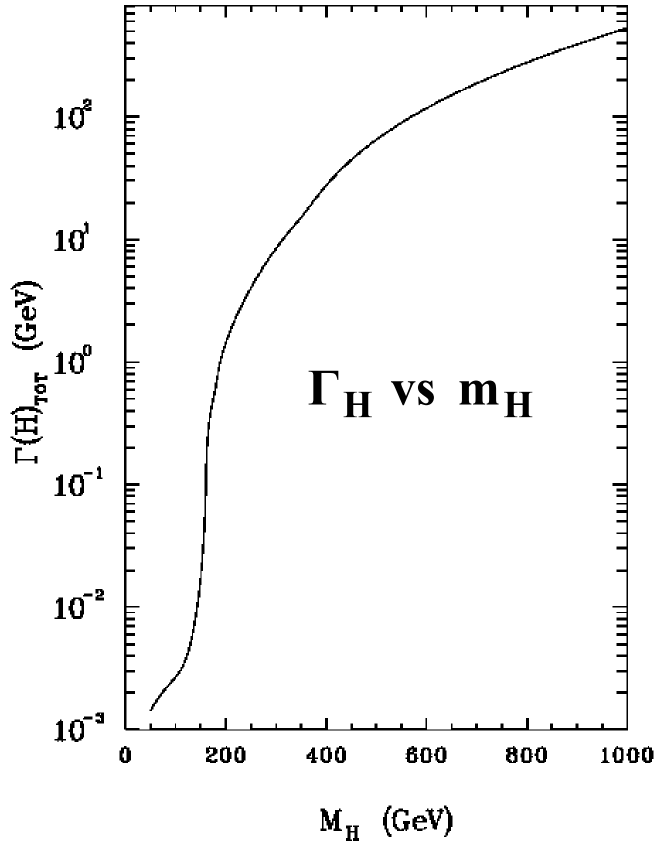
Standard Model Higgs Boson



Large QCD backgrounds: look for final states with leptons and photons

Important channels:

- $H \rightarrow \gamma\gamma$
- $H \rightarrow b\bar{b}$
- $H \rightarrow ZZ^{(*)} \rightarrow l^+l^-l^+l^-$
- $H \rightarrow WW^* \rightarrow l^+\nu l^-\nu$
- $H \rightarrow ZZ \rightarrow l^+l^-\nu\nu$
- $H \rightarrow WW \rightarrow l\nu$ jet jet



Standard Model Higgs Boson

$$\boxed{\mathrm{H} \rightarrow \gamma\gamma}$$

Signal $\sigma \times \mathrm{BR} = 43\ \mathrm{fb}\ (m_H = 100\ \mathrm{GeV})$

$\gamma\gamma$ background
(irreducible) $\dfrac{d\sigma}{dm_{\gamma\gamma}} \sim 1200\ \mathrm{fb/GeV}\ (m_{\gamma\gamma} = 100\ \mathrm{GeV})$

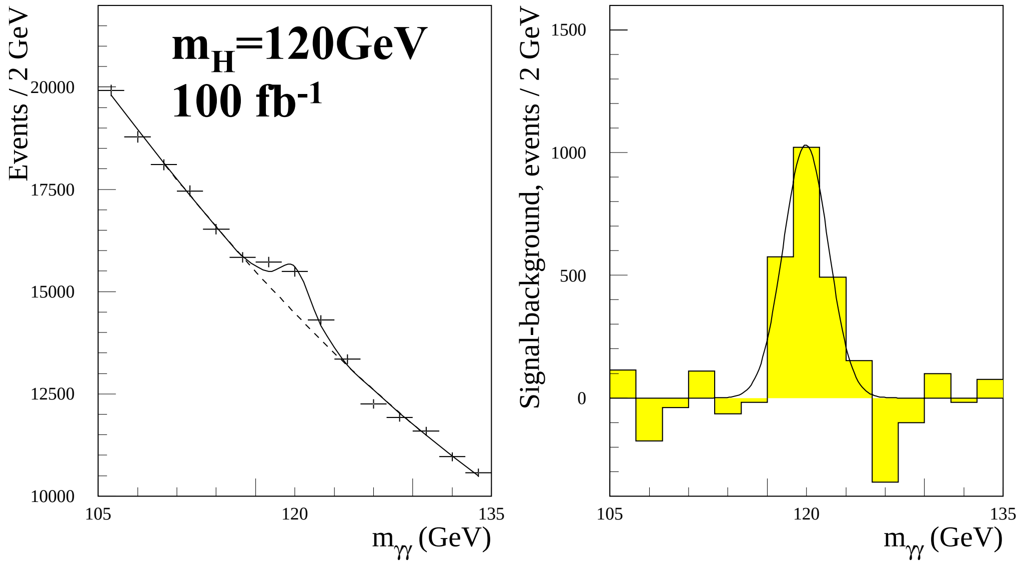
QCD jet background $\dfrac{\sigma_{\gamma,j}}{\sigma_{\gamma\gamma}} \sim 1000,\quad \dfrac{\sigma_{j,j}}{\sigma_{\gamma\gamma}} \sim 2 \times 10^6$ **(reducible)**

Analysis:

Two isolated γ's: $p_T^1 > 40$ GeV, $p_T^2 > 25$ GeV, $|\eta| < 2.5$

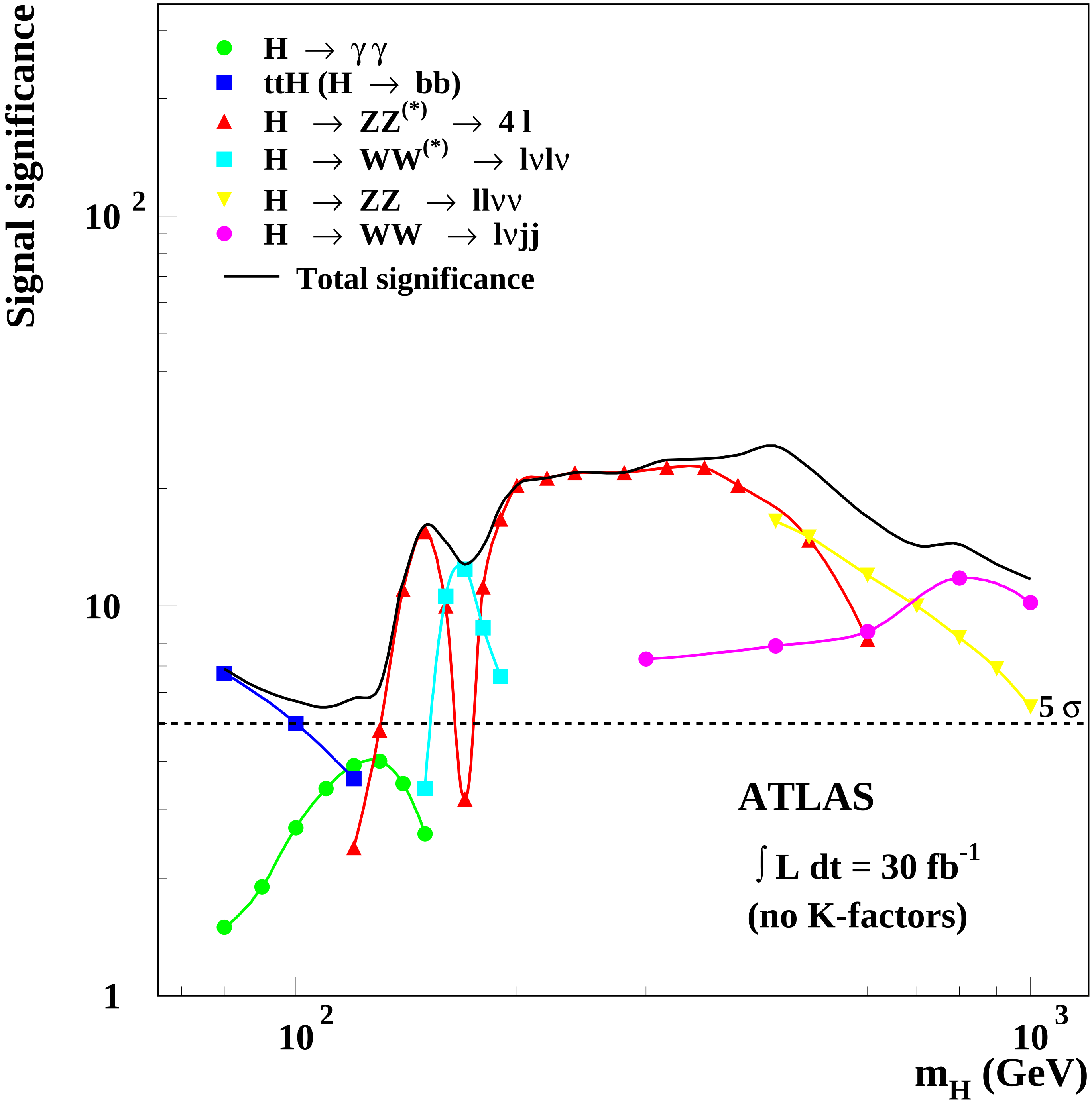
Good γ/jet separation: QCD jet background at the level of 10 to 20% of the irreducible γγ background

Good mass resolution: $\sigma_m = 1.3$ GeV for $m_H = 100$ GeV



m_H (GeV)	100	120	140
signal events	960	1200	930
$\gamma\gamma$ background	44700	30300	20800
γ - jet, jet - jet background	6700	4400	3900
Statistical significance	4.7σ	6.9σ	6.3σ

Standard Model Higgs Boson



SM Higgs can be discovered (signal > 5σ) over full mass range with 30 fb^{-1} (3 years of operation)

In most cases, more than one channel is available

Signal significance is S/B$^{1/2}$ or using Poisson statistics

Supersymmetry

Maximal extension of the Poincaré group

$$\left.\begin{array}{l}\left.\begin{array}{l}\left.\begin{array}{l}\text{3D rotations}\\ \text{pure boosts}\end{array}\right\}\text{Lorentz}\\ \text{4D translations}\end{array}\right\}\text{Poincare}'\\ \text{SUSY translations}\end{array}\right\}\text{superPoincare}'$$

Leads to the notion of superfield and superspace

$$z^{m} = \left(x^{\mu}, \theta^{\alpha}, \bar{\theta}_{\dot{\alpha}}\right) \left\{\begin{array}{l}\text{4 bosonic coordinates}\\ \text{4 fermionic coordinates}\end{array}\right.$$

A superPoincaré transformation is then a supertranslation in superspace followed by a Lorentz transformation

SUSY actions are invariant under superPoincaré

They are composed of an equal number of bosonic and fermionic degrees of freedom

Mixes fermions and bosons

Exact SUSY → there should exist fermions and bosons of the same mass

Clearly not the case: SUSY is broken

So why bother with SUSY?

Supersymmetry

A Solution to the hierarchy problem

If the Higgs is to be light without unnatural fine tuning, then (softly broken) SUSY particles should have M_{SUSY}<~ 1 TeV

GUT acceptable coupling constant evolution

The precision data at the Z mass (LEP and SLC) are inconsistent with GUT's using SM evolution, but are consistent with GUT's using SUSY evolution, if $M_{SUSY} \approx$ 1 TeV

A natural way to break EW symmetry

The large top Yukawa coupling can naturally drive the Higgs quadratic coupling negative in SUSY

Local SUSY is SUperGRAvity

Intimately connected to gravity

Supersymmetry

MSSM Particle Content

SUSY breaking ⇒

spin

0	$\frac{1}{2}$	1
$\tilde{l}_L$	l_L	
$\tilde{l}_R$	l_R	
$\tilde{\nu}_L$	ν_L	
$\tilde{q}^u_L$	q^u_L	
$\tilde{q}^u_R$	q^u_R	
$\tilde{q}^d_L$	q^d_L	
$\tilde{q}^d_R$	q^d_R	
	$\tilde{g}$	g
	$\tilde{W}^+$	W^+
	$\tilde{W}^-$	W^-
	$\tilde{W}^0$	W^0
	$\tilde{B}^0$	B^0
H^+_u	$\tilde{H}^+_u$	
H^0_u	$\tilde{H}^0_u$	
H^0_d	$\tilde{H}^0_d$	
H^-_d	$\tilde{H}^-_d$	

⇒ EW symmetry breaking ⇒

spin

0	$\frac{1}{2}$	1
$\tilde{l}_1$	l_L	
$\tilde{l}_2$	l_R	
$\tilde{\nu}_l$	ν_l	
$\tilde{q}^u_1$	q^u_L	
$\tilde{q}^u_2$	q^u_R	
$\tilde{q}^d_1$	q^d_L	
$\tilde{q}^d_2$	q^d_R	
	$\tilde{g}$	g
	χ^+_1	W^+
	χ^+_2	W^-
	χ^-_1	γ
H^+	χ^-_2	Z^0
H^-	χ^0_1	
h	χ^0_2	
H	χ^0_3	
A	χ^0_4	

Supersymmetry

At tree level, all Higgs boson masses and couplings can expressed in terms of two parameters only:

$$m_A \quad \text{and} \quad \tan\beta = \frac{\text{vev } H_u}{\text{vev } H_d}$$

Note that we have the mixings

$$B^0, W^0 \to \gamma, Z^0$$

$$\tilde{W}^{\pm}, \tilde{H}^{\pm} \to \chi^{\pm}_{1,2}$$

$$\tilde{B}^0, \tilde{W}^0, \tilde{H}^0_u, \tilde{H}^0_d \to \chi^0_{1,2,3,4}$$

$$\tilde{l}_L, \tilde{l}_R \to \tilde{l}_1, \tilde{l}_2$$

$$\tilde{q}_L, \tilde{q}_R \to \tilde{q}_1, \tilde{q}_2$$

With off-diagonal elements proportional to the fermion mass

Supersymmetry

- **If SUSY exists at the electroweak scale, a discovery at LHC should be easy**

- **Gluinos and squarks are strongly produced**

(cross sections as high as a few pb for masses as high as 1 TeV

  - **they decay through cascades to the Lightest SUSY Particle (LSP) $\tilde{\chi}_1^0$**

  - **combination of jets, leptons, E_T^{miss}**

Look for deviation from SM

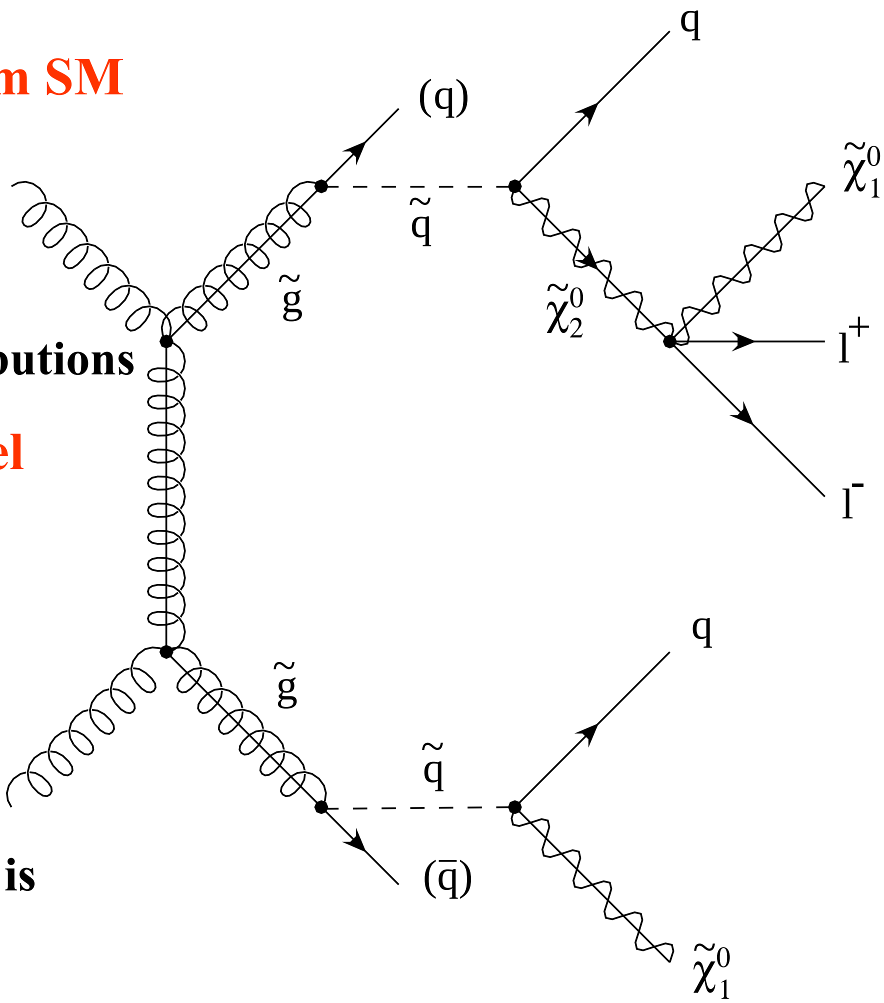
multijets and E_T^{miss}

Establish SUSY scale

effective mass distributions

Determine SUSY model parameters

the challenge



Always 2 LSP if R parity is conserved

Supersymmetry

Squarks and Gluinos

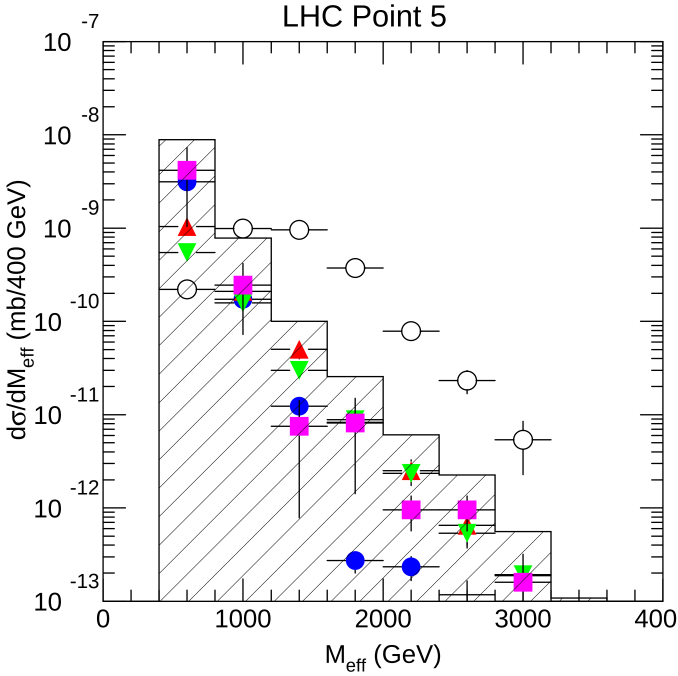
Experimental signature:

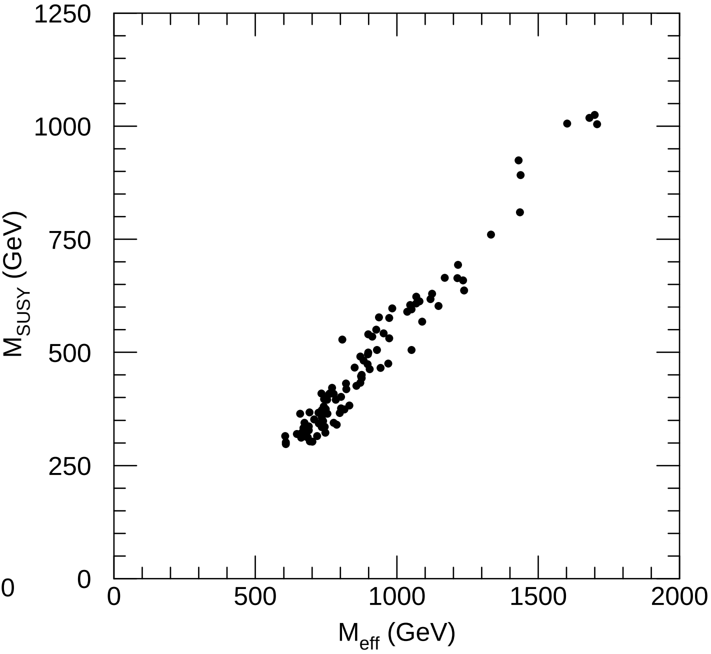
Several jets with large P_T and E_T^{miss}

Define and effective mass:

$$M_{eff} = E_T^{miss} + P_T^1 + P_T^2 + P_T^3 + P_T^4$$

$$M_{SUSY} = \min\left(M_{\tilde{g}}, M_{\tilde{u}_R}\right)$$





M_{eff} for SUSY (open circles) and for SM background (histo)

Peak of M_{eff} vs M_{SUSY} for various models

Gluino mass limits

	$1\ fb^{-1}$	$100\ fb^{-1}$
$m_{\tilde{q}} = 2m_{\tilde{g}}$	1050	1600
$m_{\tilde{q}} \approx m_{\tilde{g}}$	1800	2300
$2m_{\tilde{q}} = m_{\tilde{g}}$	2600	3600

Supersymmetry

ATLAS studies of the MSSM Higgs sector concentrate on two scenarios

- **SUSY particle masses are large, $M_{SUSY} = 1$ TeV, Higgs boson decay to SUSY particles are kinematically forbidden**
- **Studies in the framework of SUGRA models**
  - **SUSY particles are light and appear in Higgs decays competing with SM decay modes**
  - **Light Higgs particles appear in decays of SUSY particles: search for the $h \to b\bar{b}$ decay**

Important channels in the MSSM Higgs search

Assume $M_{SUSY} = 1$ TeV and $m_{top} = 175$ GeV

The SM decay channels

$$h \to b\bar{b}$$
$$h \to \gamma\gamma$$
$$H \to ZZ^* \to l^+l^-l^+l^-$$

Modes strongly enhanced at large tanβ

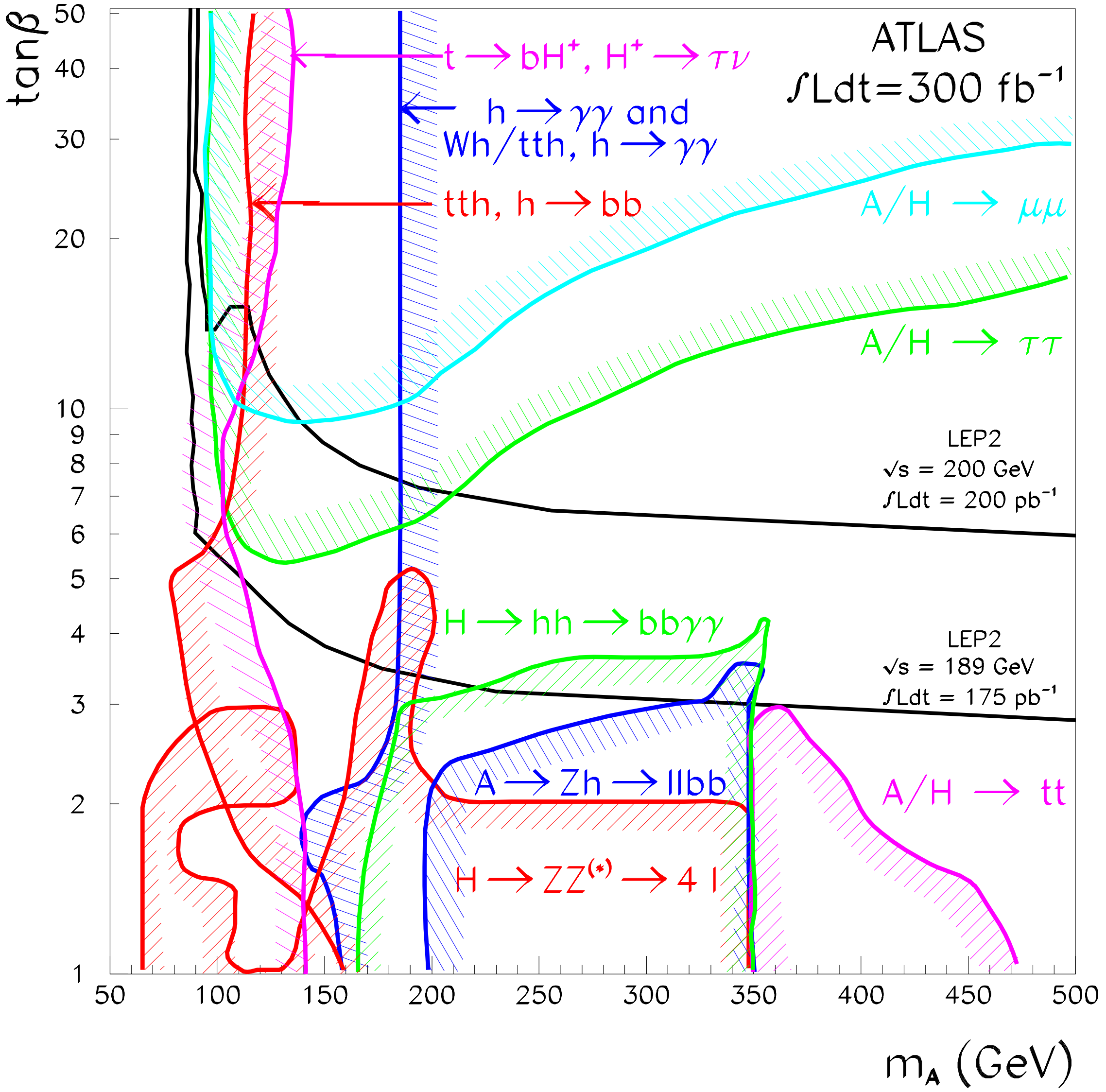
$$H/A \to \tau^+\tau^- \text{ or } \mu^+\mu^-$$

Other interesting channels

$$H/A \to t\bar{t}$$
$$H/A \to Zh \to l^+l^-\gamma\gamma \text{ or } l^+lb\bar{b}$$
$$H \to hh$$
$$t \to H^+b, \quad H^+ \to \tau\nu$$

Supersymmetry

Summary of the MSSM Higgs Search



Full parameter space covered, SM and MSSM can be distinguished for almost all cases

Most part of the parameter space covered by at least two channels, except low m_A region (covered by LEP200)

If h discovered at LEP200: A/H should be observable at LHC for m_A<~ 2 m_{top}

If A,h discovered at LEP200: the charged Higgs should be seen at LHC

New Vector Bosons

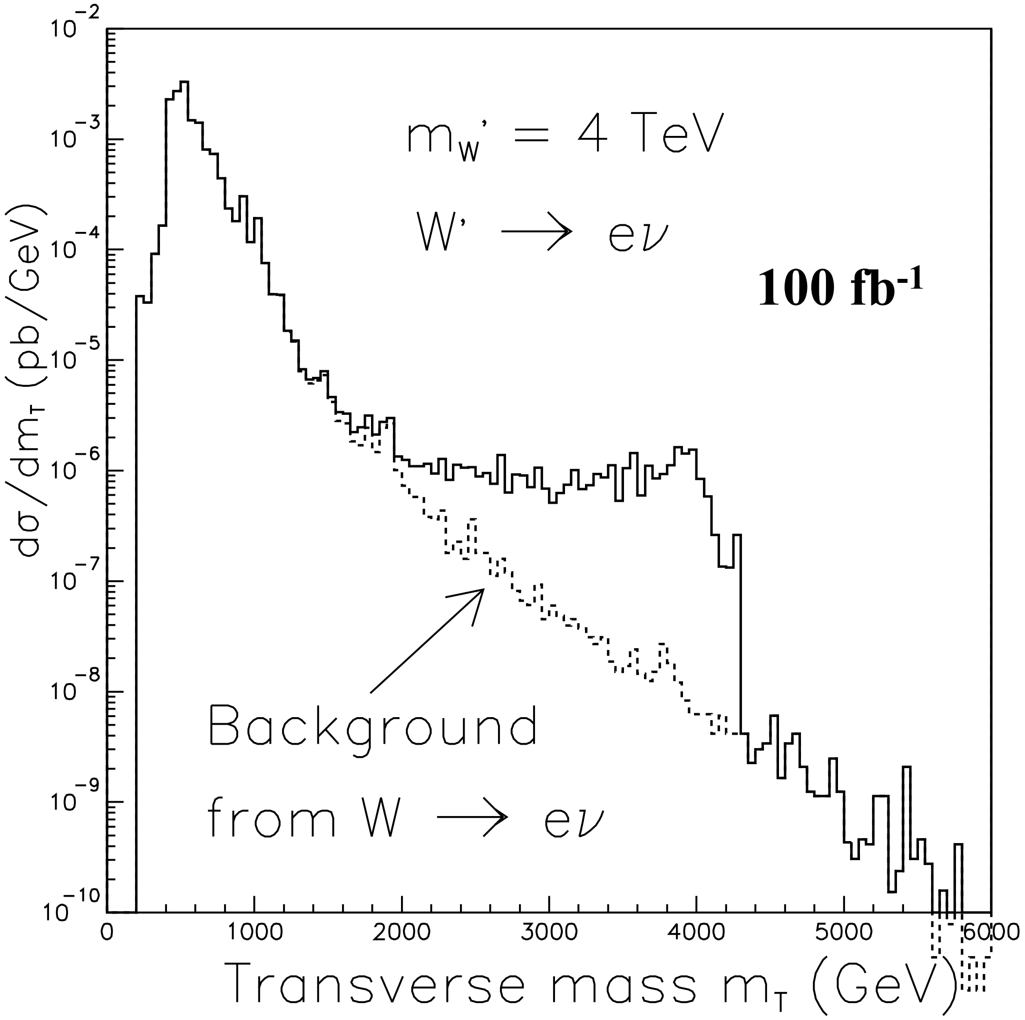
Related to generators of new symmetry groups in extension of the SM

Discovery potential for W' and Z' for models in which the couplings are the same as for the SM W and Z have been studied:

$$Z' \to f\bar{f} \text{ up to } m \sim 5\,\text{TeV}$$

Assume no significant Z-Z' mixing

$$W' \to l\nu \text{ up to } m \sim 6\,\text{TeV}$$



Extra Dimensions

Many models attempt to solve the hierarchy problem by postulating the existence of extra dimensions

e.g. Arkani-Hamed, Dimopoulos, Dvali model

SM in 3+1 D, gravitons free to propagate in 3+1+n D, where the n dimensions are compactified. The fundamental mass scale M_S is related to the Planck scale

$$M_{Pl}^2 \sim M_S^{n+2} R^n$$

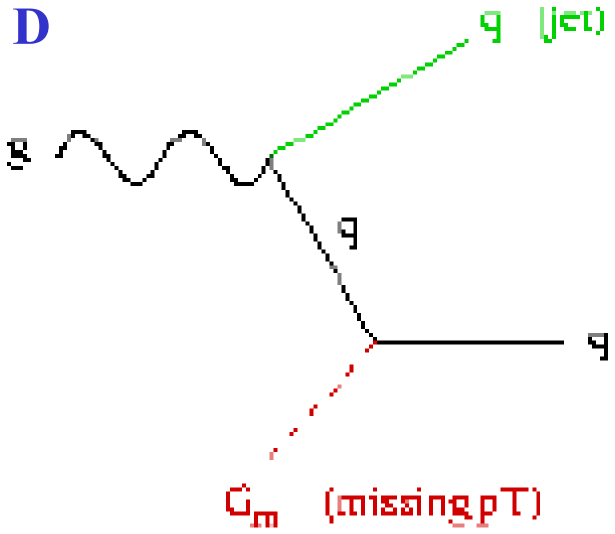
where R is the size of the compactified dimensions. Assuming $M_S \sim 1$ TeV, then

$$n = 1 \Rightarrow R \sim R(\text{solar system}) \rightarrow \text{Ruled out!!}$$
$$n \geq 2 \Rightarrow R \leq 1\text{mm}$$

Massless graviton G in 3+1+n D →
Massive KK gravitons G_M in 3+1 D

Signatures involve large E_t^{miss}:

$$pp \rightarrow G_M + j$$
$$pp \rightarrow G_M + \gamma$$
$$pp \rightarrow G_M + Z$$



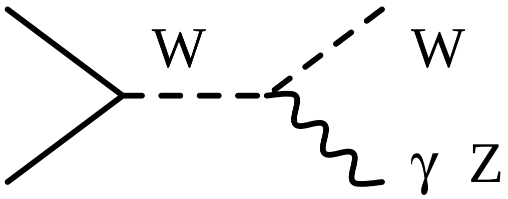
Sensitivity (100 fb^{-1}): $M_S \sim 7$ TeV

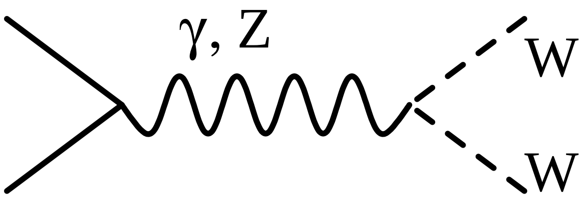
More Searches

excited quarks : $q^* \to q\gamma\gamma$ **, up to**	$m \sim 6$ **TeV**
Leptoquarks, up to	$m \sim 1.5$ **TeV**
Compositeness, up to	
from di - jet and Drell - Yan,	$\Lambda \sim 40$ **TeV**
needs calo linearity better that 2%	
Lepton flavour violation : $\tau \to \mu\gamma$	$10^{-6} - 10^{-7}$
Monopoles, up to	$m \sim 20$ **GeV**
Technicolour	

Standard Model Physics

W Physics: Triple Gauge Boson Couplings





Probe non-Abelian structure of $SU_L(2) \times U(1)$

Sensitive to new physics

Under general assumptions (Lorentz, P and C), WWγ and WWZ couplings are specified by 5 parameters: $g_1^Z, \lambda_\gamma, \lambda_Z, \kappa_\gamma, \kappa_Z$

The WWγ vertex is related to

- W magnetic moment $\mu_W = \frac{e}{2M_W}\left(g_1^Z + \kappa_\gamma + \lambda_\gamma\right)$
- W quadrupole moment $Q_W = -\frac{e}{M_W^2}\left(\kappa_\gamma - \lambda_\gamma\right)$

WW suffers from large $t\bar{t}$ background: not studied

Sensitivity from

- cross section measurement: λ-type, increase like $\hat{s}$
- P_T and angular distributions: constrain κ-type

With 30 fb^{-1} get about 3000 Wγ and 1200 WZ events

95% C.L. $\Delta g_Z^1 < 0.008$

$\lambda_\gamma < 0.0025$ $\lambda_Z < 0.0060$

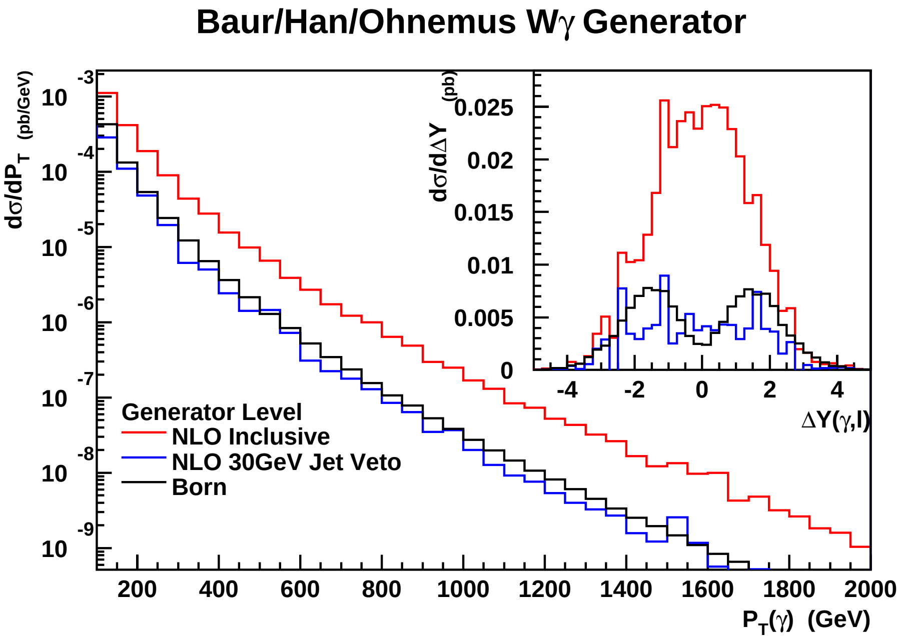
$\Delta\kappa_\gamma < 0.035$ $\Delta\kappa_Z < 0.070$

Systematics under study

Standard Model Physics

W Physics: Triple Gauge Boson Couplings

Jet veto is effective in recovering the qualitative shape of the Born distribution, including the radiation zero



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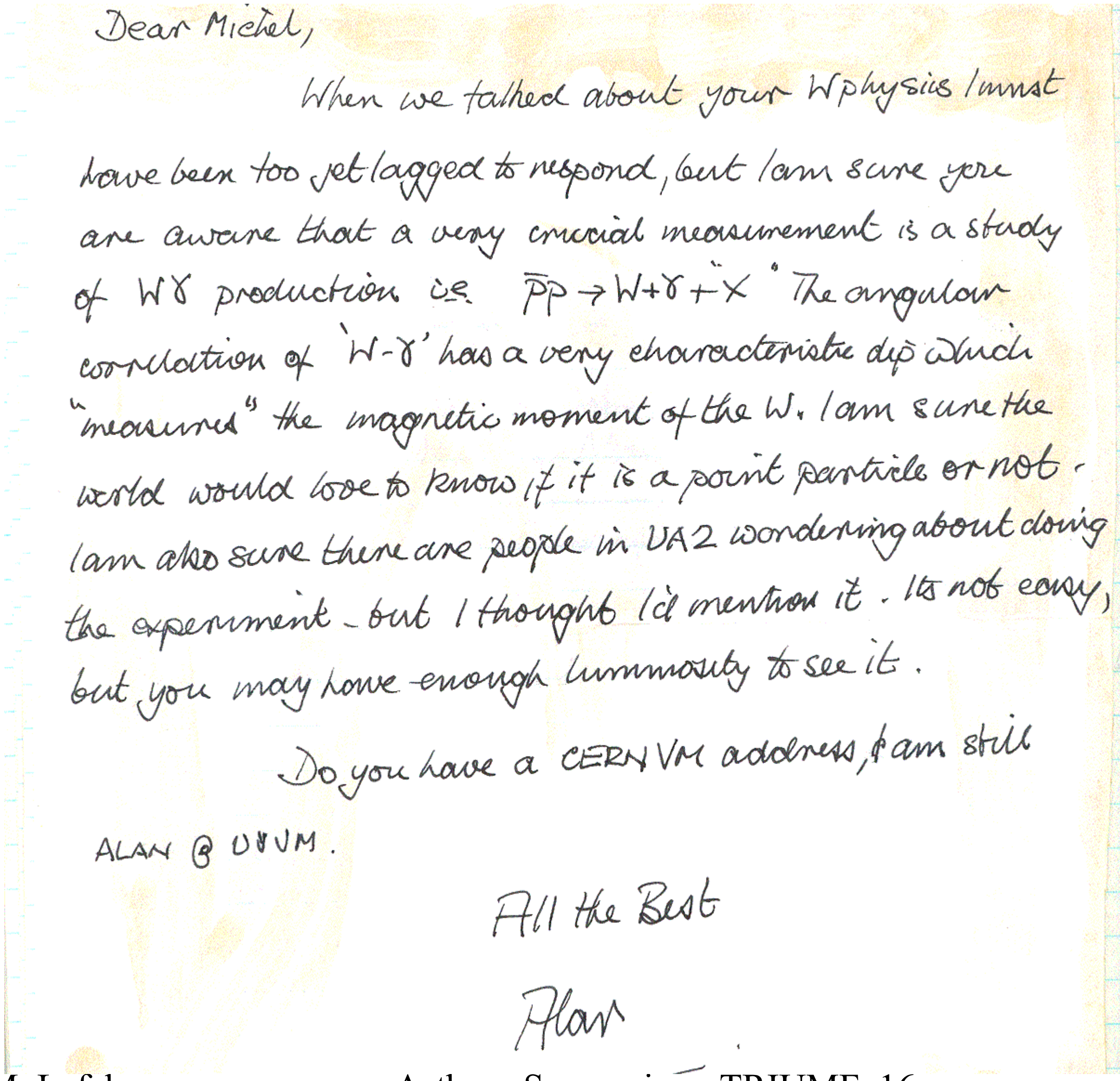


Dear Michel,

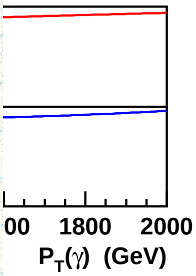
When we talked about your W physics I must have been too jet lagged to respond, but I am sure you are aware that a very crucial measurement is a study of Wγ production i.e. $\bar{p}p \to W+\gamma+X$ " The angular correlation of 'W-γ' has a very characteristic dip which "measures" the magnetic moment of the W. I am sure the world would love to know if it is a point particle or not. I am also sure there are people in UA2 wondering about doing the experiment – but I thought I'd mention it. Its not easy, but you may have enough luminosity to see it.

Do you have a CERNVM address, I am still

ALAN @ UKVM.

All the Best

Alan



Conclusions

The Large Hadron Collider has a huge potential for physics discoveries...

- quark-gluon plasma state properties
- new physics in the B system
- SM Higgs: full mass range
- MSSM Higgs: cover $m_A \times \tan\beta$ plane
- SUSY: squarks and gluinos up to m ~ 2 TeV
- Many other searches

… and for precision measurements

- W, top, Higgs, SUSY parameters, QCD, B-physics

To fully take advantage of the LHC is a big experimental challenge

- Detectors under construction
- ATLAS is one of two multi-purpose detector designed to meet the challenge!
- Crucial role of TRIUMF in ATLAS and LHC

We also need to be as ready as possible for the unexpected!