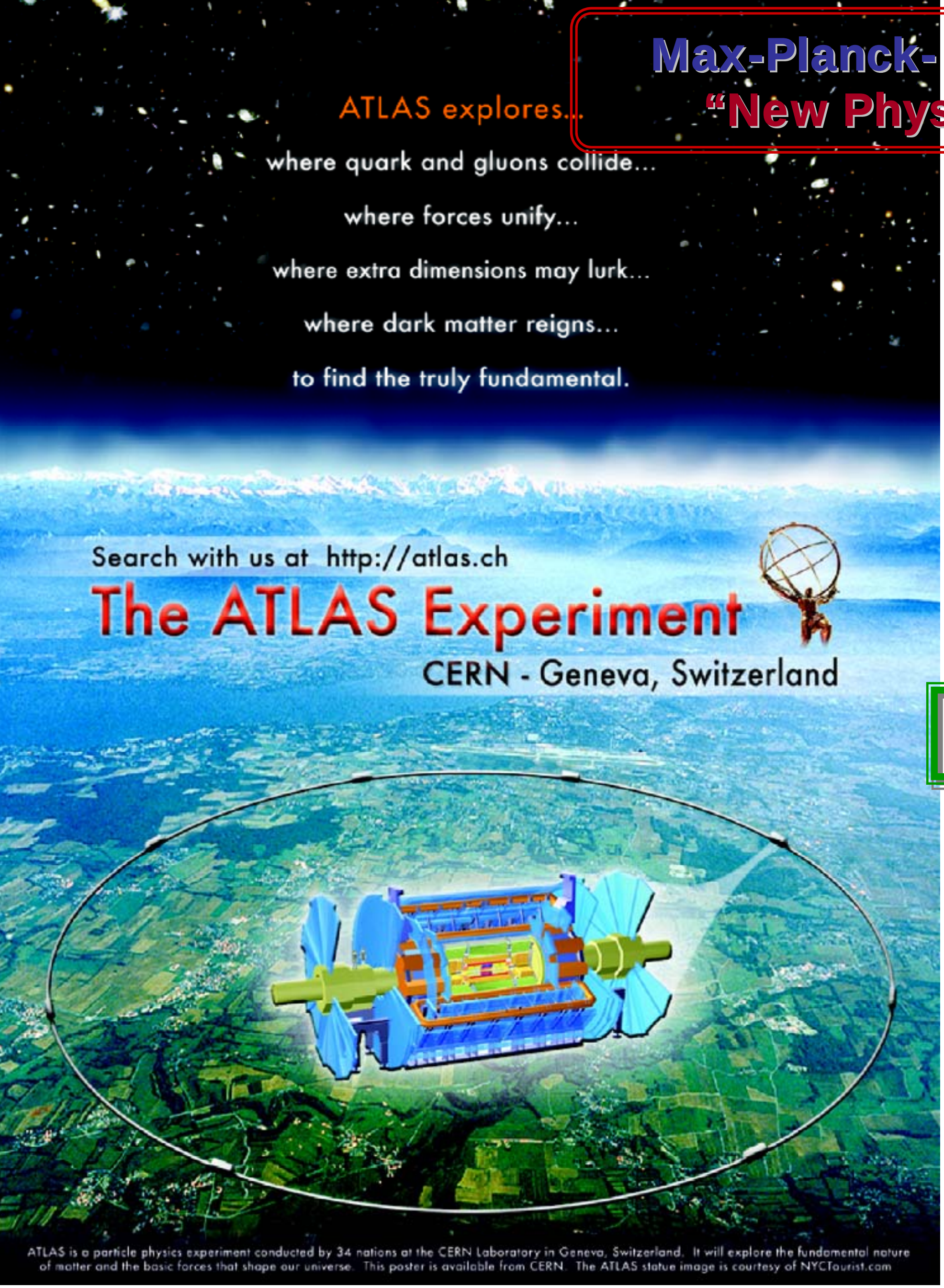
Max-Planck-Institut für Physik -ATLAS Seminar
"New Physics at the Large Hadron Collider"



ATLAS Explores…

Search for Physics Beyond SM

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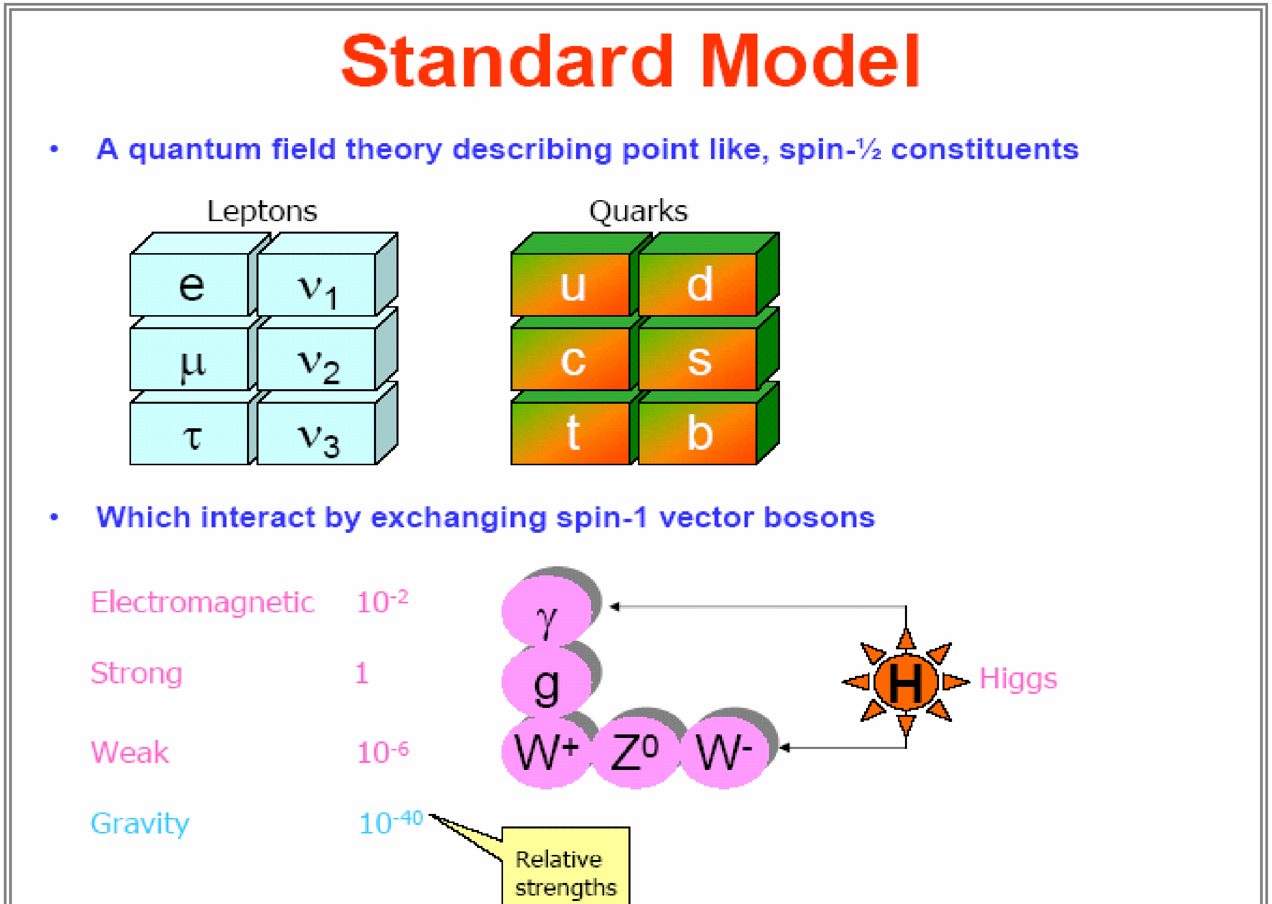
Some Unanswered important questions and puzzles

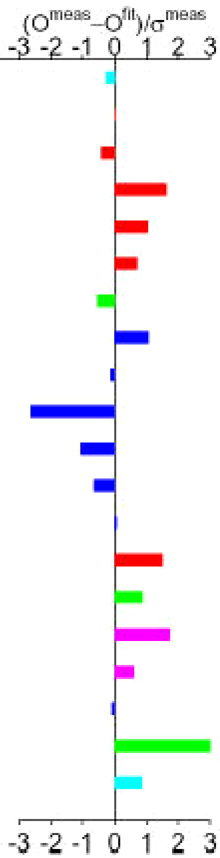
- Standard Model of particle physics describes all the available data well
  - explains most of what we observe
- All **material particles** discovered: 6 quarks, 6 leptons?
- All **force particles** discovered (except graviton): photon, W,Z, gluons



How Well does The SM work?

Winter 2002

	Measurement	Pull
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	-.27
m_Z [GeV]	91.1875 ± 0.0021	.01
Γ_Z [GeV]	2.4952 ± 0.0023	-.42
σ^0_{had} [nb]	41.540 ± 0.037	1.63
R_l	20.767 ± 0.025	1.05
$A^{0,l}_{fb}$	0.01714 ± 0.00095	.70
$A_l(P_\tau)$	0.1465 ± 0.0033	-.53
R_b	0.21646 ± 0.00065	1.06
R_c	0.1719 ± 0.0031	-.11
$A^{0,b}_{fb}$	0.0994 ± 0.0017	-2.64
$A^{0,c}_{fb}$	0.0707 ± 0.0034	-1.05
A_b	0.922 ± 0.020	-.64
A_c	0.670 ± 0.026	.06
A_l(SLD)	0.1513 ± 0.0021	1.50
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	.86
m_W [GeV]	80.451 ± 0.033	1.73
Γ_W [GeV]	2.134 ± 0.069	.59
m_t [GeV]	174.3 ± 5.1	-.08
$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	3.00
Q_W(Cs)	-72.39 ± 0.59	.84



Measurements of many experimental observables, compared to fit to the Standard Model.

Perfect agreement means everything is at "0"

Standard model VERY WELL established; no real deviations

Some Unanswered important questions and puzzles

- But, there are important **open questions** in the SM:
  - Why does matter have a mass?
  - Are particle masses generated by the Higgs mechanism?
  - Is there a Higgs particle, or maybe several?
  - Do neutrinos have mass?
  - Why the top quark is so much heavier than other quarks?

  - Why is **CP-violation** broken in the nature, i.e. matter and antimatter (C) do not behave in the same way, and mirror-world (P) is different from the original?
  - CP-violation has been observed in kaon decays,
    - but the origin of CP violation **has not yet been proven**
  - CP-violation is also needed to create our Universe, which consists of mostly matter, and not antimatter
    - SM: expect large CP-asymmetry in some rare B-decays

$$N(\overline{B}^0{}_d\text{->}J/\psi K^0{}_S) > N(B^0{}_d\text{->}J/\psi K^0{}_S)$$

$$N(\overline{B}^0{}_d\text{->}\pi^+\pi^-) > N(B^0{}_d\text{->}\pi^+\pi^-)$$

Physics Case for new High Energy Machines

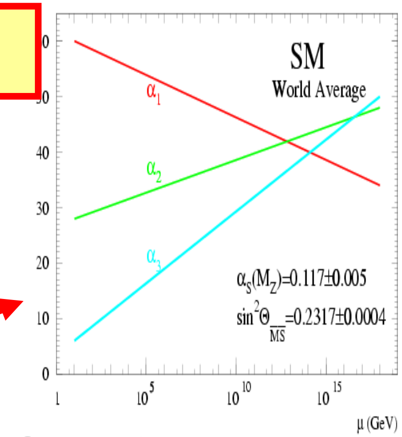
Understand the mechanism Electroweak Symmetry Breaking

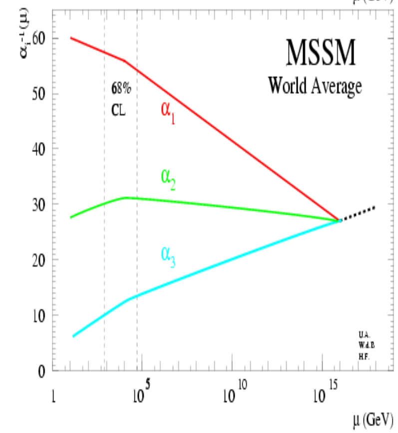
$\Rightarrow$ What is the origin of mass of the fundamental particles?

Discover physics beyond the Standard Model

$\Rightarrow$ Reminder: The Standard Model

- tells us how but not why (contains 19 parameters!)
  3 flavour families? Mass spectra? Hierarchy?
- needs fine tuning of parameters to level of 10^{-30} !
- no unification of the forces at high energy





Most popular extensions these days

If a Higgs field exists:

- Supersymmetry
- Extra space dimensions

If there is no Higgs below ~ 700 GeV

- Strong electroweak symmetry breaking around 1 TeV

Other ideas: more gauge bosons/quark & lepton substructure, Little Higgs models…

Some Unanswered important questions and puzzles (cont.)

- Can we unify all the 4 known forces and at which energy scale?
  - Can we do that with supersymmetry?
  - Why masses of electro-weak bosons are so much below the Grand Unification scale?
  - All particles in a family to become "one particle" with "unified" electro-weak-strong charge?
  - In certain SUSY models, it is more likely that a candidate for this *dark matter* – the lightest supersymmetric particle – will be seen at the LHC
- The Wilkinson Microwave Anisotropy Probe (WMAP) science team has released results from the first year of operation at the Earth-Sun L2 Lagrange point (http://lambda.gsfc.nasa.gov)
  - After WMAP – we know that 73% of the universe is "Dark Energy" and 27% is matter most of which is "Dark"
- Why is the Universe "build" of matter? (no antimatter)
- Does the proton decay?

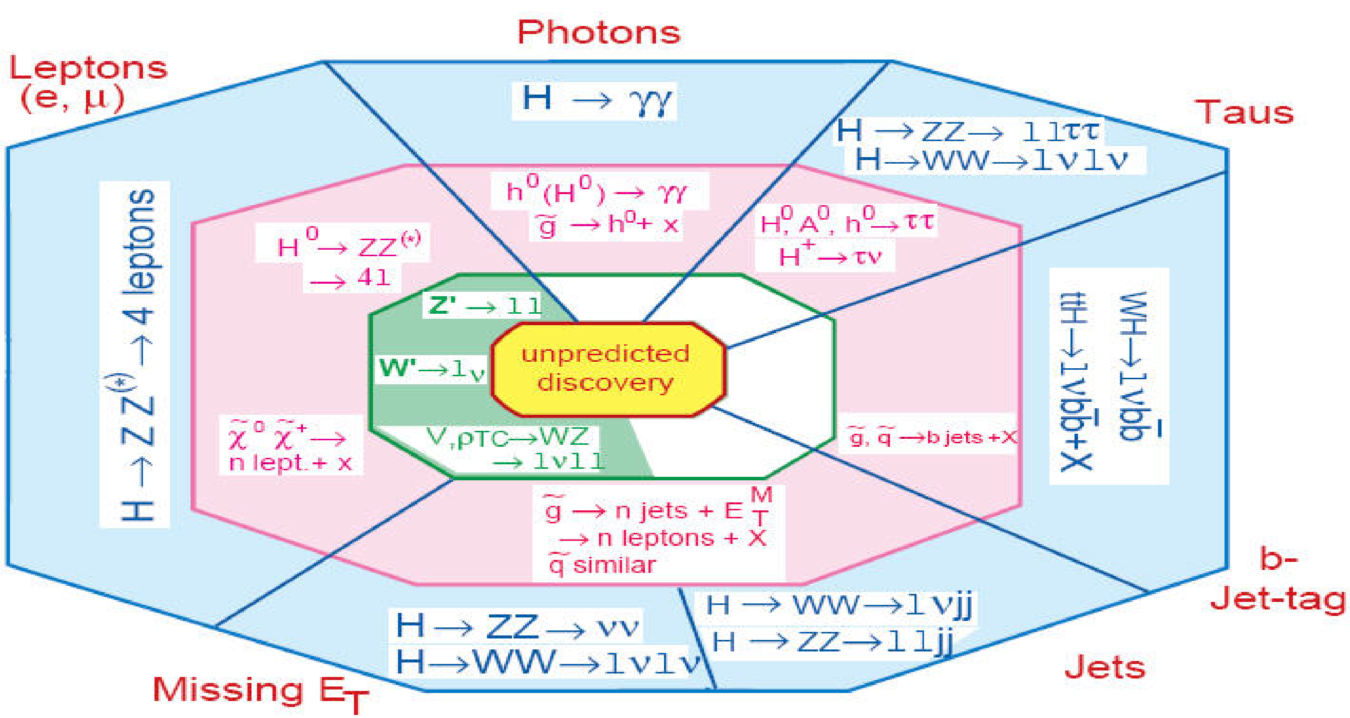
Why do we need LHC?

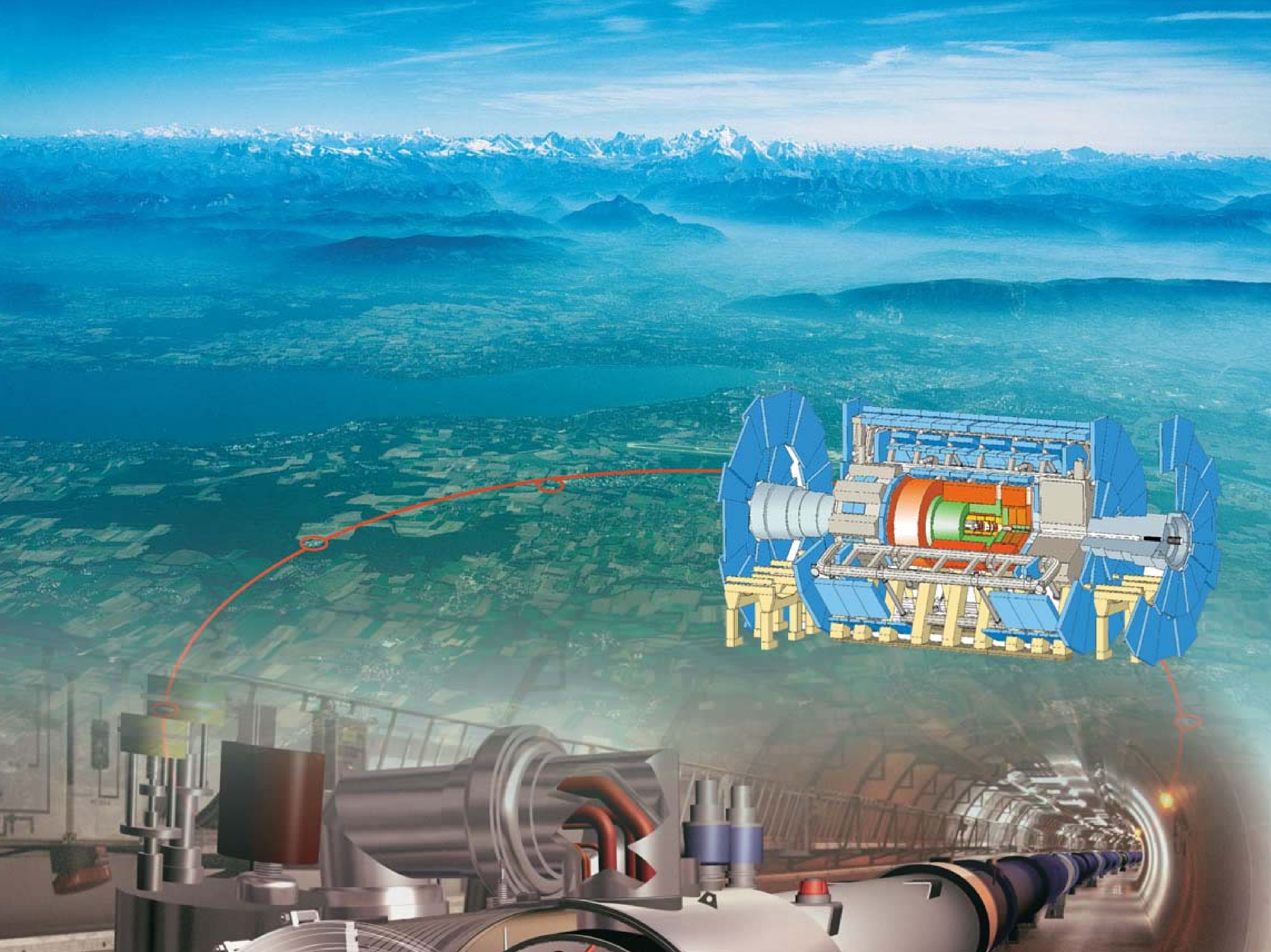
- The search for new physics phenomena is often defined as the main motivation for new experiments at higher center of mass energies
  - This is especially true for the LHC project
- We want from accelerators not just a Higgs, but **a mechanism that will stabilize** the scale of the EWSB and **explain** why the Higgs boson, and the rest of other particles, aren't heavier

- ….**so LHC is needed to answer these questions**

New Physics and required detector capabilities

Type of measurements	indicates	required for
isolated high p_t $e^\pm$, $\mu^\pm$	$W^{(*)}$, $Z^{(*)}$ decays	Higgs search top physics, "all" searches
isolated high p_t γ's	electro-magnetic process	Higgs search
τ and b-quark tagging	"rare" processes	special Higgs like searches
large missing p_t, E_t	ν like events W, Z decays	Higgs, Supersymmetry, exotic "exotica"
jets	quarks and gluons	QCD, understanding of backgrounds/efficiencies

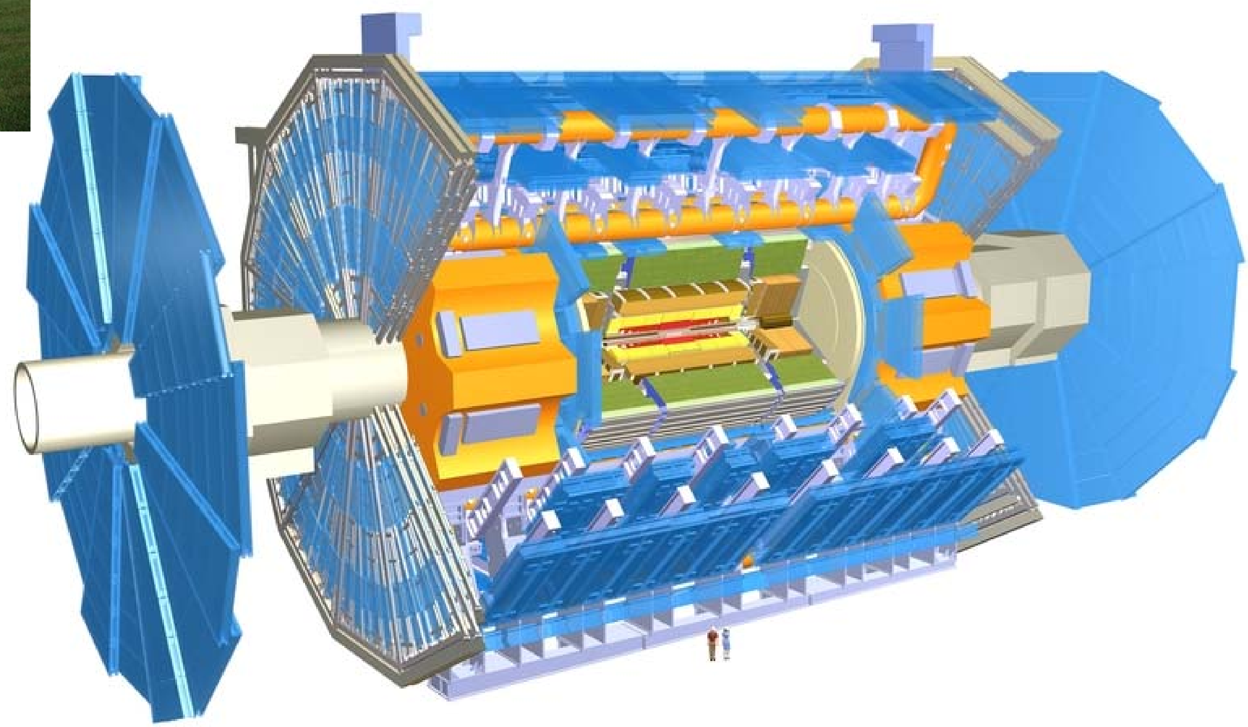




ATLAS superimposed to
the 5 floors of building 40

The ATLAS Detector

A Toroidal Lhc ApparatuS



- Tracking: Pixels 50x400 mm, Si strips and straw tube TRT, 2T central solenoidal field
- LAr accordion EM calorimeter
- LAr (EC) and Steel-Scintillator (Barrel) HCAL
- Drift tubes and CSCs in toroidal muon spectrometer, with RPCs and TGCs for triggering
- Three level trigger

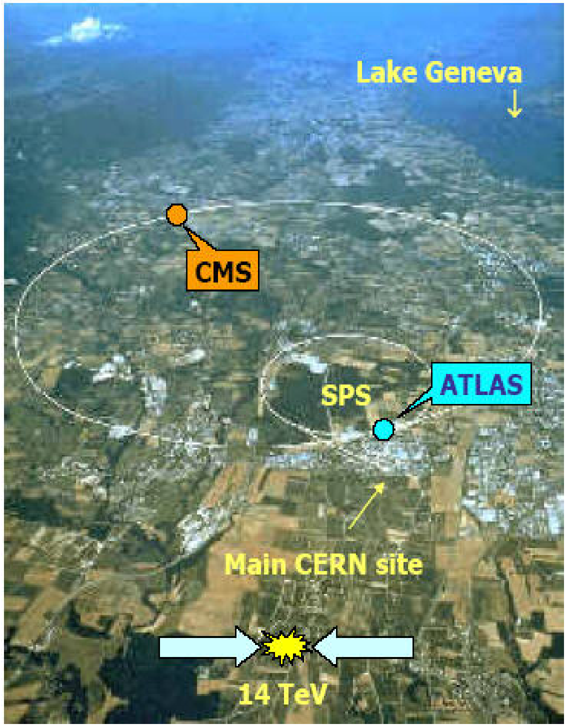
Diameter	*25 m*
Barrel toroid length	*26 m*
End-cap end-wall chamber span	*46 m*
Overall weight	*7000 Tons*

ATLAS Collaboration

34 Countries
151 Institutions
1770 Scientific Authors

Albany, Alberta, NIKHEF Amsterdam, Ankara, LAPP Annecy, Argonne NL, Arizona, UT Arlington, Athens, NTU Athens, Baku, IFAE Barcelona, Belgrade, Bergen, Berkeley LBL and UC, Bern, Birmingham, Bonn, Boston, Brandeis, Bratislava/SAS Kosice, Brookhaven NL, Bucharest, Cambridge, Carleton/CRPP, Casablanca/Rabat, CERN, Chinese Cluster, Chicago, Clermont-Ferrand, Columbia, NBI Copenhagen, Cosenza, INP Cracow, FPNT Cracow, Dortmund, JINR Dubna, Duke, Frascati, Freiburg, Geneva, Genoa, Glasgow, LPSC Grenoble, Technion Haifa, Hampton, Harvard, Heidelberg, Hiroshima, Hiroshima IT, Indiana, Innsbruck, Iowa SU, Irvine UC, Istanbul Bogazici, KEK, Kobe, Kyoto, Kyoto UE, Lancaster, Lecce, Lisbon LIP, Liverpool, Ljubljana, QMW London, RHBNC London, UC London, Lund, UA Madrid, Mainz, Manchester, Mannheim, CPPM Marseille, MIT, Melbourne, Michigan, Michigan SU, Milano, Minsk NAS, Minsk NCPHEP, Montreal, FIAN Moscow, ITEP Moscow, MEPhI Moscow, MSU Moscow, Munich LMU, MPI Munich, Nagasaki IAS, Naples, Naruto UE, New Mexico, Nijmegen, Northern Illinois, BINP Novosibirsk, Ohio SU, Okayama, Oklahoma, LAL Orsay, Oslo, Oxford, Paris VI and VII, Pavia, Pennsylvania, Pisa, Pittsburgh, CAS Prague, CU Prague, TU Prague, IHEP Protvino, Ritsumeikan, UFRJ Rio de Janeiro, Rochester, Rome I, Rome II, Rome III, Rutherford Appleton Laboratory, DAPNIA Saclay, Santa Cruz UC, Sheffield, Shinshu, Siegen, Simon Fraser Burnaby, Southern Methodist Dallas, NPI Petersburg, Stockholm, KTH Stockholm, Stony Brook, Sydney, AS Taipei, Tbilisi, Tel Aviv, Thessaloniki, Tokyo ICEPP, Tokyo MU, Tokyo UAT, Toronto, TRIUMF, Tsukuba, Tufts, Udine, Uppsala, Urbana UI, Valencia, UBC Vancouver, Victoria, Washington, Weizmann Rehovot, Wisconsin, Wuppertal, Yale, Yerevan

The Large Hadron Collider



➢Initial LHC operation:

- Energy at injection: 450 GeV/beam
- Energy at collision : 7 TeV/beam
- Bunch spacing: 25 ns
- Luminosity: **1.2 x 10^{33} $cm^{-2}s^{-1}$**
- **Total cross section: 100 mb**

➢High Luminosity:

10^{34} cm^{-2} s^{-1}

First year proton parameters:

- luminosity: 1.2 × 10^{33} $cm^{-2}s^{-1}$
- bunch crossing: 25 ns

Nominal parameters:

- luminosity: 1.0 × 10^{34} $cm^{-2}s^{-1}$
- bunch crossing: 25 ns

➔ ~ 23 min. bias events per bunch crossing

- **Some processes at Low L**

Process	σ	Events/year
$W \rightarrow l\,\nu$	15 nb	10^8
$Z \rightarrow ee$	1.5 nb	10^7
$t\bar{t}$	800 pb	10^7
$b\bar{b}$	500 μb	10^{12}
gg(m=1 TeV)	1pb	10^4
H(m=0.8TeV)	1pb	10^4

- **Mass reach up to ≈ 5 TeV**
- **Precision measurements dominated by systematic errors**

❑ 70 chrarged tracks/events with pt>1GeV/c at |η|<2.5

LHC is a factory of everything

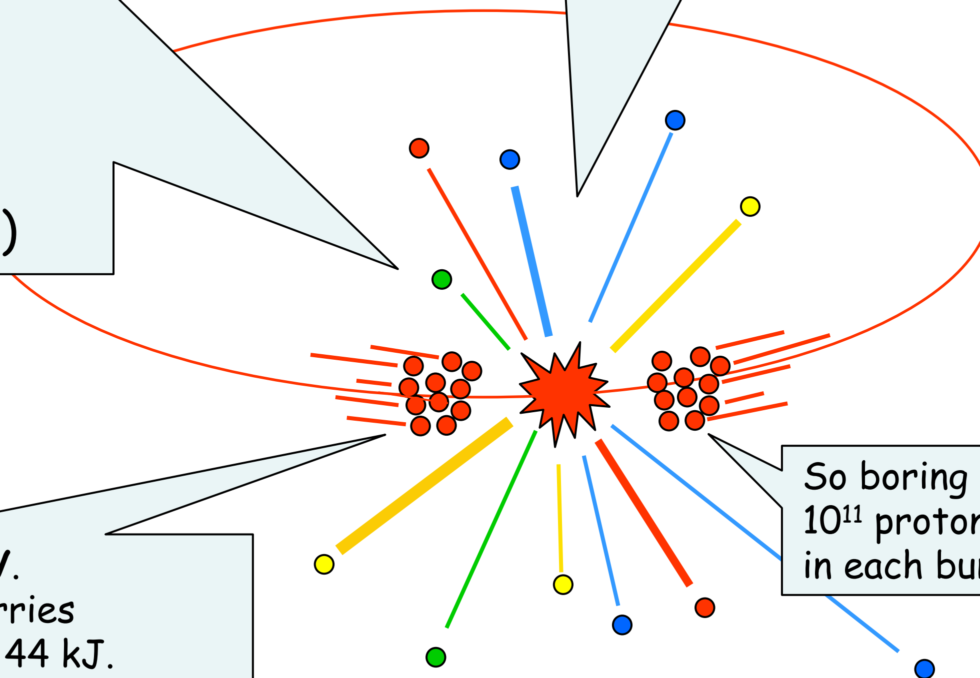
t,b,Z,W,H,SUSY..,etc

The collision point is "watched" by surrounding detector.

Some particles just escaped from the collision zone, the next collision threatens.

The detector should:
- have large coverage (catch most particles)
- be precise
- be fast (and cheap and ...)

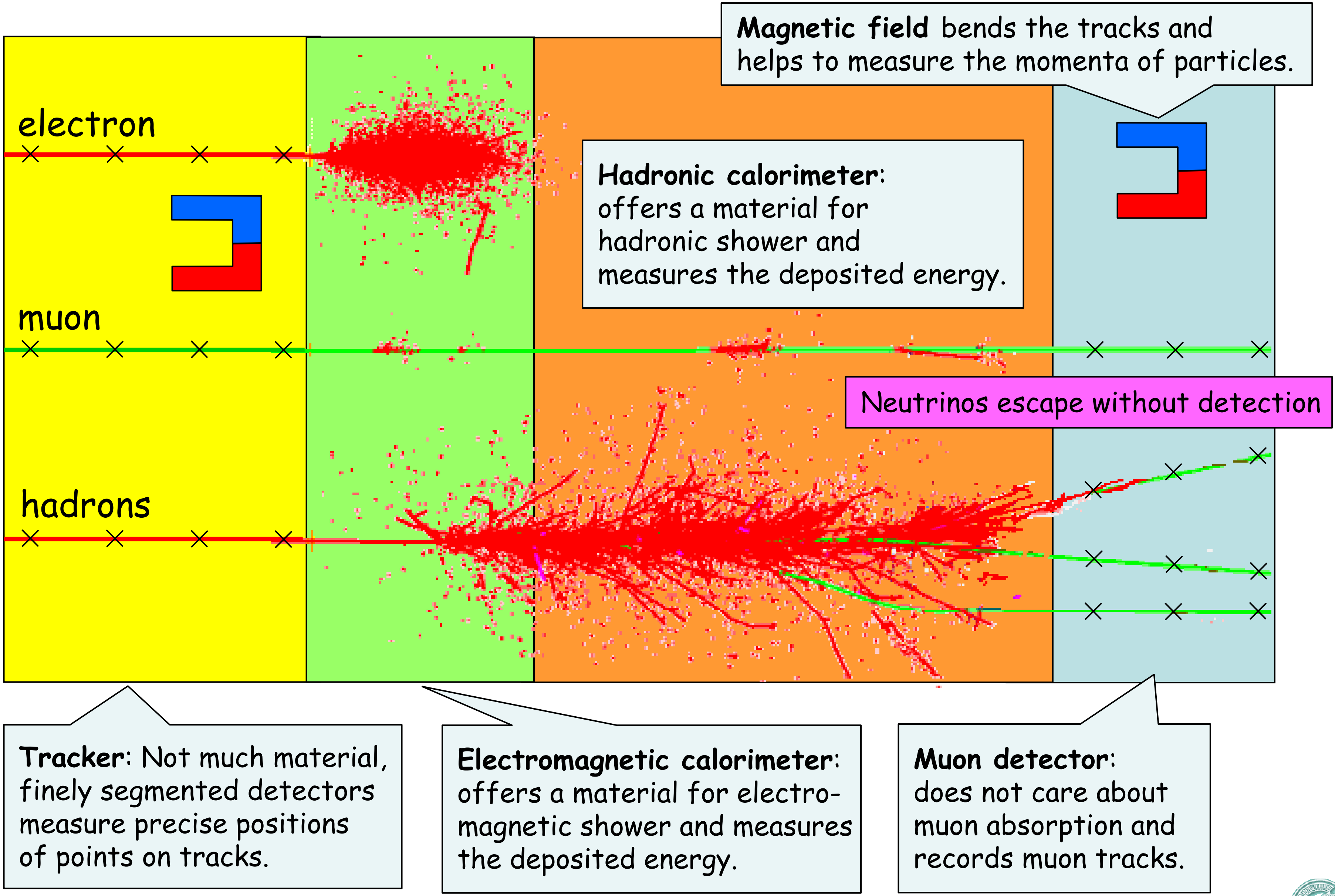
Each meeting of two bunches results in about 23 proton-proton collisions. The mean number of particles born in all these collisions is about 1500. The detector should record as many of them as possible.



So boring to paint 10^{11} protons in each bunch ...

Each proton carries energy 7 TeV.
So each bunch with 10^{11} protons carries energy $10^{11}\times7\times10^{12}$ eV = 7×10^{23} eV = 44 kJ.
This is a macroscopic energy!!!
In order to reach such kinetic energy on a bike, you go with a speed of more than 30 km/h!

Here is the general strategy of a current detector to catch almost all particles:



ATLAS Detector: Nomenclature

- at hadron colliders one often uses the pseudorapidity (η) instead of the polar angle θ:

$$\eta \equiv -\ln(\tan(\theta/2))$$

because the particle multiplicity-distribution in pseudorapidity ($dN/d\eta$) is basically flat.

- particles with high $p_T^2 \equiv px^2 + py^2$ are a signature of hard scattering, and so it is an important quantity.

- if measured in the calorimeter, especially for a jet, the corresponding quantity is the transverse energy (E^T):

$$E^T \equiv E_{deposited} \times \sin\theta$$

- since the momentum fractions of the partons taking part in the collision are not a priori known, momentum conservation cannot be used in the analysis of the events.
  - however, it is known that before the reaction there was (almost) no momentum in the plane transverse to the beam.
    - therefore the missing transverse-energy $Emiss^T$ of the event,

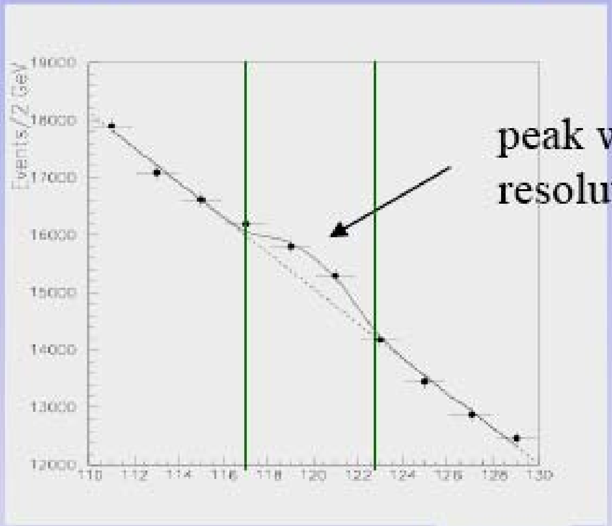
$$E_{miss}^T \equiv sqrt[(\Sigma E^T \cos\varphi))^2 + ((\Sigma E^T \sin\varphi))^2]$$

(summed over all energy deposits in the calorimeter), is very important.

    - **a large value can be a signature** for neutrino's or physics beyond the Standard Model.

How can one claim a discovery ?

Suppose a new narrow particle $X \to \gamma\gamma$ is produced:



Signal significance:

$$S = \frac{N_S}{\sqrt{N_B}}$$

N_S= number of signal events
N_B= number of background events } in peak region

$\sqrt{N_B} \equiv$ error on number of background events, for large numbers
otherwise: use Poisson statistics

> S > 5 : signal is larger than 5 times error on background.
> Gaussian probability that background fluctuates up by more than 5σ : 10^{-7} $\to$ discovery

Two critical parameters to maximize S

1. Detector resolution:

If σ_m increases by e.g. two, then need to enlarge peak region by two to keep the same number of signal events

$\longrightarrow$ N_B increases by ~ 2 (assuming background flat)

$\Rightarrow$ **$S = N_S/\sqrt{N_B}$ decreases by $\sqrt{2}$**

$\Rightarrow S \sim 1/\sqrt{\sigma_m}$

"A detector with better resolution has larger probability to find a signal"

Note: only valid if $\Gamma_H \ll \sigma_m$. If Higgs is broad detector resolution is not relevant.

m_H = 100 GeV $\rightarrow$ Γ_H ~0.001 GeV
m_H = 200 GeV $\rightarrow$ Γ_H ~ 1 GeV
m_H = 600 GeV $\rightarrow$ Γ_H ~ 100 GeV $\qquad$ **$\Gamma_H \sim m_H^3$**

2. Integrated luminosity :

$$\left.\begin{array}{l} N_S \sim L \\ N_B \sim L \end{array}\right\}$$

$\Rightarrow S \sim \sqrt{L}$

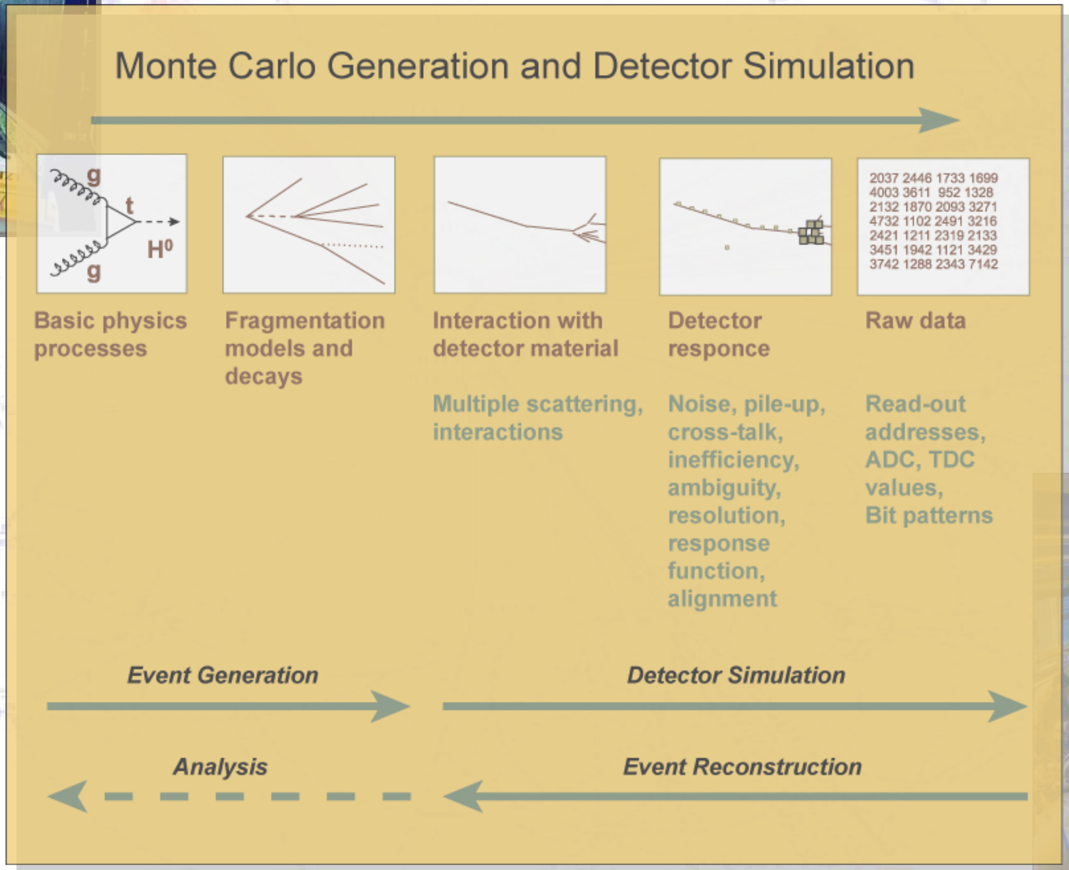
Variety of Exotic topics – Physics BSM

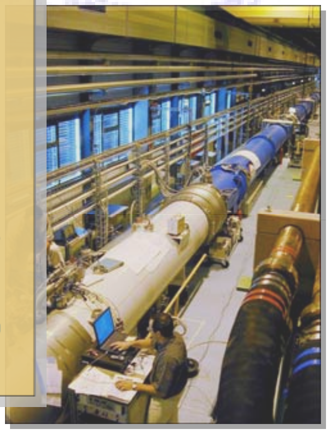
- SuperSymmetry SUSY
- Large extra dimensions:
  - direct Graviton production
  - Virtual exchange of gravitons
  - Black Holes
- Small extra dimensions:
  - KK excitations of gauge bosons: W, Z and g
  - Universal extra dimensions
  - Coupling unification
- Extended gauge symmetries:
  - Heavy Gauge bosons: Z’,W’
  - Little Higgs
  - LRSM: H++, Z’, W’, N…
- Compositeness
- **Leptoquarks**
- Excited fermions
- Heavy fermions
- Lepton Flavour Violation……

Possible Answers

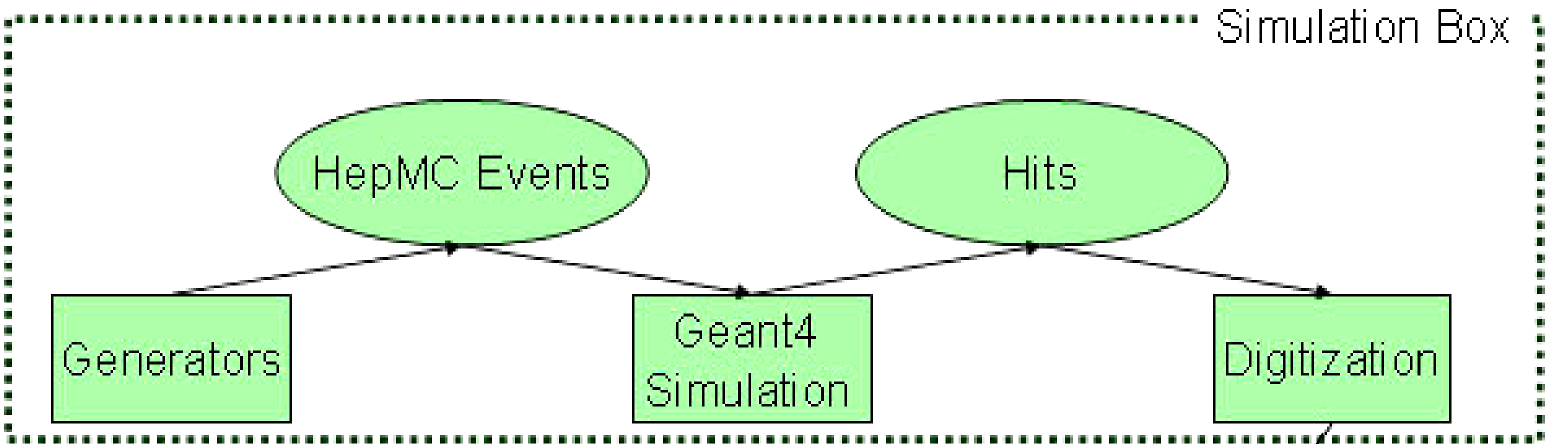
- Supersymmetry
  - it stabilize the Higgs mass
  - it is necessary in string theory
  - it leads to the unification of gauge forces
- ✓ Extra Dimensions
  - they can be used to bring down the Plank scale to the EW scale
- ✓ Strong Symmetry Breaking: Technicolor
  - Higgs boson may be a fermion-pair composite
- ✓ Little Higgs Models

ATLAS: preparing s/w chain for data taking

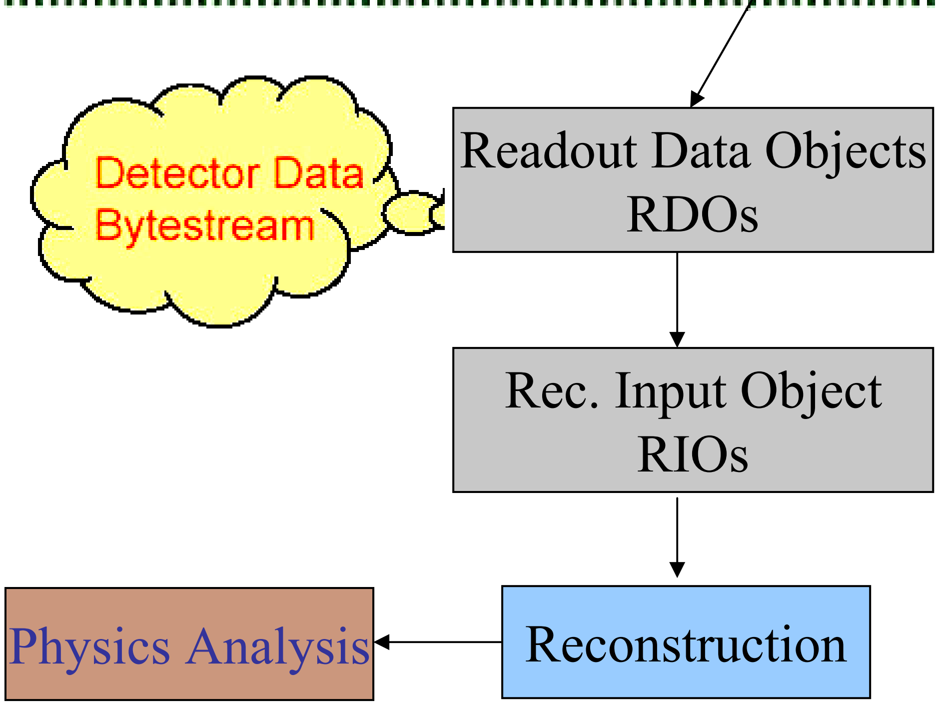




A Simplified view of the ATLAS sw

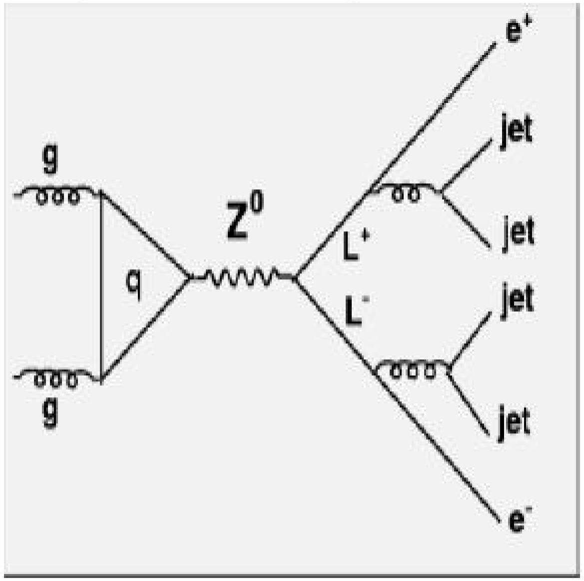


- Truth particles created with MC Event Simulation
- Truth particles passed through Detector Simulation
- Tracks and Calorimeter deposits reconstructed into particles and jets
- Reconstructed data compared with truth

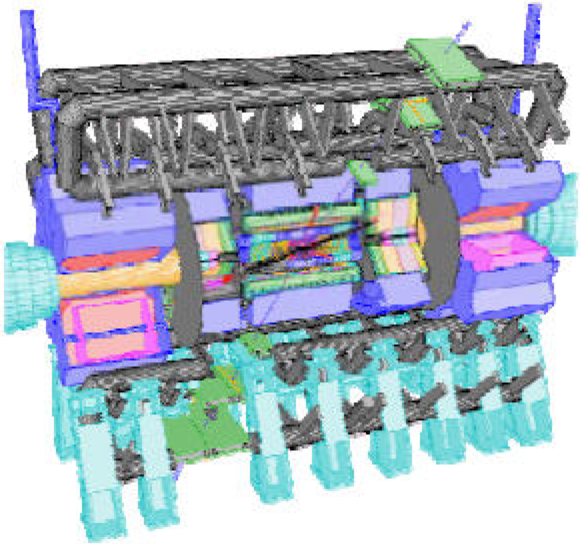


How we are making prospects

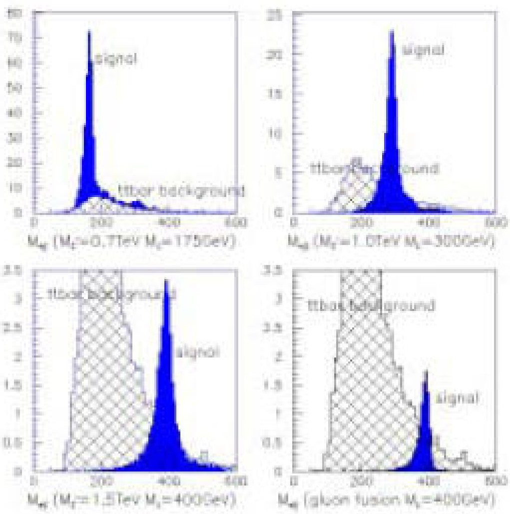
1. Event generator
   (PYTHIA, etc.)



2. Detector simulation
   (GEANT, etc.)



3. Data analysis
   (paw, root,etc.)



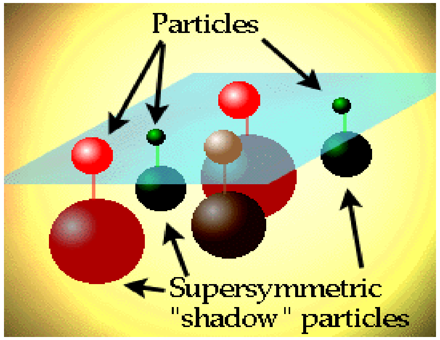
Low (10^{-33} $cm^{-2}s^{-1}$) and High (10^{-34} $cm^{-2}s^{-1}$) Luminosity

Beyond SM

- It is widely believed that the present Standard Model is a low-energy approximation of a **unified theory**
  - **= theory which unifies all 4 known forces**
    - (electromagnetic, weak, strong,gravitation)
- New models: **supersymmetry**
  - **= bosonfermion-symmetry**.
  - All particles have SUSY partners with a spin+-1/2 .
    - SUSY-partners of quarks and leptons are
      - **squarks and sleptons, with spin=0.**
    - SUSY-partners of force particles (photon, W,Z, gluon, graviton) are
      - **"photinos, winos,zinos, gluinos, gravitinos", with spin 1/2 (3/2).**
  - SUSY-particles do not have the same masses as the normal particles,
    - since no such particles have been observed yet
    - **Lightest SUSY particle is stable = dark matter candidate?**
  - SUSY-models have many new free parameters
    - wide range of signals to be studied

Should be visible in near future…

Particle	Super-partner
e,ν,u,d	$\tilde{e}, \tilde{\nu}, \tilde{u}, \tilde{d}$
γ,W,Z,h	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm, \tilde{\chi}_1^0 \dots \tilde{\chi}_4^0$



SUSY Spectrum

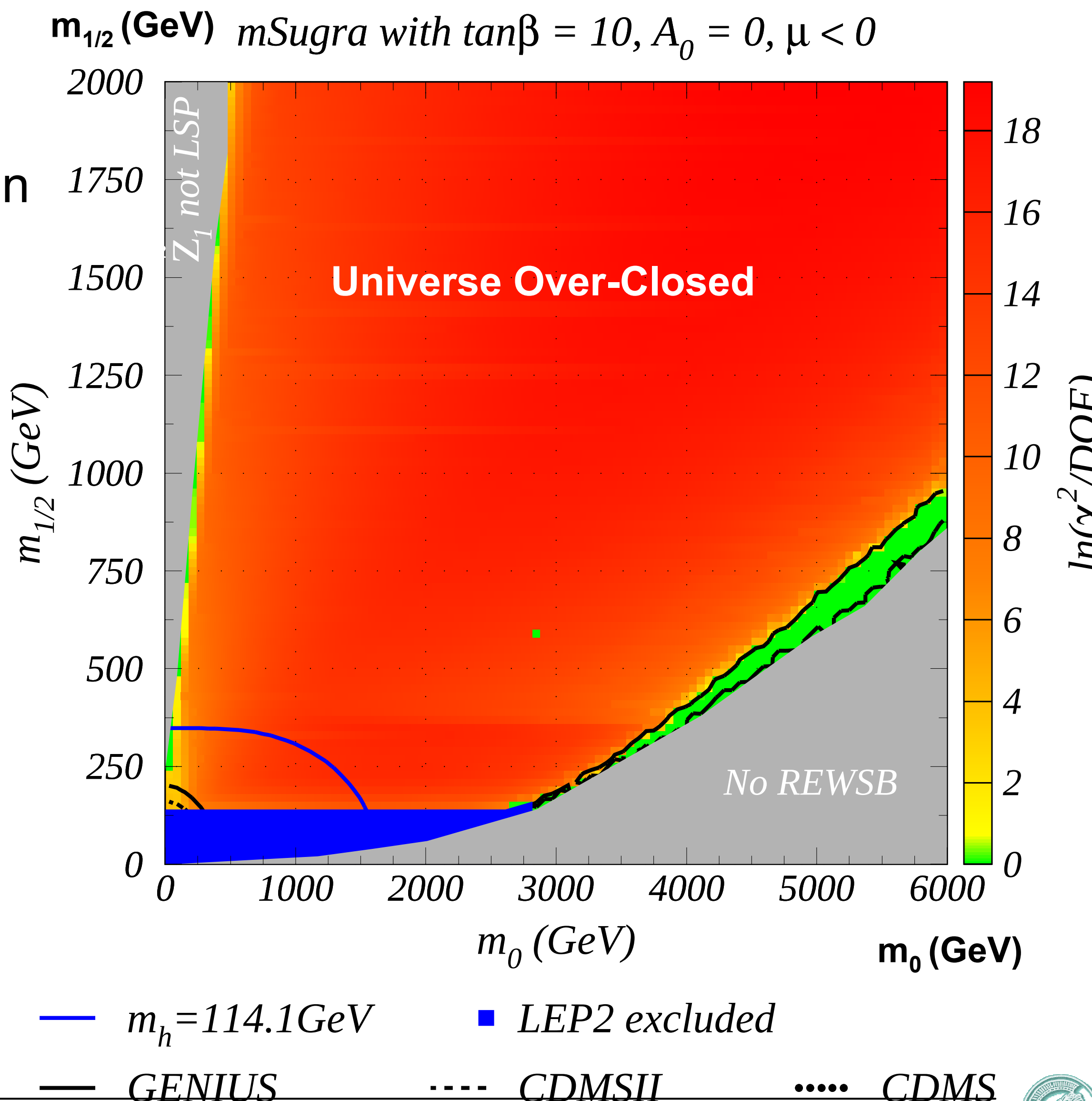
SUSY Searches@LHC

Standard Model Particles		SUSY Partners		
Particles	States	Sparticles	States	Mixtures
quarks (q)	$\binom{u}{d}_L$, u_R, d_R	squarks ($\tilde{q}$)	$\binom{\tilde{u}}{\tilde{d}}_L$, $\tilde{u}_R$, $\tilde{d}_R$	
(spin-$\frac{1}{2}$)	$\binom{c}{s}_L$, c_R, s_R	(spin-0)	$\binom{\tilde{c}}{\tilde{s}}_L$, $\tilde{c}_R$, $\tilde{s}_R$	
	$\binom{t}{b}_L$, t_R, b_R		$\binom{\tilde{t}}{\tilde{b}}_L$, $\tilde{t}_R$, $\tilde{b}_R$	$\tilde{t}_{1,2}$, $\tilde{b}_{1,2}$
leptons (l)	$\binom{e}{\nu_e}_L$, e_R	sleptons ($\tilde{l}$)	$\binom{\tilde{e}}{\tilde{\nu}_e}_L$, $\tilde{e}_R$	
(spin-$\frac{1}{2}$)	$\binom{\mu}{\nu_\mu}_L$, μ_R	(spin-0)	$\binom{\tilde{\mu}}{\tilde{\nu}_\mu}_L$, $\tilde{\mu}_R$	
	$\binom{\tau}{\nu_\tau}_L$, τ_R		$\binom{\tilde{\tau}}{\tilde{\nu}_\tau}_L$, $\tilde{\tau}_R$	$\tilde{\tau}_{1,2}$
gauge/Higgs bosons	g, Z, γ, h, H, A	gauginos/Higgsinos	$\tilde{g}$, $\tilde{Z}$, $\tilde{\gamma}$, $\tilde{H}^0_{1,2}$ }	$\tilde{\chi}^0_{1,2,3,4}$
(spin-1, spin-0)	$W^\pm$, $H^\pm$	(spin-$\frac{1}{2}$)	$\tilde{W}^\pm$, $\tilde{H}^\pm$ }	$\tilde{\chi}^\pm_{1,2}$
graviton (spin-2)	G	gravitino (spin-$\frac{3}{2}$)	$\tilde{G}$	

- If SUSY exists at the TeV scale
  - **gluinos and squarks strongly produced**
  - **Distinctive topological decays**
  - **Easy to discover**
  - **Precision measurements is the challenge**
- Main background is SUSY itself
  - Necessary to generate entire SUSY cross-section
  - + Relevant SM backgrounds

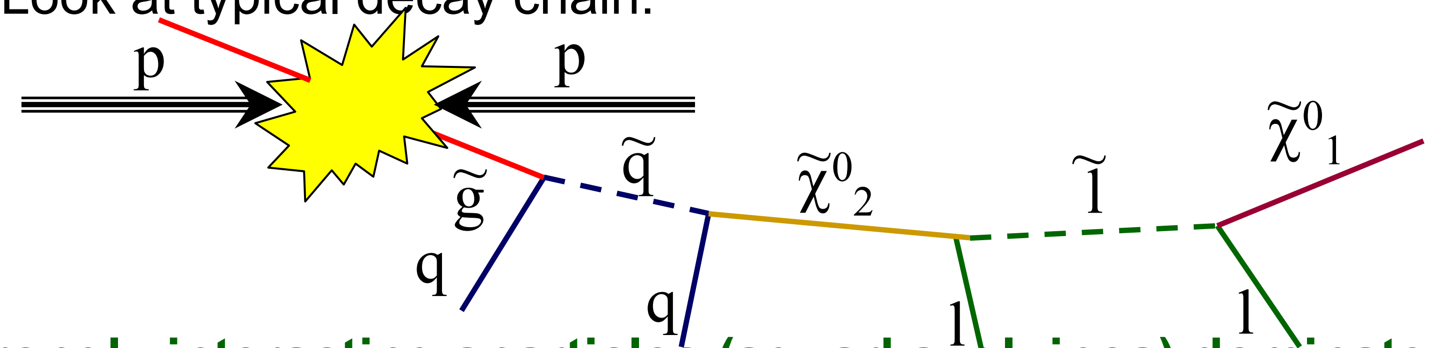
SUPERSYMMETRY

- SUSY particularly well-motivated solution to gauge hierarchy problem, unification of couplings etc.
- Also often provides natural solution to Dark Matter problem of astrophysics/cosmology.
- Much work carried out historically by ATLAS (summarised in TDR).
- Work continuing to ensure ready to test new ideas in 2007.



SUSY Signatures

- Q: What do we expect SUSY events @ LHC to look like?
- A: Look at typical decay chain:



- **Strongly interacting sparticles (squarks, gluinos) dominate production.**
- **Heavier than sleptons, gauginos etc. → cascade decays to LSP.**
- **Long decay chains and large mass differences between SUSY states**
  - **Many high p_T objects observed (leptons, jets, b-jets).**
- **If R-Parity conserved LSP (lightest neutralino in mSUGRA) stable and sparticles pair produced.**
  - **Large E_T^{miss} signature (c.f. $W \to l\nu$).**
- **Closest equivalent SM signature $t \to Wb$.**

SUGRA Models

- Characterized by m_0, $m_{1/2}$, $\tan\beta$, A_0, $\mathrm{sgn}(\mu)$
- SUGRA points selected by LHC for study:

Point	m_0 (GeV)	$m_{1/2}$ (GeV)	A_0 (GeV)	$\tan\beta$	sgn μ
1	400	400	0	2	+
2	400	400	0	10	+
3	200	100	0	2	-
4	800	200	0	10	+
5	100	300	300	2.1	+
6	200	200	0	45	-

- Total SUSY cross-section:

  ~ few pb (for M_{SUSY} ~ 1 TeV)

  ~ 1 nb (for M_{SUSY} ~ 300 GeV)

$m_{1/2}$: universality of the gaugino mass
m_0: universality of the scalar mass
A_0: unification of the trilinear coupling constant
$\tan\beta$: value of the ratio between the 2 higgs vacuum expected value and the signμ (higgsinos mixing parameter)

Inclusive Signatures

Many complex SUSY signatures:

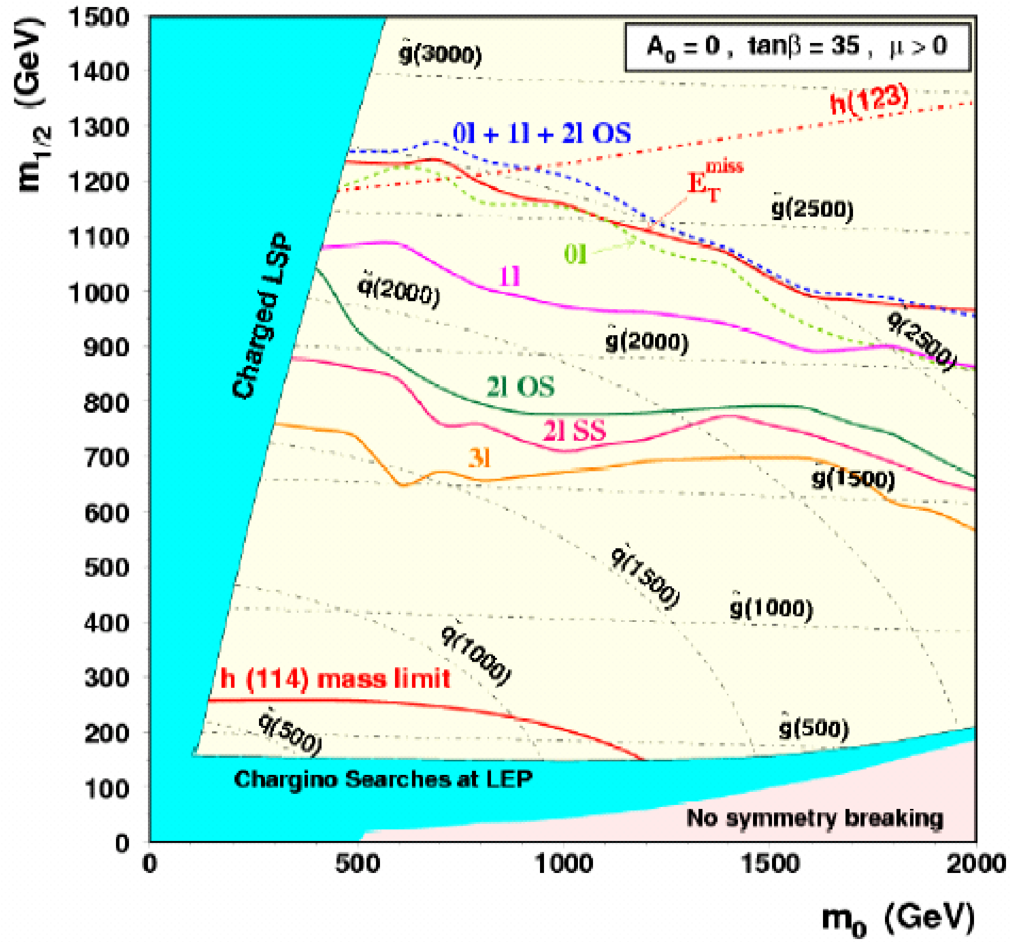
$\tilde{g} \rightarrow q\tilde{q}$

$\tilde{q} \rightarrow \tilde{\chi}_1^0\, q$ or $\tilde{\chi}_1^{\pm} q$

$\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0\, \ell^+\ell^-$ or $\tilde{\chi}_1^0\, Z^0$ or $\tilde{\chi}_1^0\, h$

$\tilde{\chi}^{\pm} \rightarrow \tilde{\chi}_1^0\, \ell^{\pm}\nu$ or $\tilde{\chi}_1^0\, W$

- Final State may consist of:
  - **Multi Jets + Missing E_T**
  - + (n = 1,2,3,4) high P_T leptons
  - + same sign (SS) lepton pairs
- Define Resulting Reach :
  - **Require at least 10 events**
  - **$S/\sqrt{B} > 5$**



$$M_{eff} \equiv \sum_{jets} E_T^{jets} + \not{E}_T$$: good measure of M_{SUSY}

$\Rightarrow$ preselect SUSY-rich sample

Estimate of Effective Mass

Once discovered, determine M_{SUSY} ($\equiv \min(m_{\tilde{q}}, m_{\tilde{g}})$) from energetic jets and E_t^{miss}:

$$M_{EFF} = \not{E}_T + \sum_{i=1}^{4} E_T^i \qquad \text{(4 hardest jets)}$$

Backgrounds modeled:

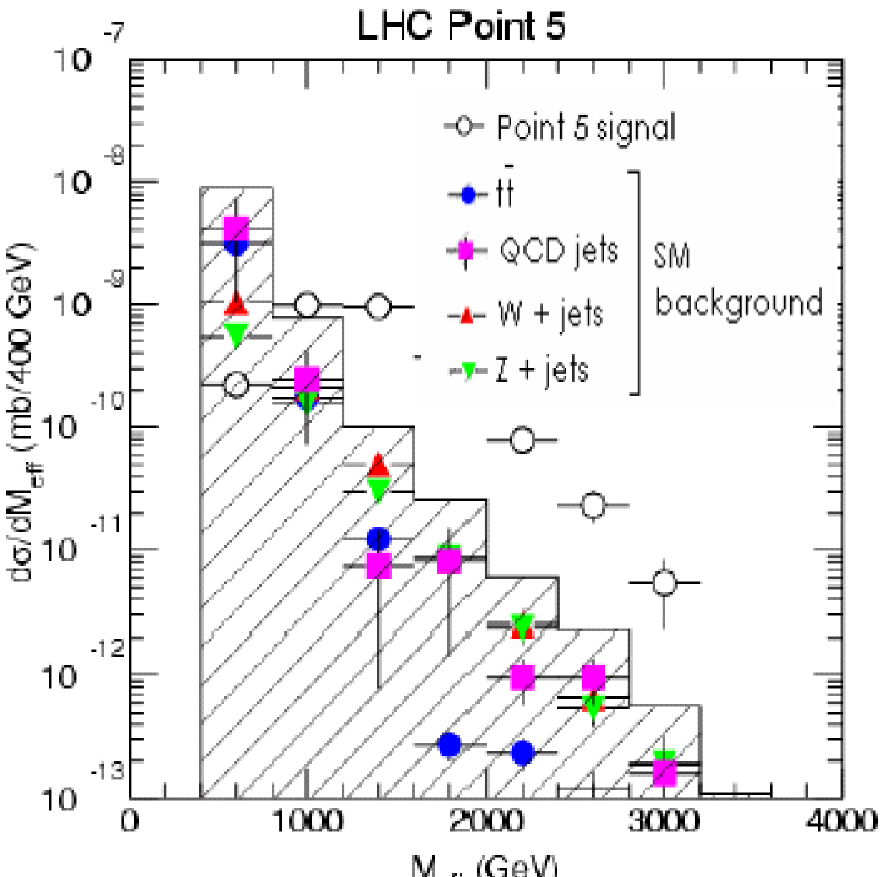
W+jet, Z+jets, $t\bar{t}$, QCD

S/B ~ 10 at high M_{EFF}

Estimate M_{SUSY} (α M_{EFF})

~ 10% precision

with accepted cross section > 1pb



Peak of M_{eff} distribution → mass scale of the strongly produced SUSY particles

Precision measurements

- Pick out specific multi-body decay modes:
  - Identify bottom of decay chain
- Measure kinematic endpoints (determines combination of masses)
  - **Example:** $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \ell^+ \ell^-$ *measures* $M(\tilde{\chi}_2^0) - M(\tilde{\chi}_1^0)$
  - squarks, gluinos mainly decay through lighter chargino or second neutralino
- Determine masses from derived constraints
- Make fit for model parameters

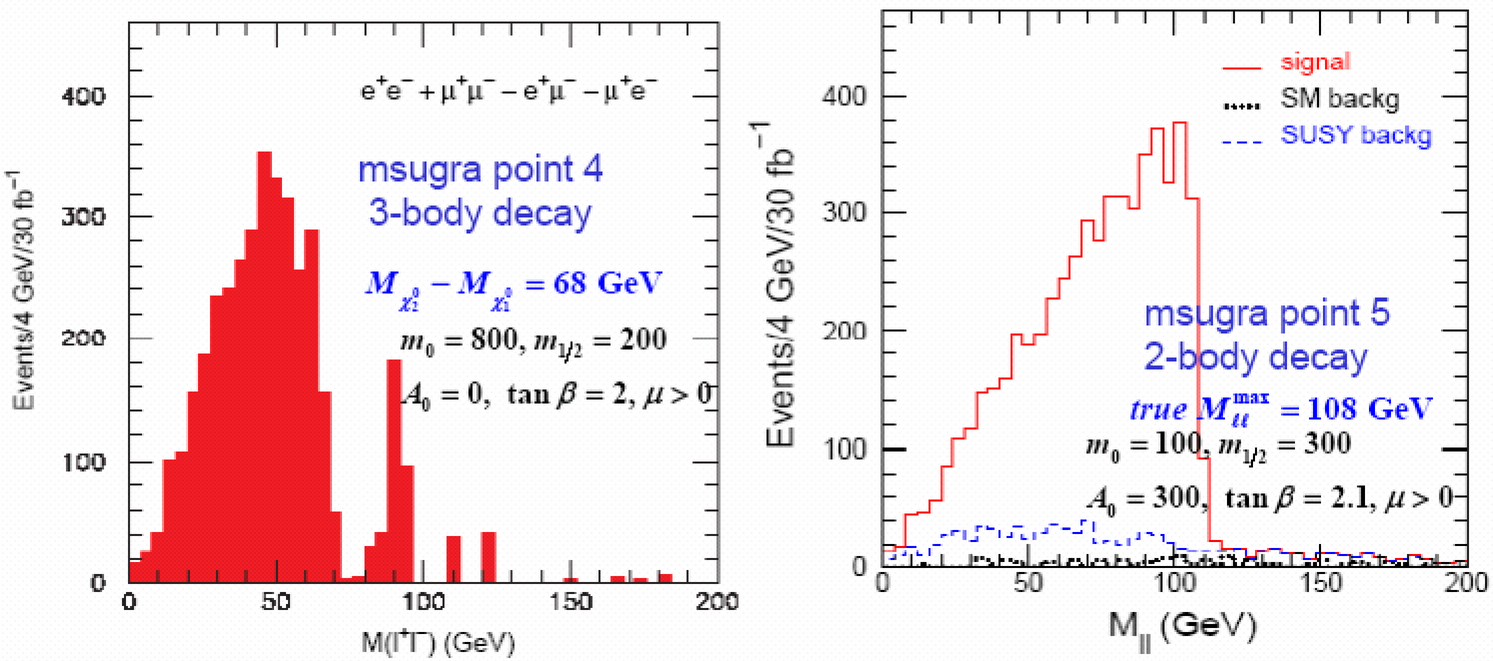
- Example (m_0, $m_{1/2}$ = 100, 300; $\tan\beta$=2): Determine constraints from measuring the kinematic end points of m_{ll}, m_{lq}, m_{llq}

$$\tilde{q}_L \rightarrow \tilde{\chi}_2^0 q \rightarrow \tilde{\ell}_R^{\pm} \ell^{\mp} q \rightarrow \tilde{\chi}_1^0 \ell^+ \ell^- q$$

- **Mass reconstruction from di-lepton endpoints**

3-body decay: $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell^+ \ell^- \Rightarrow M_{\ell\ell} < M_{\tilde{\chi}_2^0} - M_{\tilde{\chi}_1^0}$

2-body decay: $\tilde{\chi}_2^0 \to \tilde{\ell}^\pm \ell^\mp \to \tilde{\chi}_1^0 \ell^+ \ell^- \Rightarrow M_{\ell\ell} < \frac{\sqrt{(M^2_{\tilde{\chi}_2^0} - M^2_{\tilde{\ell}})(M^2_{\tilde{\ell}} - M^2_{\tilde{\chi}_1^0})}}{M_{\tilde{\ell}}}$



SM background removed by subtracting distributions with opposite flavor leptons
precision in end-point measurement: ~ 1-2 %

R-Parity Violation ($R\!\!\!/_p$)

- $R = (-1)^{3(B-L)+2S}$ $\begin{cases} R = -1 \text{ for SUSY particles} \\ R = +1 \text{ for SM particles} \end{cases}$
- Elegant way of imposing at the same time baryon and lepton numbers conservation in SUSY, but no theoretical reason for conservation!
- $R\!\!\!/_p$ superpotential of the MSSM:

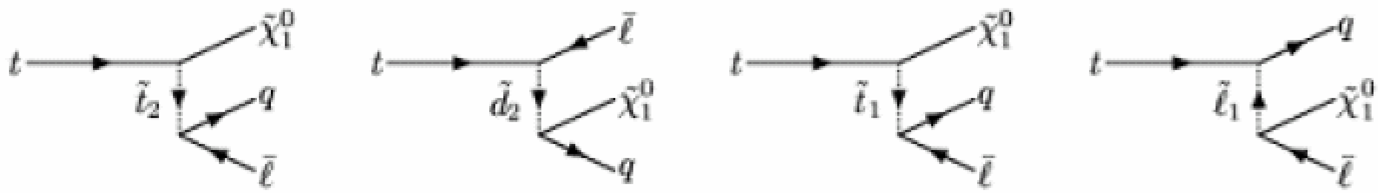
$$W_{R\!\!\!/_p} = \lambda_{ijk} L_i L_j \overline{E}_k + \lambda'_{ijk} L_i Q_j \overline{D}_k + \lambda''_{ijk} U_i^c D_j^c \overline{D}_k + \mu_i L_i H_2$$

where λ_{ijk}, λ'_{ijk} and μ_i violate leptonic number
λ''_{ijk} violates baryonic number
$L_i(Q_i)$ → Left-handed lepton (quark) doublet chiral superfields
$E_i(U_i,D_i)$ → Right-handed lepton (quark) singlet chiral superfields
i,j,k → generation indices

Example:

• **Study of top quark decays within $\not{R}_p$ into a single neutralino, with only $\lambda'_{i3k} \neq 0$**

It leads to diagrams:



• **If one sfermion is much lighter than the others → leading contribution to top-quark decay.**

• **We assume $m_{slepton} < m_{squark}$ and keep only $\lambda'_{131} \neq 0$**

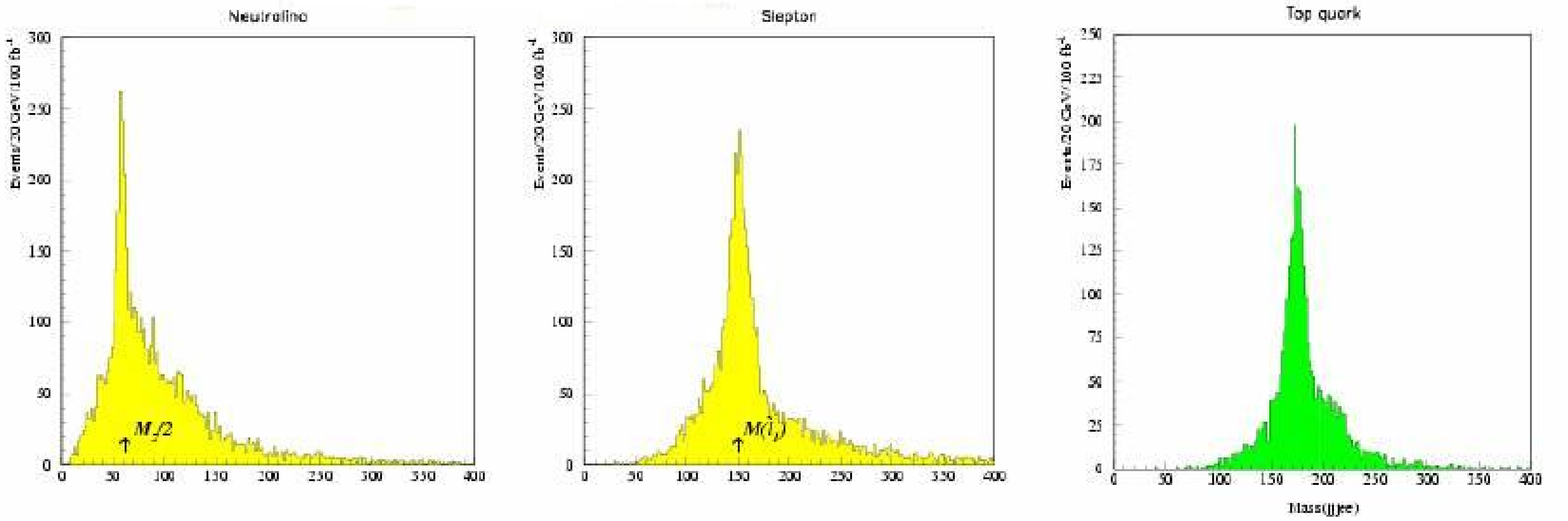
• **Taking parameters:**

M_2=120 GeV ; μ=-300 ; tanβ=10 ;
- **$m_{slepton}$=150 GeV < m_{top} → two-body decay**
- **$m_{slepton}$=230 GeV > m_{top} → three-body decay**

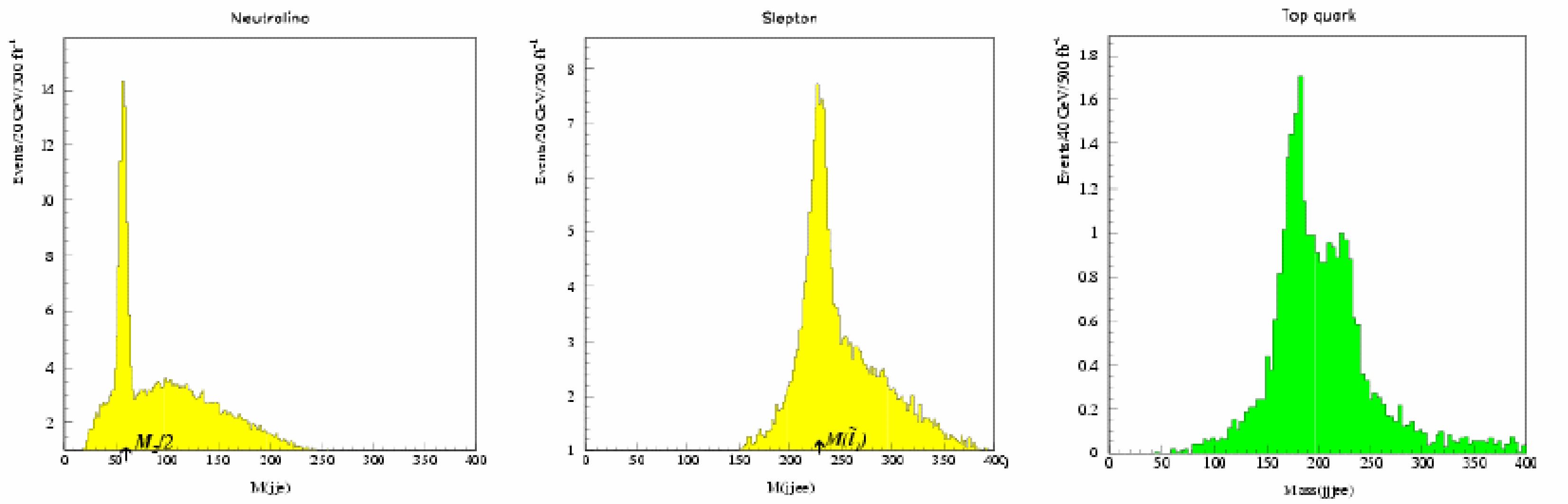
3-body decay: $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \ell^+ \ell^- \Rightarrow M_{\ell\ell} < M_{\tilde{\chi}_2^0} - M_{\tilde{\chi}_1^0}$

2-body decay: $\tilde{\chi}_2^0 \rightarrow \tilde{\ell}^\pm \ell^\mp \rightarrow \tilde{\chi}_1^0 \ell^+ \ell^- \Rightarrow M_{\ell\ell} < \dfrac{\sqrt{(M^2_{\chi_2^0} - M^2_{\tilde{\ell}})(M^2_{\tilde{\ell}} - M^2_{\chi_1^0})}}{M_{\tilde{\ell}}}$

$m_{slepton} = 150$ GeV



$m_{slepton} = 230$ GeV



Prospects for Leptoquark Searches with ATLAS/LHC

N. Benekos (MPI), V. A. Mitsou (*IFIC –Valencia*), I. Panagoulias *(NTUA Athens)*, Th. Papadopoulou *(NTUA Athens)*

Theoretical Motivation

- Leptoquarks (LQ) are hypothetical particles which appear in many SM extensions to explain **symmetry between leptons and quarks**
  - SU(5) GUT model
  - superstring-inspired models
  - 'colour' SU(4) Pati-Salam model
  - composite models
  - Technicolor
- LQs are coupled to both leptons and quarks and carry SU(3) color, fractional electric charge, baryon (B) and lepton (L) numbers

- LQs can have:
  - spin 0 (scalar) ► couplings fixed, i.e., no free parameters
  - Isotropic decay
    - (in angular distribution)
  - spin 1 (vector) ► anomalous magnetic (κ_G) and electric quadrupole (λ_G) model-dependent couplings
    - Yang-Mills coupling: $\kappa_G=\lambda_G=0$
    - Minimal coupling: $\kappa_G=1$, $\lambda_G=0$
- Experimental evidence searched:
  - indirectly: LQ-induced 4-fermion interactions
  - directly: production cross sections at collider experiments

Leptoquark Classification

Buchmuller, Rückl, Wyler (BRW) model (1987)

- Assumptions:
  - LQs only couple to quarks, leptons and gauge bosons (with dimensionless couplings)
  - LQ interactions invariant under SM gauge group $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$
- LQs are classified by:
  - fermion number, $F=3B+L$
  - ► F = 0, 2
  - spin ► $J=0$ (scalar) or $J=1$ (vector)
  - charge ► Q_{em}= ±1/3, ±2/3, -4/3, -5/3

- *Intergenerational mixing is severely restricted by FCNC data* ⇒ LQ appear in 3 quark/lepton generations
- *LQ-mediated π and K helicity-suppressed decays not observed* ⇒ chiral LQ couplings to fermions

14 chiral LQ species per/generation:

- **7 scalar LQs** (3 singlets, 3 doublets, 1 triplet)
- **7 vector LQs** (3 singlets, 3 doublets, 1 triplet)

Phenomenology

couple to $\ell^- q$, νq (F = 2)

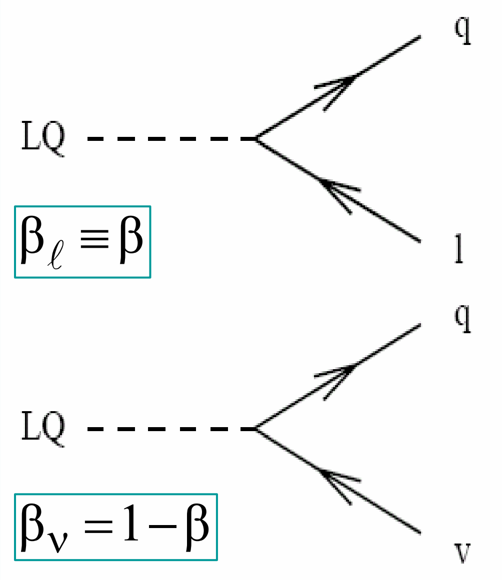
couple to $\ell^+ q$, $\bar{\nu} q$ (F = 0)

F	spin	species
2	0	$S_{0,L}$; $S_{0,R}$; $\tilde{S}_{0,R}$; $S_{1,L}$
2	1	$V_{1/2,L}$; $V_{1/2,R}$; $\tilde{V}_{1/2,L}$
0	0	$S_{1/2,L}$; $S_{1/2,R}$; $\tilde{S}_{1/2,L}$
0	1	$V_{0,L}$; $V_{0,R}$; $\tilde{V}_{0,R}$; $V_{1,L}$

labeled by weak isospin and lepton helicity

Decays:

- LQs decay to $\ell^{\pm}$q and/or νq with branching ratios β_ℓ, β_ν = 0, 0.5, 1 (depending on the quantum numbers)
- Scalar LQs decay isotropically
- Vector LQs decay ~ $(1+\cos\theta^*)^2$

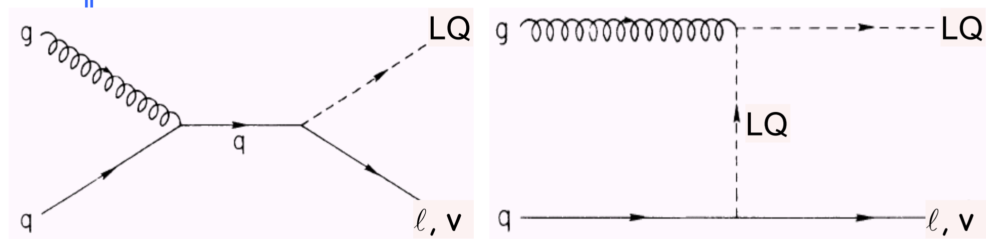


- **Each LQ characterized by two parameters:**
  - LQ mass M_{LQ}
  - LQ-ℓ-q Yukawa coupling, λ
- **Resonance width** $\Gamma \sim \lambda^2 \cdot m_{LQ}$

LQ Production processes at LHC

- **Single production**
  - strongly depends on λ
  - possible signatures:
    - $\ell^+\ell^-$ + jet
    - $\ell\nu$ + jet
    - $\nu\nu$ + jet
  - Main background: Zjet & tt

qg→ ℓ LQ, qg→ ν LQ

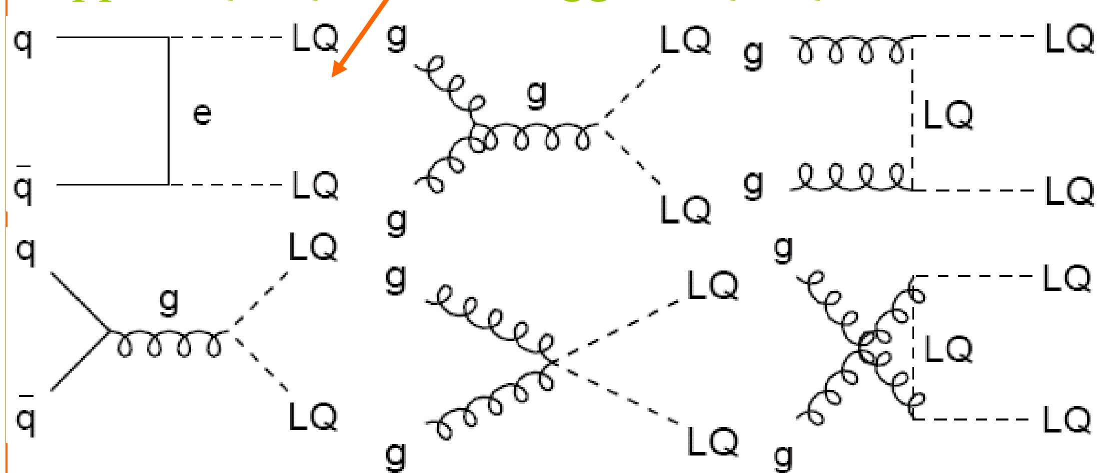


- λ-dependent process
- does not contribute significantly to 2nd & 3rd generation

- **Pair production**
  - Practically independent of Yukawa coupling λ (only g-LQ-LQ vertex)
  - Depends mainly on LQ mass

$q\bar{q}$→LQ LQ

gg→LQ LQ



Leptoquark Decay

$\beta = Br(LQ \to lq)$

Each generation can decay into 3 final states:

Exclusive to the Hadron Machines

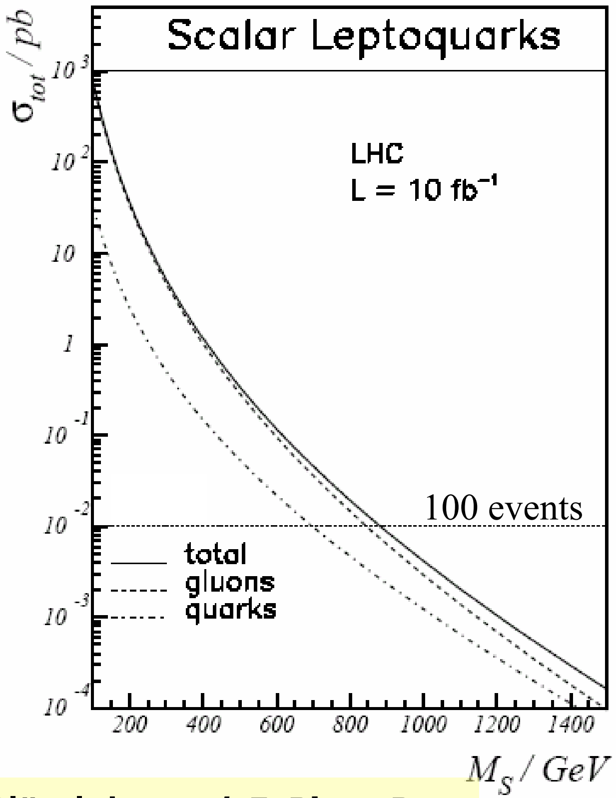
	1st Generation	2nd Generation	3rd Generation
$\beta = 1$	$LQ\,\overline{LQ} \to e^- e^+ q\bar{q}$	$LQ\,\overline{LQ} \to \mu^+ \mu^- q\bar{q}$	$LQ\,\overline{LQ} \to \tau^+ \tau^- q\bar{q}$
$\beta = 0.5$	$LQ\,\overline{LQ} \to e^\pm \nu_e q_i q_j$	$LQ\,\overline{LQ} \to \mu^\pm \nu_\mu q_i q_j$	$LQ\,\overline{LQ} \to \tau^\pm \nu\, q_i q_j$
$\beta = 0$	$LQ\,\overline{LQ} \to \nu_e \nu_e q\bar{q}$	$LQ\,\overline{LQ} \to \nu_\mu \nu_\mu q\bar{q}$	$LQ\,\overline{LQ} \to \nu_\tau \nu_\tau q\bar{q}$

This talk! →

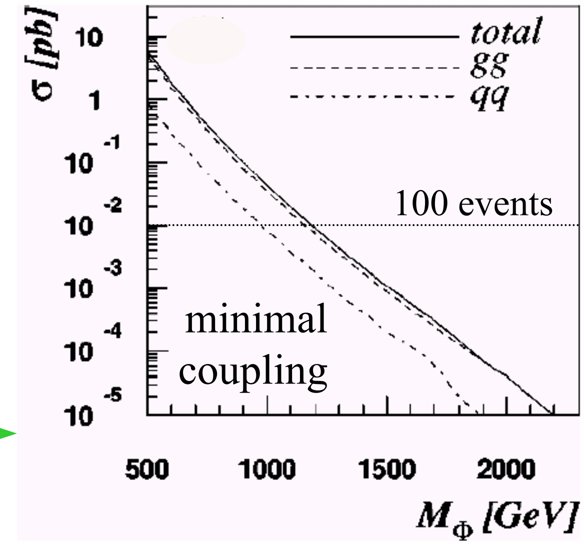
$LQ\,LQ \to llqq$	2l+2j	$BR = \beta^2$
$LQ\,LQ \to l\nu qq$	l+MET+2j	$BR = 2\beta(1-\beta)$
$LQ\,LQ \to \nu\nu qq$	MET+2j	$BR = (1-\beta)^2$

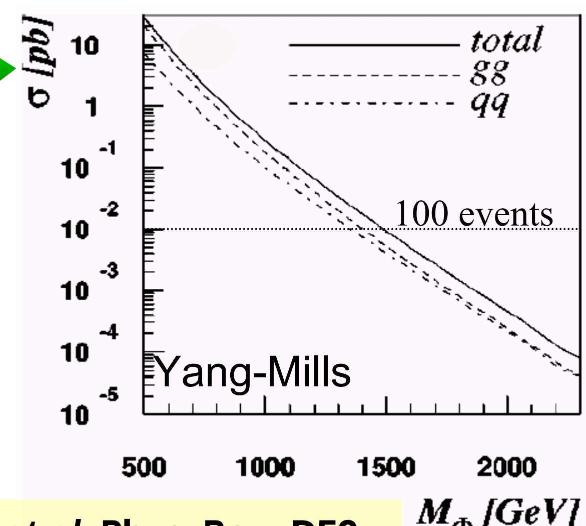
LQ Production rates at LHC

- Pair production cross sections
  - $q\bar{q} \rightarrow$ LQ LQ: ~30% of total production (for $m_{LQ} \approx 1$TeV)



Vector LQs





Scalar LQs

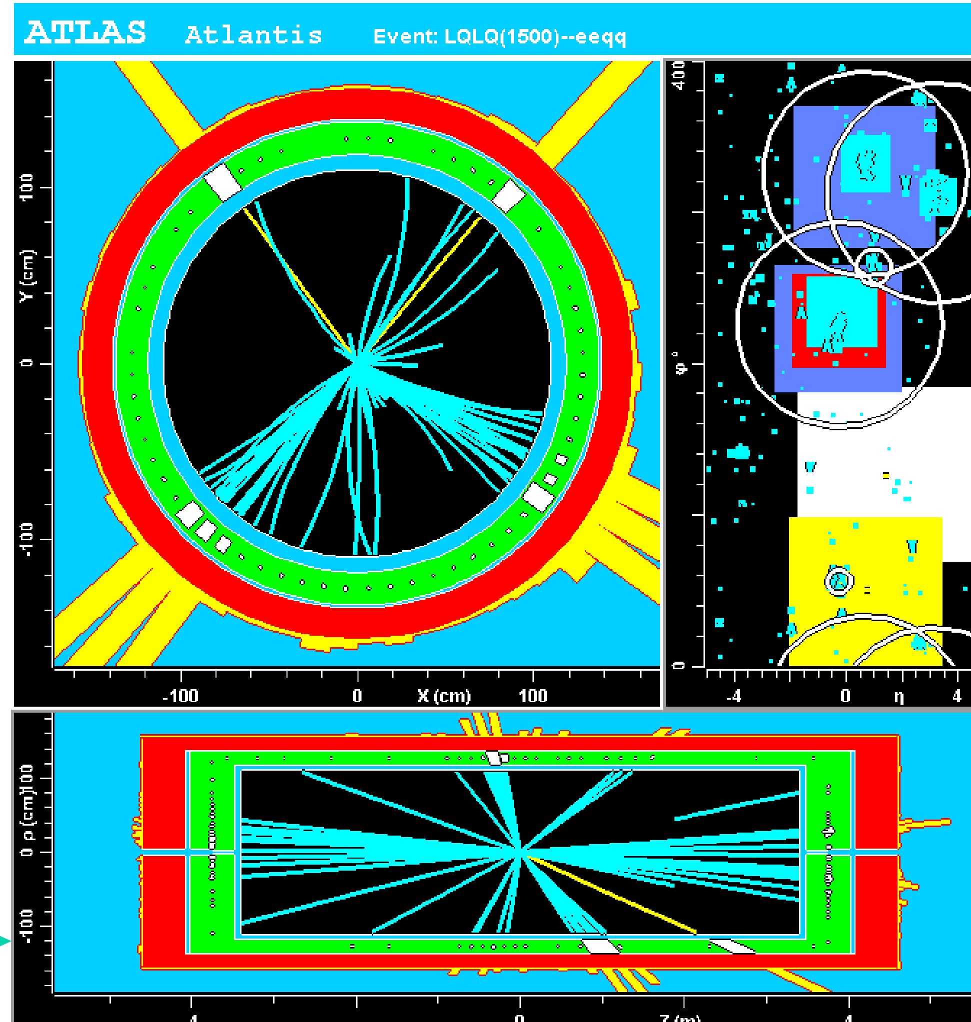
Blümlein *et al*, Z. Phys. D 76 (1997) 137

Belyaev *et al*, Phys. Rev. D59 (1999) 075007

Leptoquarks in ATLAS

- Scalar leptoquarks
- Pair production
  - ℓℓjj channel
  - νν jj channel
  - independent of λ!
- Simulation tools:
  - PYTHIA
    - $qq \to LQ\ LQ$
    - $gg \to LQ\ LQ$
  - ATLAS fast simulation *(ATHENA-ATLFAST)*

$LQ\ LQ \to e^+e^-qq$
m_{LQ}=1500 GeV
(schematic view)



2leptons + 2jets topology

- Signal
  - LQ LQ → $\ell^+ q \ell^- q$
  - 1st and 2nd generation LQs
  - Scalar e^-u & μ^-c
  - $\beta=1$ ➡ $S_0^R(^{-1}/_3)$
  - $\beta=0.5$ ➡ $S_0^L(^{-1}/_3)$, $S_1(^{-1}/_3)$
  - $\lambda \geq 10^{-6}$ (LQ : resonance)

M_{LQ} (TeV)	σ (fb)	
	1st gener.	2nd gener.
1.0	5.0	4.8
1.2	1.3	1.3
1.3	0.71	0.68
1.5	0.22	0.21
1.7	0.074	0.070
2.0	0.015	0.014

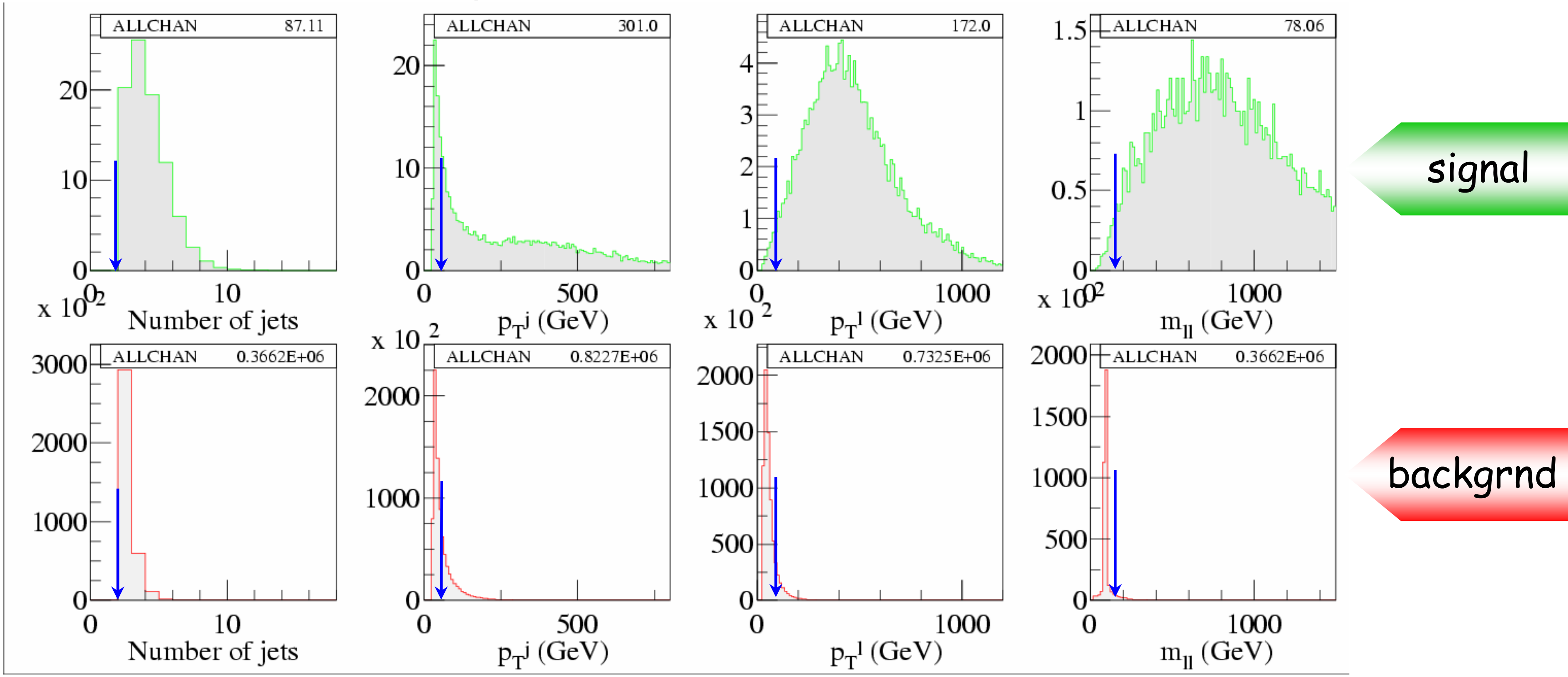
- Background
  - QCD: huge, but eliminated after high-p_T isolated leptons and high-$m_{\ell j}$ cuts are applied
  - Drell-Yan: eliminated by high-$m_{\ell j}$ cut

Process	σ×BR (pb)
Zjet ($\ell\ell jj$)), p_T > 20 GeV	1 380
tt ($\ell \nu j \ell \nu j$)	11
ZZ ($\ell\ell jj$)	1.2
ZW ($\ell\ell jj$)	1.2
WW ($\ell \nu \ell \nu$)	3.3

- First level cuts:
  - At least 2 jets with p_T>30 GeV and $|\eta|<5.0$
  - 2 same-flavour, opposite- sign leptons with p_T>30 GeV and $|\eta|<2.5$

lljj: selection variables

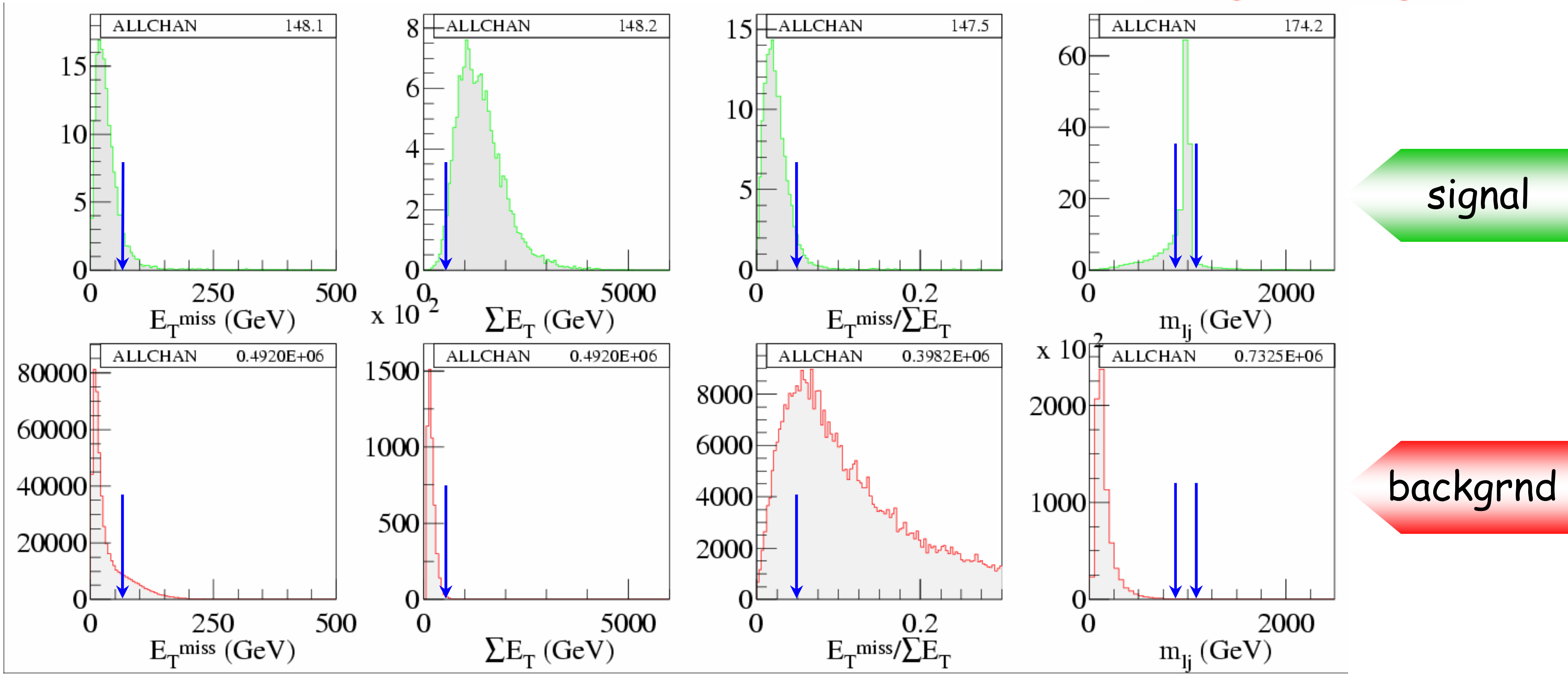
- Signal (m_{LQ}=1 TeV):
  - Many high-p_T jets
  - Two high-p_T leptons
- Background:
  - $Z \rightarrow \ell^+\ell^-$ peak at $m_{\ell\ell}$✡90 GeV
- After first-level cuts



lljj: selection variables (cont.)

- $\sum E_T$: sum of transverse energy in the calorimeters
- $m_{\ell j}$: lepton-jet invariant mass for two leading jets (minimum- $\Delta m_{\ell j}$ combination)

M(l1j1) - M(l2j2)
M(l1j2) - M(l2j1)

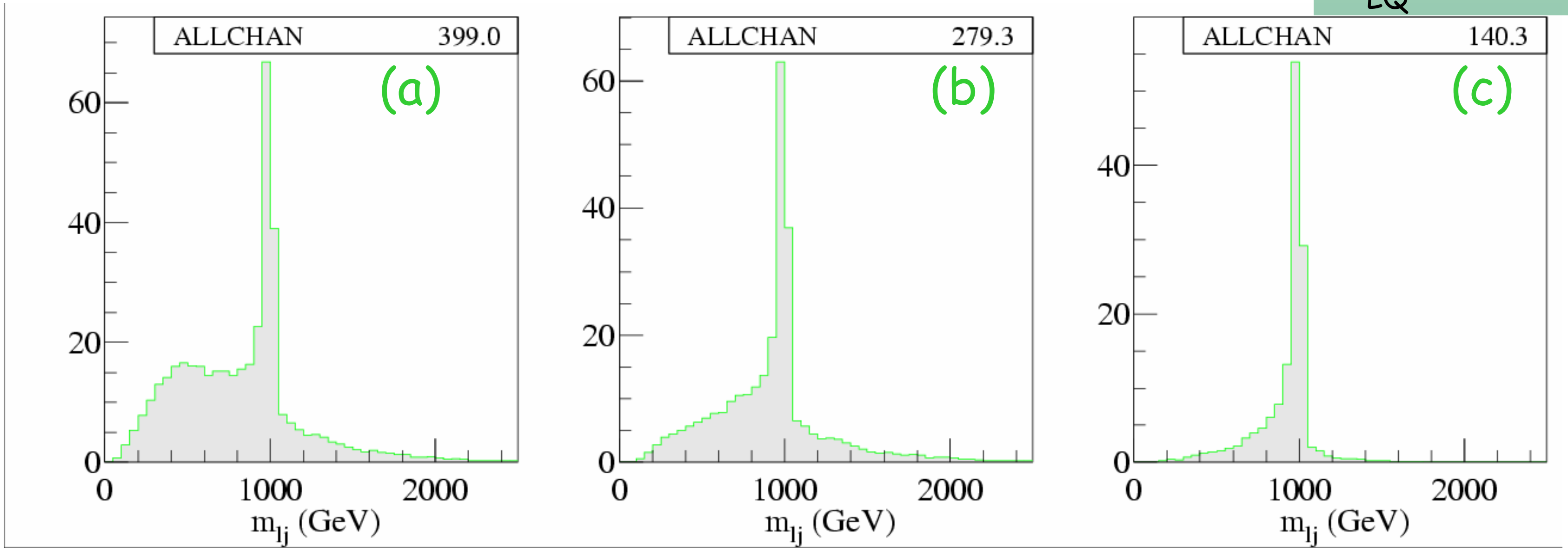


lljj: m_{lj} invariant mass

$m_{\ell j}$ combination	$\|m_{\ell j}-m_{LQ}\| < 100$ GeV	
	# events	%
(a) all combinations	136	34%
(b) two leading jets	126	45%
(c) two leading jets; minimum-$\Delta m_{\ell j}$ combination	98	70%

Provides clearest signal

m_{LQ}=1 TeV

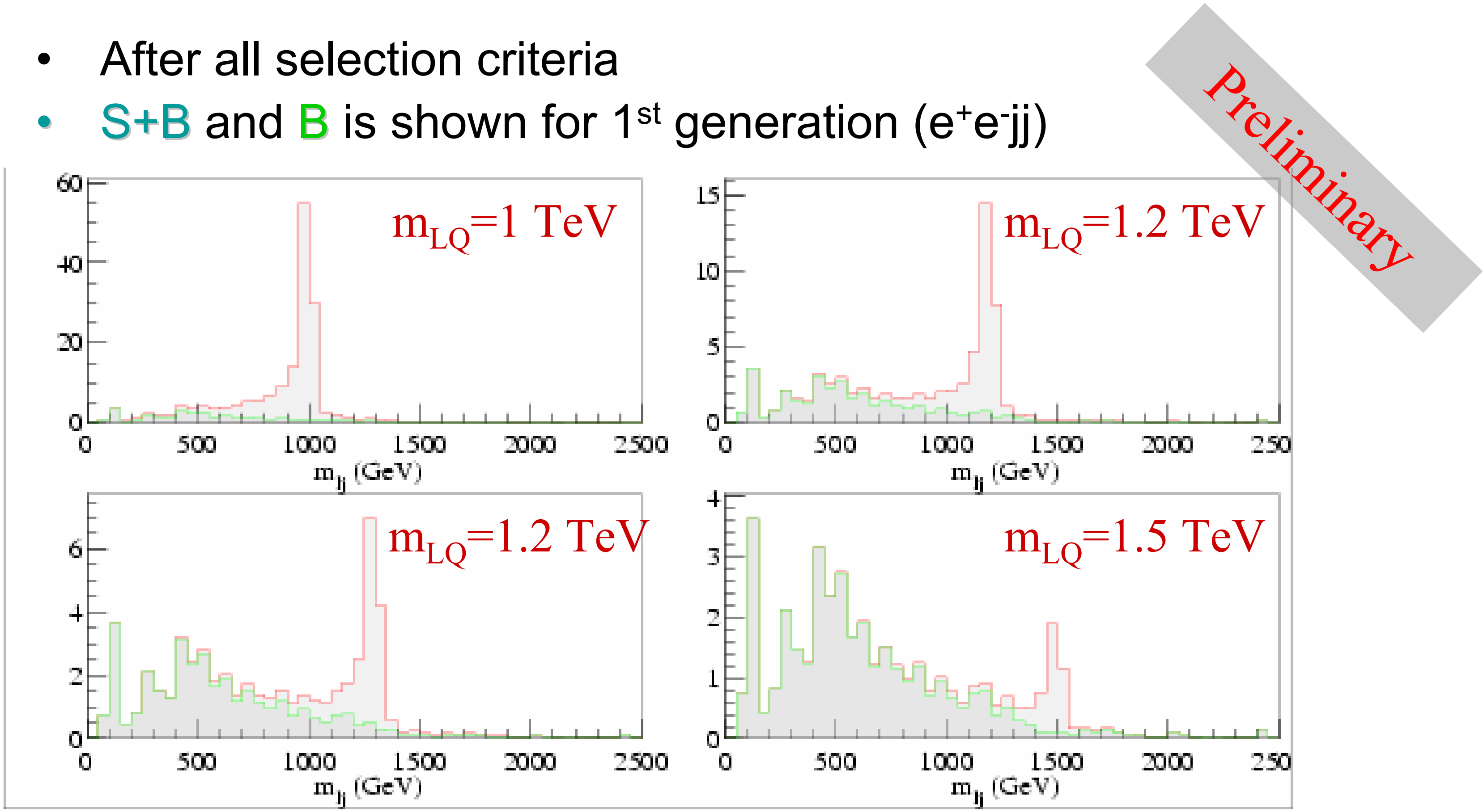


lljj: selection cuts (tentative)

- Similar cuts imposed for both eejj & μμjj channels
- Cuts optimized to maximize significance for all leptoquark masses
  - at least 2 jets with $p_T > 70$ GeV and $|\eta| < 5.0$
  - 2 same-flavour, opposite- sign leptons with $p_T > 100$ GeV and $|\eta| < 2.5$
  - $m_{\ell\ell} > 180$ GeV *(for Z peak)*
  - $E_T^{miss} < 70$ GeV *(for tt background)*
  - $\sum E_T > 570$ GeV
  - $E_T^{miss} / \sum E_T < 0.05$
  - mass window: $|m_{\ell j} - m_{LQ}| < 100$ GeV
  - m_{LQ} reconctructed from two leading jets with minimum-$\Delta m_{\ell j}$ combination

lljj: signal and background

- After all selection criteria
- S+B and B is shown for 1st generation (e^+e^-jj)



- Signal can be observed for M_{LQ} ~ 1.3 TeV
- Channel background-free for M_{LQ}>1.8 TeV but signal cross section very small (<0.07 fb)

lljj: signal significance

- First generation leptoquarks
- Integrated luminosity $\int\mathcal{L}$=30 fb^{-1}

Preliminary

M_{LQ} (TeV)	Signal	Background	S/√B
1.0	126	4.65	58
1.2	27.6	4.14	14
1.3	16.1	3.46	10.7
1.5	4.49	1.86	5.9

- Signal can be clearly observed for m_{LQ} = 1.3 TeV
- Similar results obtained for μμjj channel

Effective Signal Expected = $\varepsilon \times \sigma$

ETmiss + 2jets topology

- 1st and 2nd generation LQs
  - Scalar νd & νs
  - LQ LQ $\rightarrow$ νν qq
  - Signal is difficult to be separated from SM background (Z jet irreducible background)
- 3rd generation LQs
  - LQ LQ $\rightarrow$ νν bb
  - $\beta = 0 \Rightarrow \tilde{S}_{1/2}(^{+1}/_{3})\ S_1(^{+2}/_{3})$,
  - $\beta = 0.5 \Rightarrow S_0^L(^{-1}/_{3}),\ S_1(^{-1}/_{3})$

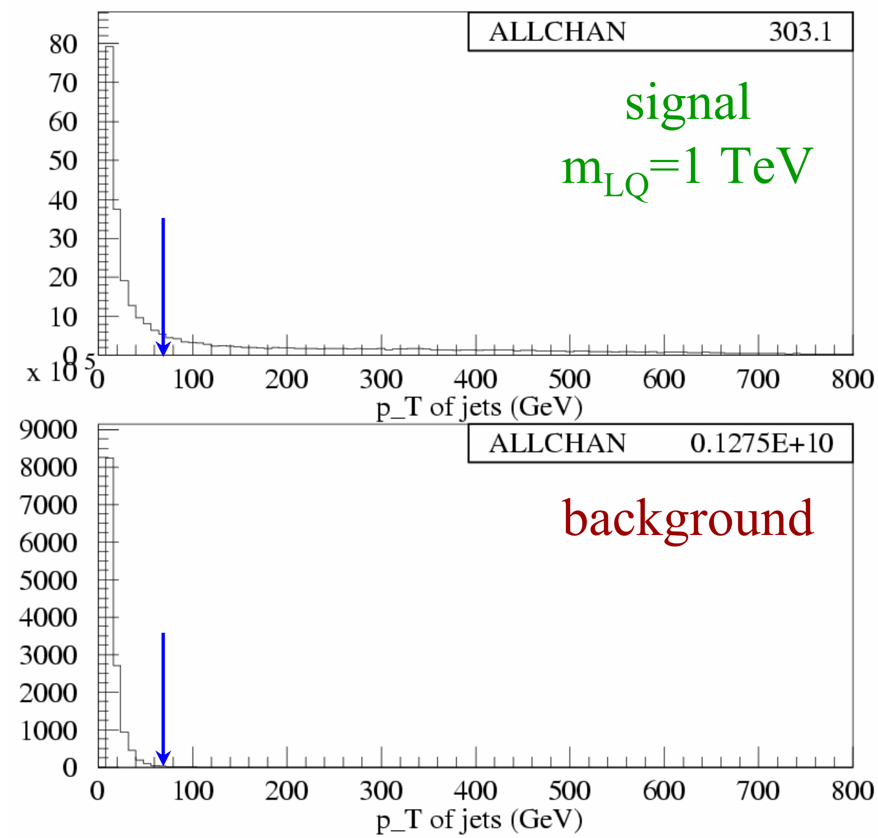
Process	σ×BR (pb)
Zjet (ννjj)	22 000
Wjet (ℓνjj)	38 400
tt (ℓνbℓνb)	51.6
ZZ (ννbb)	0.6
ZW (bblν)	1.3
ZW (ννjj)	3.6
WW (ℓνjj)	30.5

- Background
  - Zjet background irreducible
  - Main backgrounds: tt, ZZ, ZW(bbℓν)
  - All other SM backgrounds are eliminated from b-tagging and lepton-veto

vvjj: selection criteria (tentative)

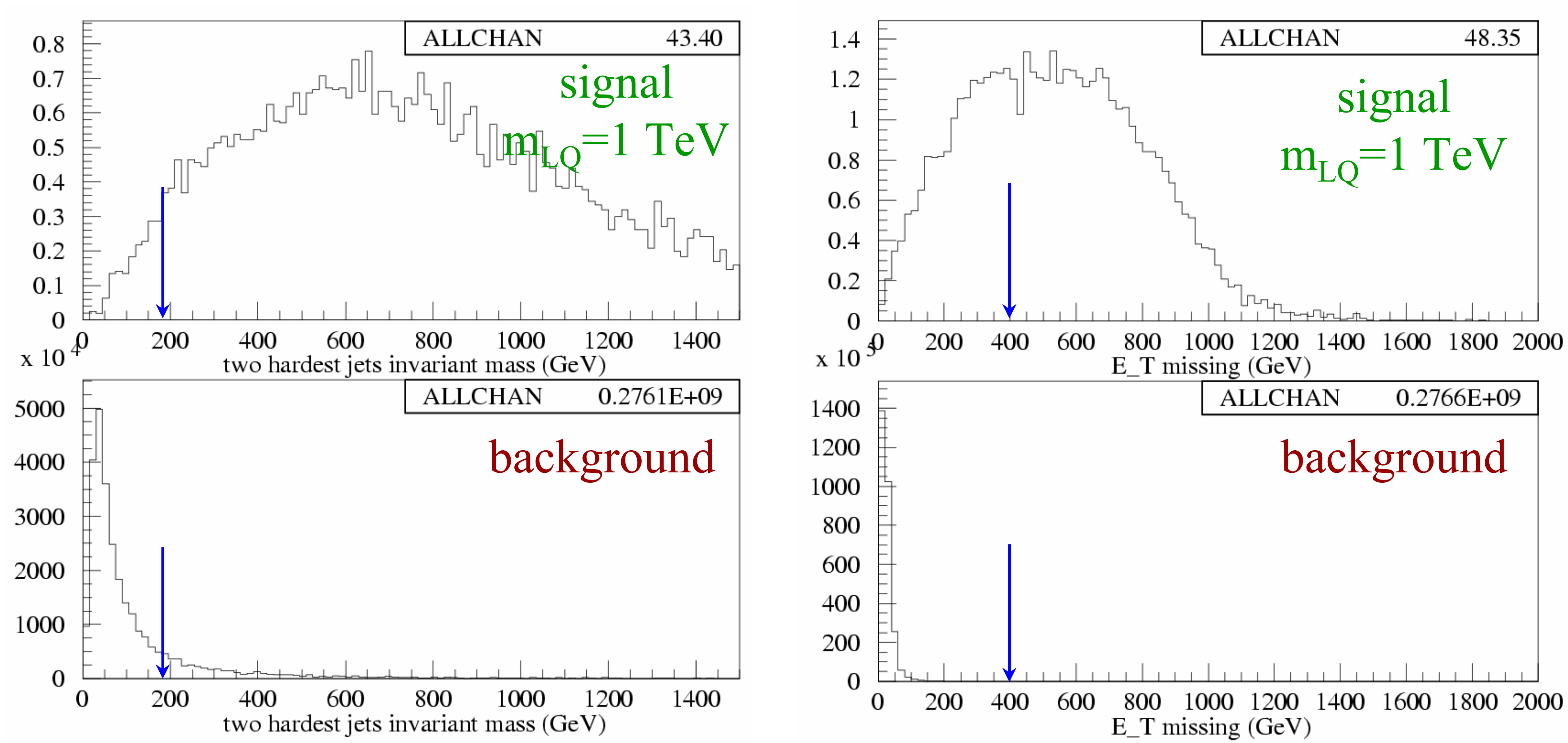
- Selection criteria maximize significance for high leptoquark masses

  - At least 2 b-jets with $p_T > 70$ GeV and $|\eta| < 5.0$
  - No isolated leptons
  - $m_{jj} > 180$ GeV
  - $E_T^{miss} > 400$ GeV
  - $30^o < \varphi_{j\text{-}j} < 150^o$ for the two leading jets
  - $\varphi_{j\text{-}pTmiss} > 60^o$ for the two leading jets



vvjj: selection variables

- Variables shown before applied cuts (p_T^{jet}>10 GeV)
- Main cut: large E_T^{miss} due to escaping neutrinos

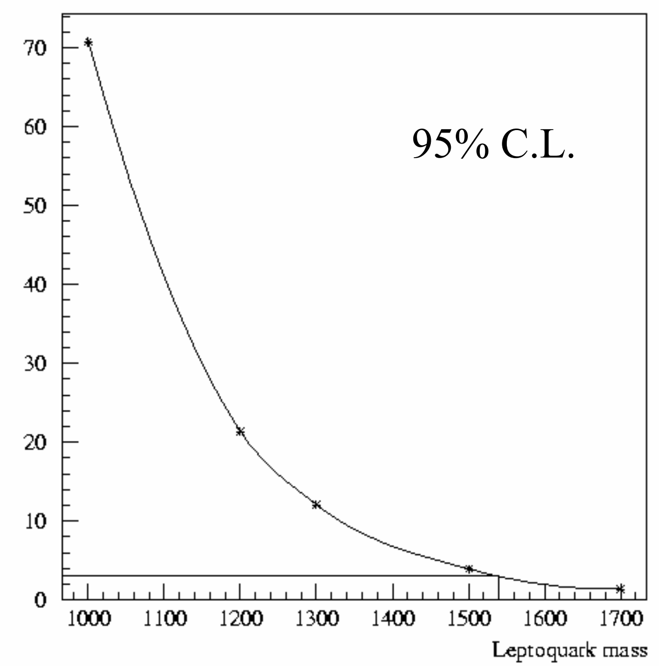


vvjj significance

- Third generation leptoquarks: LQ LQ → vbvb
- Integrated luminosity $\int L=30\ fb^{-1}$
- No mass peak is reconstructed (only excess of events)
- Signal observable for masses up to m_{LQ}=1.3 TeV
- Exclusion limits (95% C.L.) up to m_{LQ} ~1.5 TeV

Preliminary

m_{LQ} (TeV)	σ x BR (fb)	eff. (%)	signal	SM bgd	S/√B
1.0	4.84	48.7	70.7	3.4	38.3
1.2	1.28	55.5	21.3	3.4	11.5
1.3	0.68	59.1	12.1	3.4	6.5
1.5	0.21	61.6	3.9	3.4	2.1
1.7	0.07	64.3	1.4	3.4	0.7



LQ search-Conclusions

- ATLAS at the LHC is going to explore the existence of leptoquarks with masses up to m_{LQ}~1.5 TeV independently of the Yukawa coupling
- 1st- or 2nd-generation scalar leptoquarks can be observed up to $m_{LQ} \approx 1.3$ TeV, in the LQ $LQ \to \ell\ell qq$ channel (if $\beta=1$)
- 3rd-generation LQs are observable up to $m_{LQ} \approx 1.3$ TeV, if they only couple to a **neutrino** & a **b-quark**, via the LQ $LQ \to \nu\nu bb$ channel
- Possibility to study other species of LQs by combining/investigating other channels

ATLAS Exotics WG

Plans for Rome Workshop

It is the right time to ask ourselves the following question:

What exotics can we do for Rome?

How are we going to proceed ?

Plans for Rome Workshop (cont.)

- Most of the exotics topics have already been done with ATLFAST
- Our goal is to to redo most of them with full simulation using Rome-Layout
- Study reconstruction with Rome-Layout, including noise and pile-up
- Develop tools for TeV scale analyses
- **Also detector studies at the TeV scale:**

No Physics without good understanding of the detector

energy Calibration
Reconstruction efficiency
Refining energy resolution
Charge misidentification
for electrons and muons
PID
b-tagging
- Forward-jets tagging

→ For High Energy Particles

the same priority as physics analyses

- Studies of the detector response at the TeV scale **is needed not only for Rome, but beyond**.
- **The Rome Workshop will be a golden opportunity to test the software and the computing model**

What Exotics for Rome

❑ Z', G*, H++....	di-leptons channels
❑ Signal of W', Z', excited quarks,.....ect	di-jets channels
❑ Signals of heavy scalar Higgs, Strong Dynamics VV, G*, Z',...	WW, WZ, ZZ
❑ Little Higgs Model, technipions	Wb, Zb, Hb
❑ Excited fermions	γ+jets, lγ lZ
❑ Leptoquarks	l+jets
❑ LED, leptoquarks	MET + jets
❑ Non resonante excess of events:	ll, γγ, jj, tt
❑ Black Holes:	all SM particles

Invitation

Leptoquarks

Compositeness

Technicolor

Extra Dimensions

Little Higgs

LFV

New particles

SERVE YOURSELF

CONCLUSIONS

- The search for the Higgs boson(s) and the search for the Supersymmetric particles can be considered as "safe searches", as they **fit well** into today's theoretical fashions.

- In addition to safe searches one might be tempted to search for less fashionable *exotic new phenomena*
  - Such new phenomena,
    - like new forces leading to CP violation or lepton number violation, lepton-quark structure

  might simply exist because they are not forbidden by any fundamental reason.

- Such searches are often **motivated** by the possibility that the guidance from our theoretical methods has not yet reached a mature status.

These exotic searches require certainly a "gambling mentality" as they lead to **"all or nothing"** results.

As an Epilogue

LEP 2 HERA Tevatron LHC & NLC

? ? ?

desert ?

New Physics ?

- **All hopes are shifted to future colliders !**

" Ithaki gave us the rewarding travel ……! "

C. Kavafys