SUSY or not, what is the evidence? Status and perspectives of collider searches – Part IA

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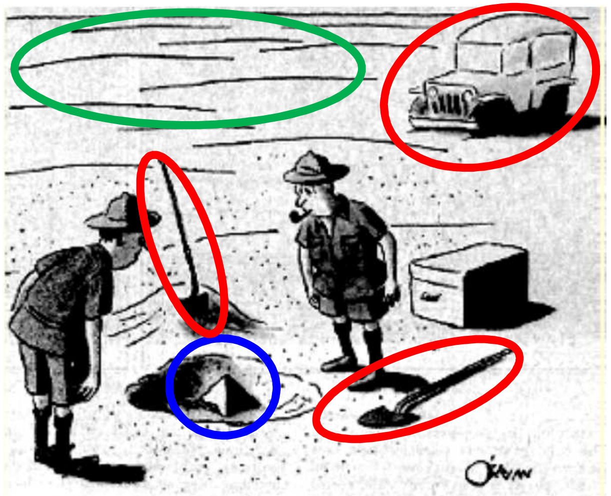
Lectures at Niels Bohr Institute



"This could be the discovery of the century. Depending, of course, on how far down it goes"

Part I (2 lectures)
Motivation + the tools to dig
Part II (3 lectures + 2 exercises)
Direct SUSY searches at LHC
Part III (1 lecture)
Other searches, overview and prospects

W 30-Oct	Th 31-Oct	Fr 01-Nov
--	Lecture IIA **Exercise 1**	Lecture IIC **Exercise 2**
Lecture IA Lecture IB	**Exercise 1** Lecture IIB	**Exercise 2** Lecture III

Who am I ?

❑ Member of ATLAS since 1998

1998-2010: Building, qualification and commissioning of the ATLAS Electromagnetic liquid argon calorimeter with cosmics and first data. Co-editor of the paper summarizing the performance of the ATLAS Liquid Argon Calorimeter [EPJ **C70** (2010) 723].

2005-2010: Preparation of physics analysis in top and beyond the Standard Model (W', Z' and Supersymmetry) physics.

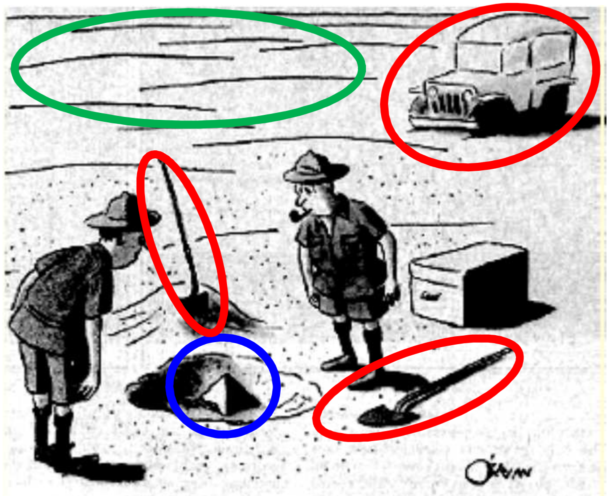
2010: Co-editor of the CONF notes / paper measuring the first W and Z cross-section [JHEP **1012** (2010) 060].

2010-2012: Co-convenor of the ATLAS Supersymmetry Working group. 50 articles submitted to journals ($\sim$ 20% of ATLAS articles with collision data).

- Lecture in the 100th Les Houches Summer School "Particle Physics and Cosmology"
  - ✓ Slides (http://pralavop.web.cern.ch/pralavop/20130724_PralavorioLesHouchesPartI.pdf, http://pralavop.web.cern.ch/pralavop/20130725_PralavorioLesHouchesPartII.pdf) and proceedings (http://pralavop.web.cern.ch/pralavop/LesHouchesPralavorio.pdf)
- Writing **"Lessons for SUSY from the LHC after the first run"**, summarizing ATLAS+CMS SUSY results after run I for the EPJC special edition "SUSY after the Higgs discovery"

  → To appear Feb 2014
- Bibliography page : **http://www.cern.ch/pralavop/phd.html**

About these lectures



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- Each lecture should last 1:00 max [~30-40 slides per lecture] → Don't hesitate to interrupt me to ask questions during the lecture.
- We have also time for questions at the end of the lecture, during coffee break, via mail (pascal.pralavorio@cern.ch).

Lectures Part I

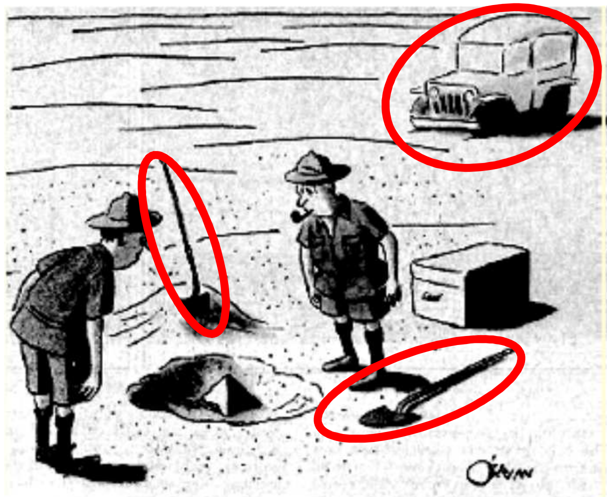
❑ **Part I : Ingredients needed for a SUSY search at LHC** → "What drives the sensitivity to SUSY at LHC ?"

400 m hurdles
➔ 10 hurdles to clear

A
1. Scale and New Physics
2. Guide to find New physics
3. Detector description
4. Object Reconstruction
5. Monte Carlo Simulation

B
6. Discriminating variables
7. Background Estimation
8. Fit Results
9. Result Interpretation
10. Signal Region Definition

"Pure logical thinking cannot yield us any knowledge of the empirical world; all knowledge of reality starts from experience and ends in it."
A. Einstein (1933)



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Motivation + the tools to dig

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Scale and new physics (1)

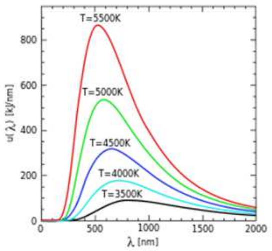
G_N = 6.7 10^{-11} $kg^{-1}.m^3.s^{-2}$ (1687), **c** = 3 10^8 $m.s^{-1}$, α = 7.10^{-3}

❑ Beginning of XXth century reveals 3 previously unknown scales

- New physics closely connected to these new scales !

Planck scale (1900)

Solve blackbody problem



$\hbar$ = 6.6 10^{-25} GeV.s

$\Lambda_{Pl} = \sqrt{\hbar c/G_N}$
= 1.9 10^{19} GeV

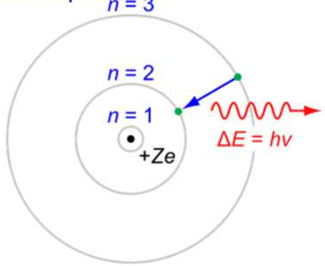
Quantum mechanics breaks down → quantum gravity

Early cosmology (gravitational waves) ??
Black holes ???

Bohr scale (1913)

Solve classical atom problem

www.nature.com/bohr100



$$a_0 = \frac{4\pi\varepsilon_0\hbar^2}{m_e e^2} = \frac{\hbar}{m_e\, c\,\alpha} \sim \mathrm{O}(10^{-10})\ \mathrm{m}$$

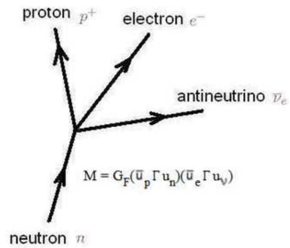
$\Lambda_{Atom} = \hbar c/a_0$
= 1.9 10^{-6} GeV

Classical mechanics breaks down → quantum mechanics

Confirmed since 1914

Fermi scale (1933)

Describe the neutron decay



G_F = 1.2 10^{-5} GeV^{-2}

$\Lambda_{Weak} = 1/\sqrt{G_F}$
= 3.10^2 GeV

ElectroWeak symmetry breaks down → Weak+EM

Confirmed since 2012!

Scale and new physics (2)

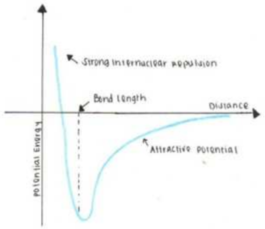
G_N = 6.7 10^{-11} $kg^{-1}.m^3.s^{-2}$ (1687), **c** = 3 10^8 $m.s^{-1}$, **α** = 7.10^{-3}

❑ Later in XXth century, 2 other unknown scales appears

- New physics closely connected to these new scales !

Yukawa scale (1935)

Describe the proton-neutron interaction



$$r_0 = \frac{\hbar}{M_\pi c} = 1.4 \cdot 10^{-15}\,\mathrm{m}$$

$$M_\pi c^2 \simeq 140\,\mathrm{MeV}$$

$$\Lambda_{Yuk} \sim \Lambda_{QCD} = O(10^{-1})\ \mathrm{GeV}$$

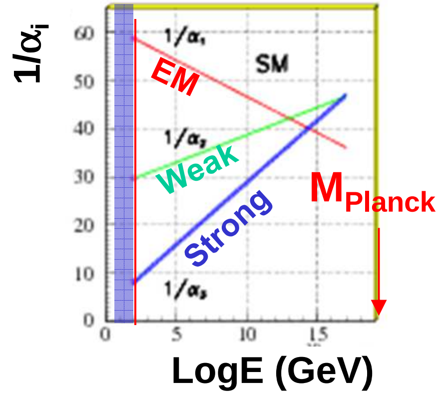
Chiral symmetry breaks down because of massive quarks [Nambu 1960] → QCD

Explore thoroughly by 50-60's colliders

GUT scale (1974)

Solve the quantized electric charge (e – p) problem

SO(10) ⊃SU(5)⊃ SU(3)xSU(2)xU(1)



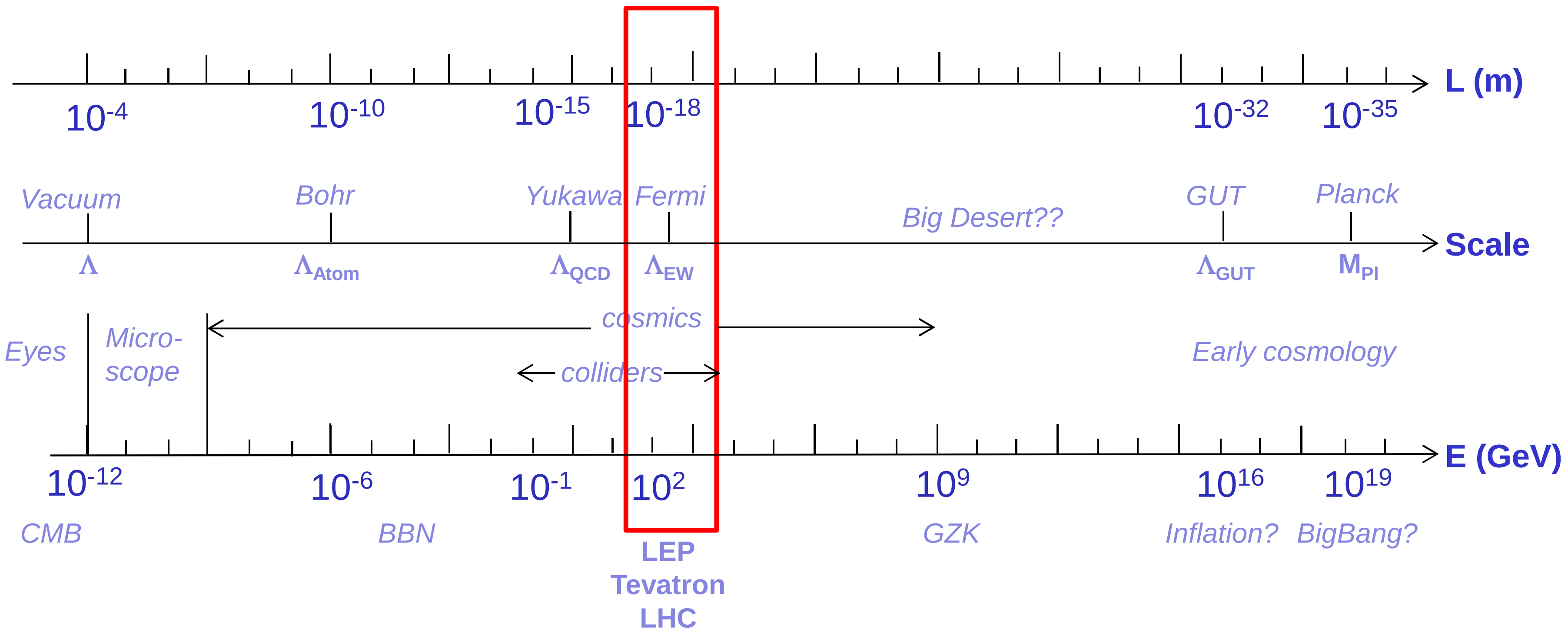
$$\Lambda_{GUT} = 10^{15\text{-}16}\ \mathrm{GeV}$$

EM, Weak and Strong forces unify → only one charge

Early cosmology (inflation) ??

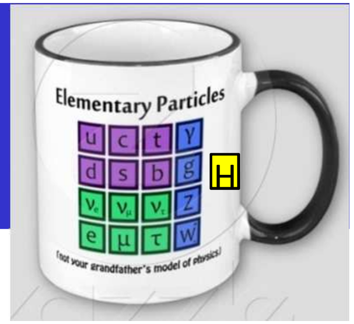
Scale and new physics (3)

❑ **Recap of the infinitesimal scales**



Weak scale is the highest scale that we can study systematically (i.e. at **colliders**)

SM and new physics (1)



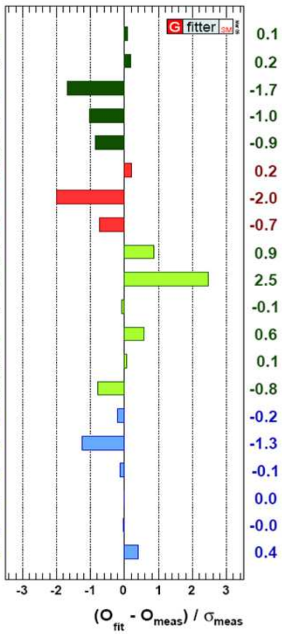
- **Standard Model (SM) is beautifully alive up to Λ_{EW} …**
  - … and now complete (!) but suffers from several diseases

The Good	The Bad	The Ugly

The Good

Predictive + agreement w data

Parameter	Input value	Fit value
M_Z [GeV]	91.1875 ± 0.0021	91.1876 ± 0.0021
Γ_Z [GeV]	2.4952 ± 0.0023	2.4956 ± 0.0015
σ^0_{had}	41.540 ± 0.037	41.478 ± 0.014
R^0_l	20.767 ± 0.025	20.741 ± 0.018
$A^{0,l}_{FB}$	0.0171 ± 0.0010	0.01624 ± 0.0002
A_l (LEP)	0.1465 ± 0.0033	0.1473 ± 0.0009
A_l (SLD)	0.1513 ± 0.0021	$0.1465^{+0.0007}_{-0.0010}$
$\sin^2\phi^l_{eff}(Q_{FB})$	0.2324 ± 0.0012	$0.23151^{+0.00010}_{-0.00012}$
$A^{0,c}_{FB}$	0.0707 ± 0.0035	0.0737 ± 0.0005
$A^{0,b}_{FB}$	0.0992 ± 0.0016	$0.1032^{+0.0007}_{-0.0006}$
A_c	0.670 ± 0.027	$0.6679^{+0.00042}_{-0.00036}$
A_b	0.923 ± 0.020	$0.93463^{+0.00007}_{-0.00008}$
R^0_c	0.1721 ± 0.0030	0.17225 ± 0.00006
R^0_b	0.21629 ± 0.00066	0.21577 ± 0.00005
$\Delta\alpha^{(5)}_{had}(M_Z^2)$	2768 ± 22	2764^{+22}_{-21}
M_W [GeV]	80.399 ± 0.023	$80.371^{+0.008}_{-0.011}$
Γ_W [GeV]	2.098 ± 0.048	2.092 ± 0.001
$\overline{m}_c$ [GeV]	1.25 ± 0.09	1.25 ± 0.09
$\overline{m}_b$ [GeV]	4.20 ± 0.07	4.20 ± 0.07
m_t [GeV]	173.1 ± 1.3	173.6 ± 1.2

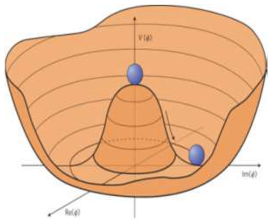


The Bad

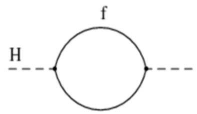
Hierarchy/Naturalness problem

Higgs (J=0) couples to all vacuum massive particles, but not protected by any symmetry

J=1 massless when gauge sym. exact
J=1 mass protected by gauge sym. (broken)
J=½ mass protected by chiral sym. (broken)



Radiative corrections to Higgs mass



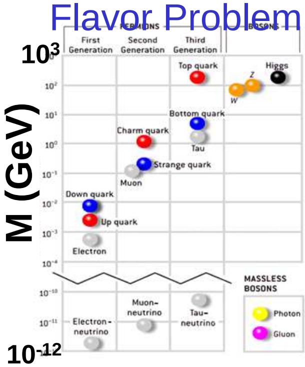
$$\Delta M^2 = \kappa \Lambda^2_{NP}$$

Λ=New Physics Scale

Neutrino are massive (originally m_ν=0)

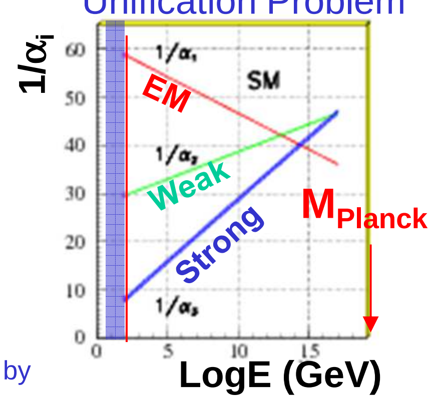
The Ugly

Flavor Problem



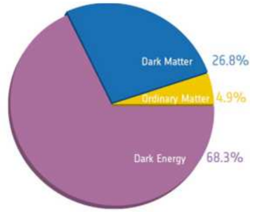
Problem of CP Violation by strong force (Axion ?)

Unification Problem



How to include gravity ?

Dark sector ?



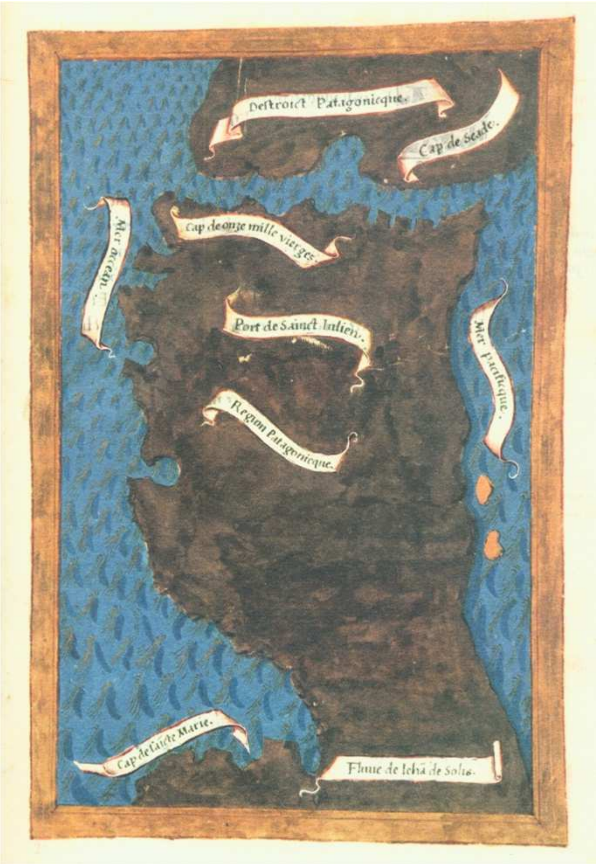
Why ~no anti-matter today ?

New physics should lie beyond SM !

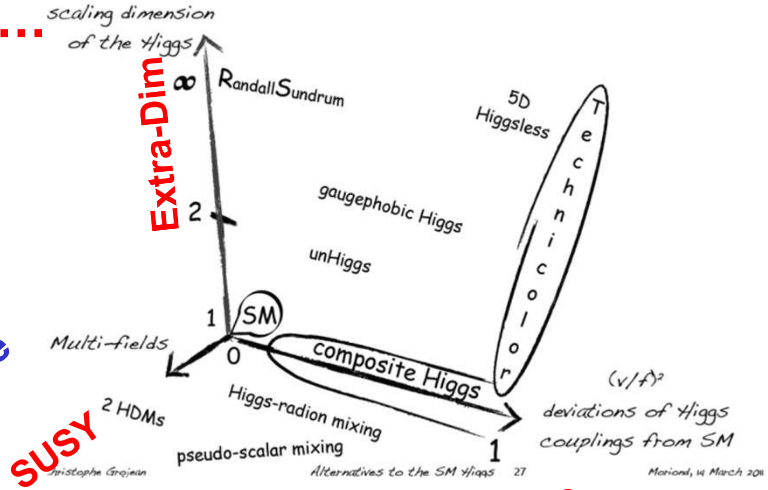
SM and new physics (2)

❑ **Use naturalness to discover New Physics …**

Strait of Magellan (Pigafetta, 1520)



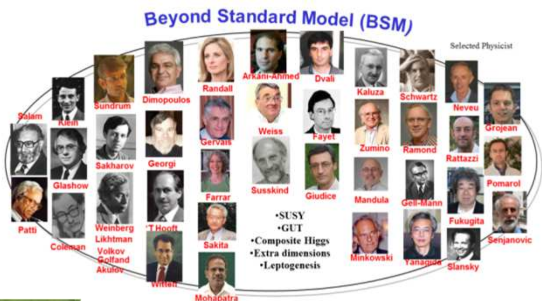
"Conqueror of the Sea: the story of Magellan" S. Zweig



C. Grojean, Moriond EW (March 2011)

Composite

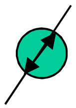
New Physics rugby game



SM and new physics (3)

H. Murayama (hep-ph/0002232) G. Giudice (0801.2562)

- **… because we can guess the Scale of New Physics (Λ) !**
  - ✓ Several criteria exist : here use Rad. Corrections(2) < $m_{Part.}$ (2)



r_e

e

1. Electron self-energy

If no NP $r_e > r_{nucleus}$!!
Need $\Lambda_{NP} \sim 1/r_e$

electrostatic energy of a sphere of radius r: $E \approx \frac{\alpha}{r} < m_e c^2 \Rightarrow \Lambda < \frac{m_e}{\alpha} \approx 70\ \text{MeV}$

magnetic energy of spinning sphere: $E \approx \frac{\mu^2}{r^3}, \mu = \frac{e\hbar}{2m_e c} < m_e c^2 \Rightarrow \Lambda < \frac{m_e}{\alpha^{1/3}} \approx 3\ \text{MeV}$

New physics (positron) at $m_e = 0.5\ \text{MeV}$ $[(m_e)_{obs} \sim (m_e)_0 + \kappa m_e \ln(m_e rc)]$

~9% if $r=1/M_{Pl}$

π

2. Pion mass difference

QED contribution: $\frac{3\alpha}{4\pi}\Lambda^2 < M^2_{\pi^+} - M^2_{\pi^0} \Rightarrow \Lambda < 850\ \text{MeV}$

New physics (hadrons) at $M_\rho = 770\ \text{MeV}$

K

3. Neutral kaon mass difference

$$\frac{G_F^2 f_K^2}{6\pi^2}\sin^2\theta_c \Lambda^2 < \frac{M_{K_L^0} - M_{K_S^0}}{M_{K_L^0}} \Rightarrow \Lambda < 2\ \text{GeV}$$

New physics (charm) at $m_c = 1.2\ \text{GeV}$

Amazing successes when reinterpreting the past ! Nature seems to like naturalness …

Reminder ($\hbar=c=\varepsilon_0=1$):
$m_e \sim 0.5$ MeV
$\alpha = e^2/4\pi \sim 7.10^{-3}$
$r_e \sim 3.10^{-15}$ m

?

The weak scale

$$\delta m_h^2 = \frac{3G_F}{4\sqrt{2}\pi^2}\left(4m_t^2 - 2m_W^2 - m_Z^2 - m_h^2\right)\Lambda^2 < m_h^2 \Rightarrow \Lambda < 500\ \text{GeV}$$

New physics at the EW scale !!

SM and new physics (4)

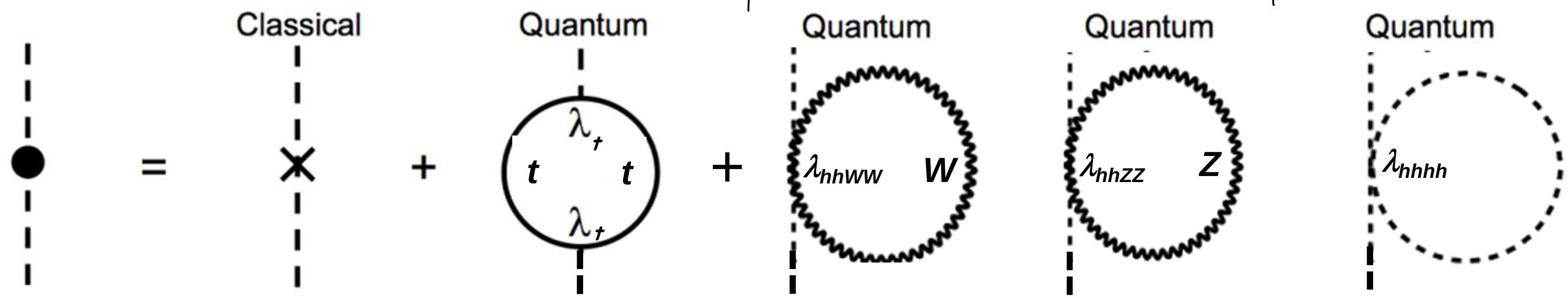
❑ Can we restore Higgs naturalness ?

Most dangerous !

Fermion Yukawa coupling $\lambda_t = \sqrt{2} m_t / v \approx 1$

Gauge coupling $\lambda_{hhVV} = 2m_{W,Z}^2/v^2$

Self-coupling $\lambda_{hhhh} = 3m_h^2/v^2$



$$m_h^2 = (m_h^2)_0 - \frac{3G_F}{4\sqrt{2}\pi^2}(4m_t^2)\Lambda_{NP}^2 + \frac{3G_F}{4\sqrt{2}\pi^2}(2m_W^2 + m_Z^2 + m_h^2)\Lambda_{NP}^2$$

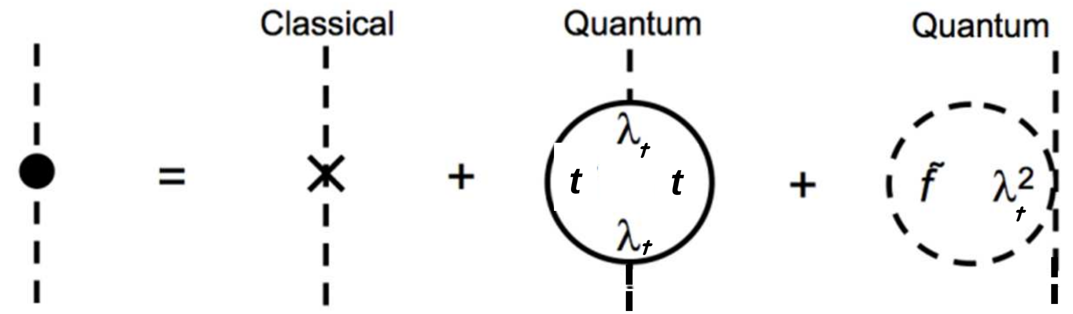
$\Lambda_{NP}=M_{Pl}$ ➔ $(125)^2$ = 36,127,890,984,789,307,394,520,932,878,928,933,023 – 36,127,890,984,789,307,394,520,932,878,928,917,398

Note that Vector/Scalar Bosons have opposite sign compare to fermions

SM and new physics (4')

❑ Can we restore Higgs naturalness ?

- 1970 : Add a new broken symmetry (SUSY) to SM to protect Higgs mass
- 1979 : Higgs is not elementary but composite, first manifestation of a new strong force
- 1998-99 : Extra spatial Dimensions, where gravity propagates in, reformulate the problem



Fermion Yukawa coupling

$y_t = \lambda_t = \sqrt{2} m_t / v$

$\sqrt{2} G_F = v^2$

$$m_h^2 = (m_h^2)_0 - \frac{3G_F}{4\sqrt{2}\pi^2}(4m_t^2)\Lambda_{NP}^2 + \frac{3G_F}{4\sqrt{2}\pi^2}(4m_{\tilde{t}}^2)\Lambda_{NP}^2$$

$$+ \frac{3G_F}{\sqrt{2}\pi^2}(m_t^2 - m_{\tilde{t}}^2)\ln(\Lambda_{NP}/m_h)$$

Yes ! if O(weak-scale) mass for SUSY top partners and similarly for W, Z and Higgs…

SM and new physics (4'')

NPB306 (1988) 63; JHEP09 (2012) 035

Can we restore Higgs naturalness ?

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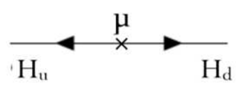
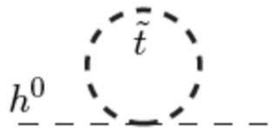
$$m_Z^2 = -2(m_{h_u}^2 + |\mu|^2)$$

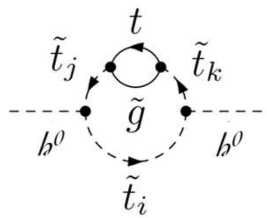


$$\delta m_{h_u}^2 = -\frac{3y_t^2}{4\pi^2} m_{\tilde{t}}^2 (1 + a^2/2) \log \frac{\Lambda}{m_{\tilde{t}}}$$



Guess the mass of the new particles

$$\delta m_{\tilde{t}}^2 = -\frac{8\alpha_s}{3\pi} M_3^2 \log \frac{\Lambda}{m_3}$$



Note: Gravitino, sleptons and 1/2nd generation squarks not constrained by Naturalness

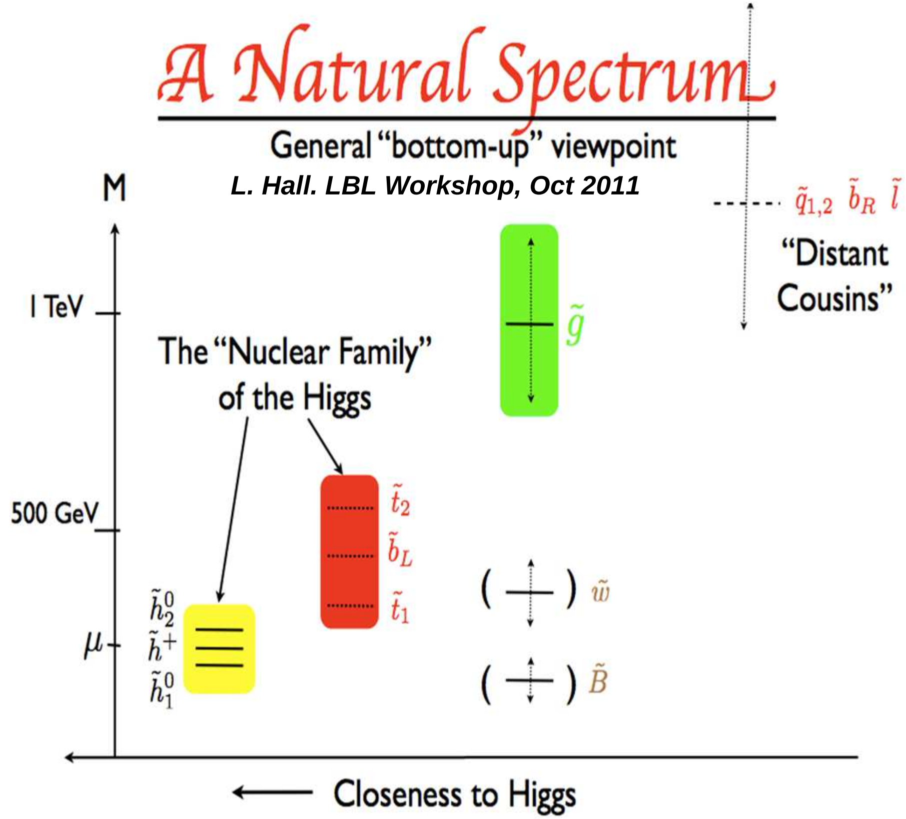
… and m(gluino)<1.5 TeV to protect the stop mass !

SM and new physics (5)

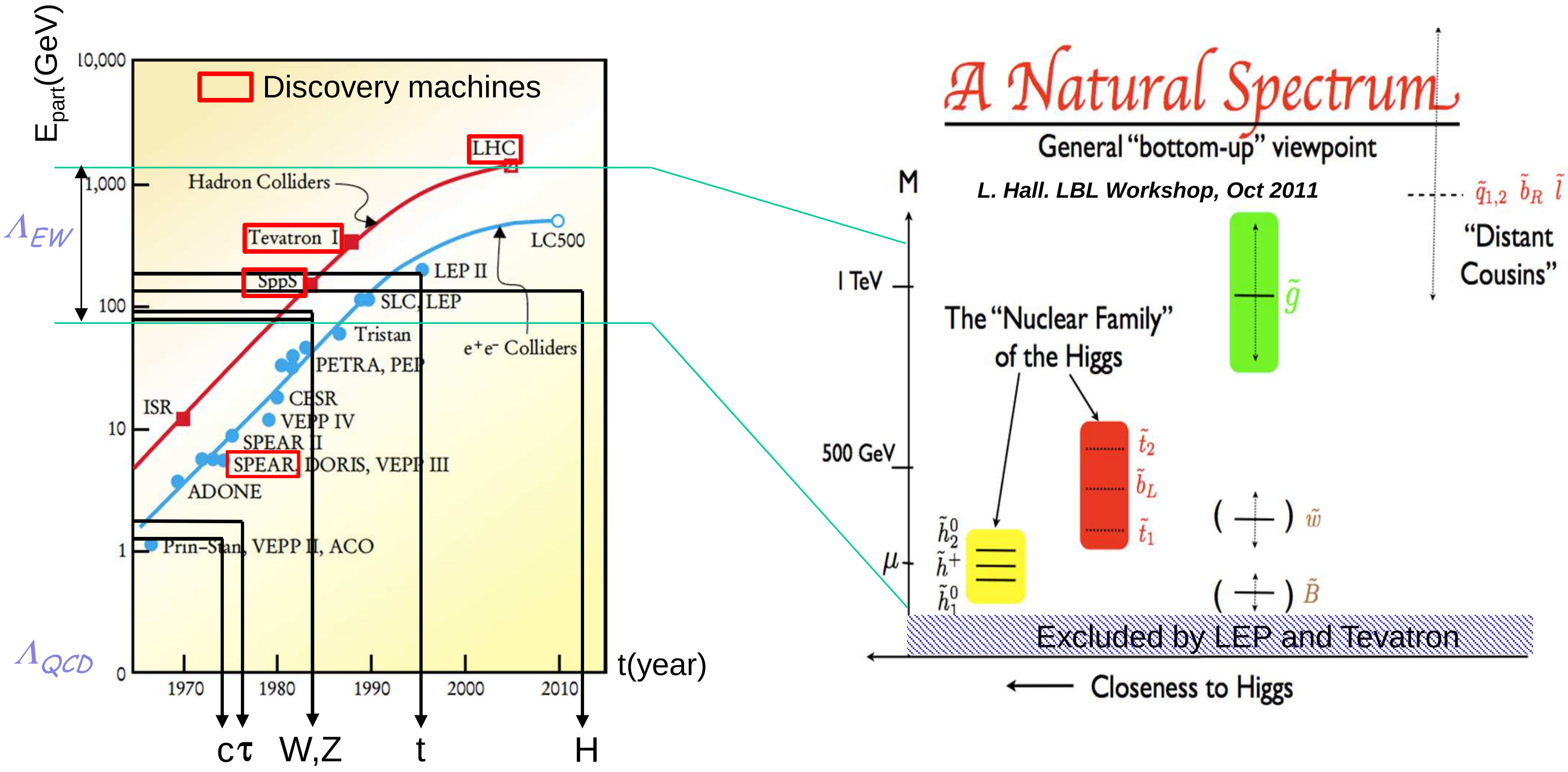
Can we restore naturalness ?

- 1970 : Add a new broken symmetry (SUSY) to SM to protect Higgs mass
- 1979 : Higgs is not elementary but composite, first manifestation of a new strong force
- 1998-99 : Extra spatial Dimensions, where gravity propagates in, reformulate the problem

For less than 10% tuning



SM and new physics (6)

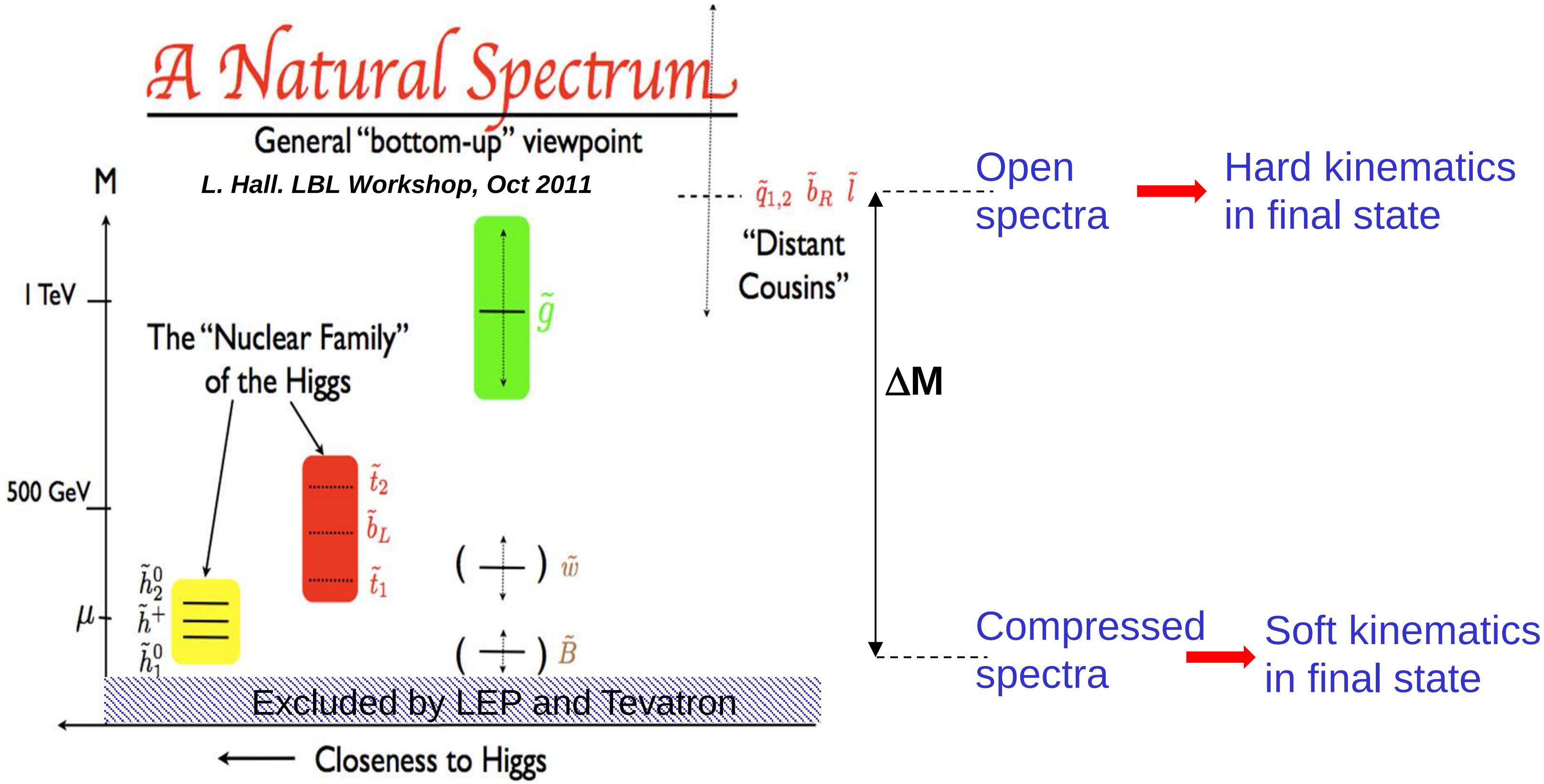


LHC* can cover the **best motivated** SUSY phase space **for the first time** !!

*The largest and the most complex machine ever constructed by humans (From Nobel Prize 2013 Press release)

Framework of these lectures

Can we **discover** (at least) one super-partner **or invalidate** the Natural version of MSSM ?



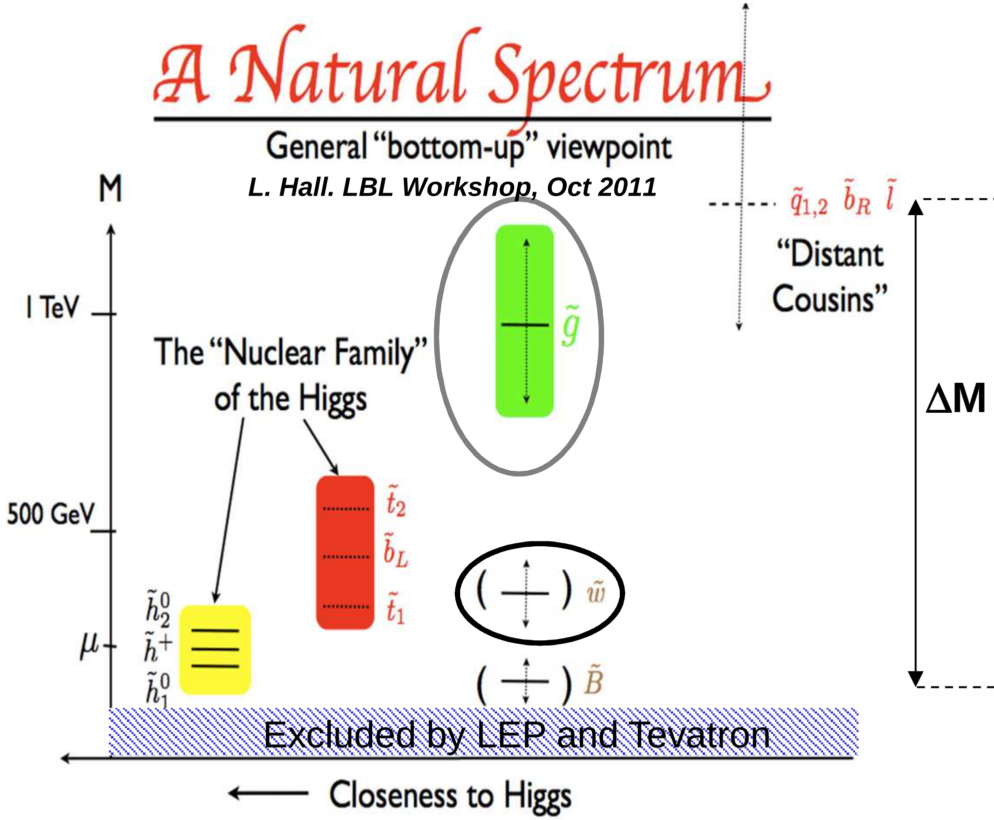
Systematic exploration based on the >200 public SUSY analyses (ATLAS+CMS)

Framework of these lectures

Exercise 1 + Homeworks

Can we **discover** (at least) one super-partner **or invalidate** the Natural version of MSSM ?

Exercise 2 + Homeworks



Open spectra → Hard kinematics in final state

Compressed spectra → Soft kinematics in final state

Systematic exploration based on the >200 public SUSY analyses (ATLAS+CMS)

Part I : Teaser

EW Neutral Current (Z^0)

Can we **discover** (at least) one super-partner **or invalidate** the ~~Natural version of MSSM ?~~

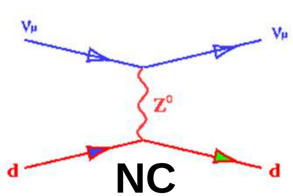
1- Need to be sure of your tools (background estimate, stat, …)

The results that were obtained from this small CERN chamber (Block *et al.* 1964) included a limit on the ratio of "elastic" neutral-current (NC) events to charged-current (CC) events: $\sigma(\nu_\mu + p \rightarrow \nu_\mu + p)/\sigma(\nu_\mu + n \rightarrow \mu^- + p) < = 0.03$ for events with proton momentum above 250 MeV/c. The accepted ratio is about 0.12. The CERN result was just wrong, following a book-keeping error (the actual 90% confidence limit was < 0.09). As is often the case in physics, the error was uncovered by a graduate student, Michel Paty from Strasbourg, who found a limit < = 0.20 and put this number in his thesis (Paty, 1965). The CERN group intended to publish an erratum, but (since there seemed to be little interest in our limit) we decided to wait for the results from a forthcoming propane run, since that would measure scattering from free as well as bound protons, and we could exploit the better kinematic constraints. However, the propane run was delayed by more than two years and the corrected limit for the ratio of < 0.12 ± 0.06 was not published until 1970 (Cundy *et al.* 1970).

2- Need to have a well designed search strategy

Gargamelle's priorities

1. W search
2. deep inelastic scattering, scaling
3. current algebra sum rules, CVC, PCAC
4. Diagonal Model
5. $\Delta S = 1$ processes, inverse hyperon decay, $\overline{\nu_\mu} + p \rightarrow \Lambda + \mu^+$
6. inverse muon decay, $\nu_\mu + e^- \rightarrow \mu^- + \nu_e$
7. electron–muon universality
8. neutral-current search
9. form factors in exclusive reactions
10. search for heavy leptons



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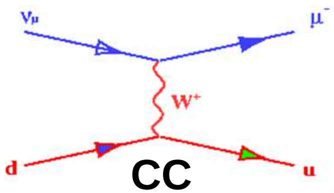
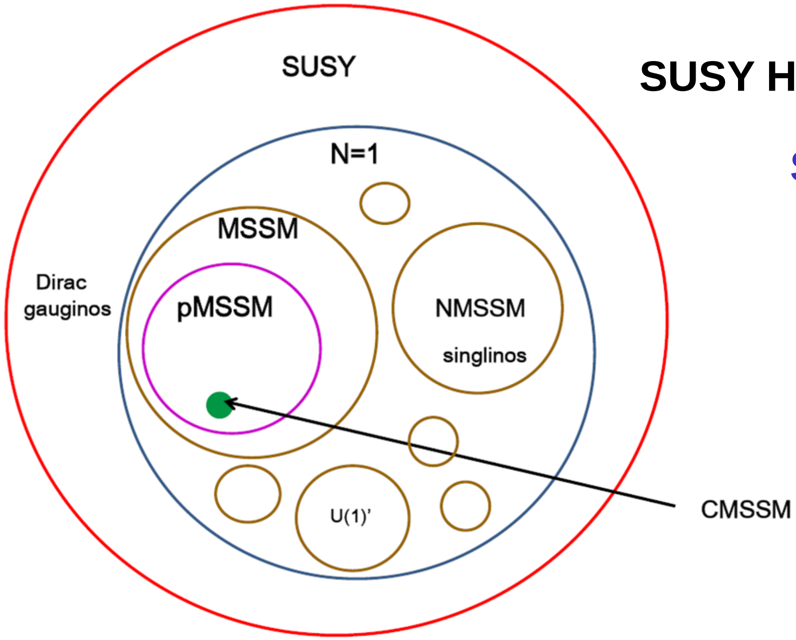


CC

That's why we will spend some time on understanding carefully all our tools today

SUSY Framework (1)

SUSY Theory phase space



T. Rizzo (SLAC Summer Institute, 01-Aug-12)

Warning : Weak Scale SUSY is only a small part of SUSY phase space !!

MSSM=Minimal Supersymmetry Standard Model (i.e. based on parsimony principle)

MSSM a.k.a Weak Scale SUSY :
29 sparticles + 4 Higgs undiscovered

	Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
SUSY Higgses	Higgs bosons	0	+1	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$
Strong SUSY	squarks	0	−1	$\tilde{u}_L\ \tilde{u}_R\ \tilde{d}_L\ \tilde{d}_R$	(same)
				$\tilde{s}_L\ \tilde{s}_R\ \tilde{c}_L\ \tilde{c}_R$	(same)
				$\tilde{t}_L\ \tilde{t}_R\ \tilde{b}_L\ \tilde{b}_R$	$\tilde{t}_1\ \tilde{t}_2\ \tilde{b}_1\ \tilde{b}_2$
Weak SUSY	sleptons	0	−1	$\tilde{e}_L\ \tilde{e}_R\ \tilde{\nu}_e$	(same)
				$\tilde{\mu}_L\ \tilde{\mu}_R\ \tilde{\nu}_\mu$	(same)
				$\tilde{\tau}_L\ \tilde{\tau}_R\ \tilde{\nu}_\tau$	$\tilde{\tau}_1\ \tilde{\tau}_2\ \tilde{\nu}_\tau$
	neutralinos	1/2	−1	$\tilde{B}^0\ \tilde{W}^0\ \tilde{H}_u^0\ \tilde{H}_d^0$	$\tilde{N}_1\ \tilde{N}_2\ \tilde{N}_3\ \tilde{N}_4$
	charginos	1/2	−1	$\tilde{W}^\pm\ \tilde{H}_u^+\ \tilde{H}_d^-$	$\tilde{C}_1^\pm\ \tilde{C}_2^\pm$
	gluino	1/2	−1	$\tilde{g}$	(same)
	goldstino (gravitino)	1/2 (3/2)	−1	$\tilde{G}$	(same)

R-parity (P_R or R_P)= -1 SUSY, +1 SM

SUSY Framework (2)

❑ Notations

- For neutralino and charginos I' ll use Greek or Capital Roman letter.
  - ✓ Sometimes I'll forget the tilde above the letter.
- LSP = Lightest Supersymmetric Particle. In this lecture LSP will be $\tilde{G}$ or $\tilde{\chi}_1^0$

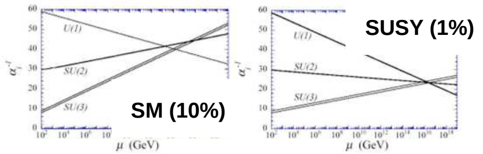
Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$
squarks	0	−1	$\tilde{u}_L\ \tilde{u}_R\ \tilde{d}_L\ \tilde{d}_R$	(same)
			$\tilde{s}_L\ \tilde{s}_R\ \tilde{c}_L\ \tilde{c}_R$	(same)
			$\tilde{t}_L\ \tilde{t}_R\ \tilde{b}_L\ \tilde{b}_R$	$\tilde{t}_1\ \tilde{t}_2\ \tilde{b}_1\ \tilde{b}_2$
sleptons	0	−1	$\tilde{e}_L\ \tilde{e}_R\ \tilde{\nu}_e$	(same)
			$\tilde{\mu}_L\ \tilde{\mu}_R\ \tilde{\nu}_\mu$	(same)
			$\tilde{\tau}_L\ \tilde{\tau}_R\ \tilde{\nu}_\tau$	$\tilde{\tau}_1\ \tilde{\tau}_2\ \tilde{\nu}_\tau$
neutralinos	1/2	−1	$\tilde{B}^0\ \tilde{W}^0\ \tilde{H}_u^0\ \tilde{H}_d^0$	$\tilde{N}_1\ \tilde{N}_2\ \tilde{N}_3\ \tilde{N}_4$
charginos	1/2	−1	$\tilde{W}^\pm\ \tilde{H}_u^+\ \tilde{H}_d^-$	$\tilde{C}_1^\pm\ \tilde{C}_2^\pm$
gluino	1/2	−1	$\tilde{g}$	(same)
goldstino (gravitino)	1/2 (3/2)	−1	$\tilde{G}$	(same)

$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$

$\tilde{\chi}_1^{+/-}\ \tilde{\chi}_2^{+/-}$

SUSY Framework (3)

❑ A beautiful and straightforward extension of Standard Model

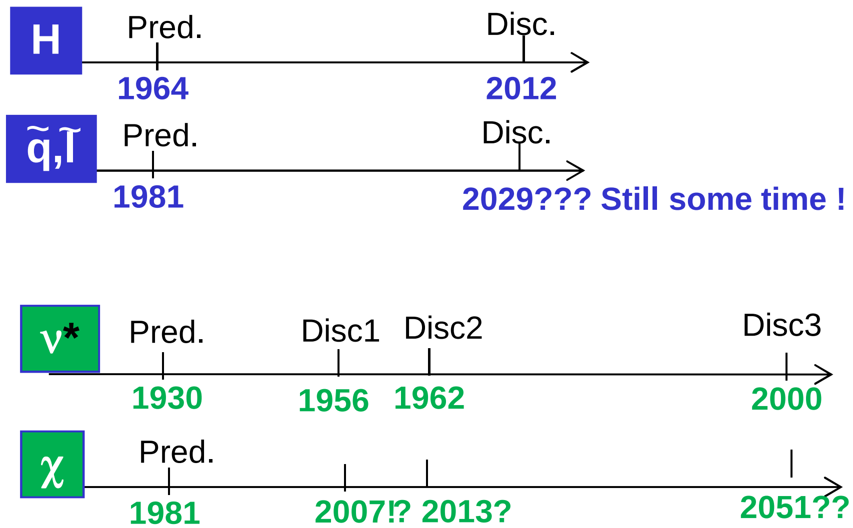
The Good	The Bad	The Ugly
Only possible extension of Poincare group (N generators) ▪ *Translation in Superspace $n_B = n_F$* $Q_\alpha \left\| \begin{matrix} \text{Fermion} \\ \text{Boson} \end{matrix} \right\rangle = \left\| \begin{matrix} \text{Boson} \\ \text{Fermion} \end{matrix} \right\rangle$ **Can solve most SM diseases** ▪ *Restore naturalness* ▪ *Include gravity* ▪ *Dark Matter candidate* ▪ *Unify forces at M~10^{16} GeV*  **Bonus:** ▪ *Predict a light Higgs Mass<130 GeV* ▪ *Perturbative → predictive*	**Predict many new scalar particles** ▪ *And also some Majorana particles* ▪ *Don't know their masses …* ▪ *… and experimentalists know they are very hard to find* **Add a new quantum number** ▪ *Call R-parity* ▪ *Prevent proton decay if conserved [MSSM hypothesis]… But not really justified theoritically*	**Escape 30 years of searches** **How to Break SUSY ?** ▪ *Softly broken (SB) in hidden sector* ▪ *SUGRA, GMSB, AMSB* **Flowed by new parameters !** ▪ *+ 105 in minimal version, mainly because of soft breaking*

SUSY Framework (3’)

- **Majorana particles and elementary scalars are generally hard to find …**
  - but constitute most of the SUSY particle spectrum !
  - So not alarming that it takes us some time …

MSSM a.k.a Weak Scale SUSY :
29 sparticles + 4 Higgs undiscovered

21 **scalars** + 5 **Majorana** + 3 **others fermions**



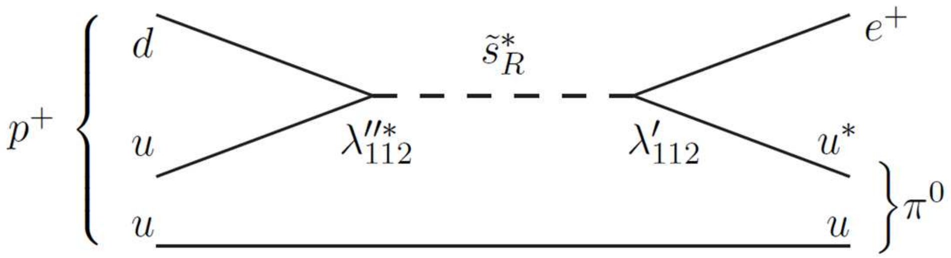
* Assuming Majorana Neutrino

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$
squarks	0	−1	$\tilde{u}_L\ \tilde{u}_R\ \tilde{d}_L\ \tilde{d}_R$	(same)
			$\tilde{s}_L\ \tilde{s}_R\ \tilde{c}_L\ \tilde{c}_R$	(same)
			$\tilde{t}_L\ \tilde{t}_R\ \tilde{b}_L\ \tilde{b}_R$	$\tilde{t}_1\ \tilde{t}_2\ \tilde{b}_1\ \tilde{b}_2$
sleptons	0	−1	$\tilde{e}_L\ \tilde{e}_R\ \tilde{\nu}_e$	(same)
			$\tilde{\mu}_L\ \tilde{\mu}_R\ \tilde{\nu}_\mu$	(same)
			$\tilde{\tau}_L\ \tilde{\tau}_R\ \tilde{\nu}_\tau$	$\tilde{\tau}_1\ \tilde{\tau}_2\ \tilde{\nu}_\tau$
neutralinos	1/2	−1	$\tilde{B}^0\ \tilde{W}^0\ \tilde{H}_u^0\ \tilde{H}_d^0$	$\tilde{N}_1\ \tilde{N}_2\ \tilde{N}_3\ \tilde{N}_4$
charginos	1/2	−1	$\tilde{W}^\pm\ \tilde{H}_u^+\ \tilde{H}_d^-$	$\tilde{C}_1^\pm\ \tilde{C}_2^\pm$
gluino	1/2	−1	$\tilde{g}$	(same)
goldstino (gravitino)	1/2 (3/2)	−1	$\tilde{G}$	(same)

SUSY Framework (3'')

❑ MSSM and R-parity

- Generally SUSY can easily make the proton to decay !



or e^+K^0, $\mu^+\pi^0$, μ^+K^0, $\nu\pi^+$, νK^+, …

τ_{Proton}<1 s for [$m_{\tilde{d}}$=O(1) TeV+ λ~O(1)] but experimentally $\tau_{Proton}>10^{39}$ s !!!

- 4 possible solutions:
  - ✓ R-Parity is a new conserved symmetry (RPC) ! → no proton decay, Sparticle decays ends with a LSP, sparticle pair produced, Dark Matter candidate (=Stable LSP). **MSSM Hypothesis**
  - ✓ R-Parity Violated (RPV) but small → Detector-stable or metastable particles
  - ✓ R-Parity Violated (RPV) but sizeable → "Prompt" Lepton or baryon number violation
  - ✓ Rparity continuous symmetry ~ N=2/N=1 SUSY.

R-Parity "nature" drives the experimental signatures

SUSY Framework (3''')

❑ The dark side of SUSY: How SUSY is broken ?

- Sparticles are not mass degenerate with particles → SUSY is broken
- Can not be spontaneously (like EW) → happens in a hidden sector

Supersymmetry breaking origin (Hidden sector)		MSSM (Visible sector)
vev <F>	Messenger	m_{Soft}

- **SUGRA** : $\langle F\rangle^{1/2}=10^{11}$GeV, Mess=Gravity → $m_{Soft}=\langle F\rangle/M_{Pl} \sim 0.1\text{-}1$ TeV
  - ✓ LSP = χ_1^0
- **AMSB** : $\langle F\rangle=m_{3/2}$, Mess=Gravity (at one/two loop) → $m_{Soft}=(\beta g_a/g_a)\langle F\rangle/M_{Pl} \sim 0.1\text{-}1$ TeV
  - ✓ LSP = χ_1^0 (Wino Like)
- **GMSB** : $\langle F\rangle^{1/2}=10^{4\text{-}5}$ GeV, Mess=10TeV Gauge Bosons → $m_{Soft}=\alpha_a\langle F\rangle/4\pi M_{Mess} \sim 0.1\text{-}1$ TeV
  - ✓ LSP = **Gravitino**

LSP nature drives the experimental signatures

SUSY Framework (3’’’)

❑ Some key parameters of MSSM in the 105 new ones !

MSSM: 29 sparticles + 4 Higgs undiscovered

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$
squarks	0	−1	$\tilde u_L\ \tilde u_R\ \tilde d_L\ \tilde d_R$	(same)
			$\tilde s_L\ \tilde s_R\ \tilde c_L\ \tilde c_R$	(same)
			$\tilde t_L\ \tilde t_R\ \tilde b_L\ \tilde b_R$	$\tilde t_1\ \tilde t_2\ \tilde b_1\ \tilde b_2$
sleptons	0	−1	$\tilde e_L\ \tilde e_R\ \tilde \nu_e$	(same)
			$\tilde \mu_L\ \tilde \mu_R\ \tilde \nu_\mu$	(same)
			$\tilde \tau_L\ \tilde \tau_R\ \tilde \nu_\tau$	$\tilde \tau_1\ \tilde \tau_2\ \tilde \nu_\tau$
neutralinos	1/2	−1	$\tilde B^0$ (Bino) $\tilde W^0$ (Wino) $\tilde H_u^0\ \tilde H_d^0$ (Higgsino)	$\tilde N_1\ \tilde N_2\ \tilde N_3\ \tilde N_4$
charginos	1/2	−1	$\tilde W^\pm$ (Wino) $\tilde H_u^+\ \tilde H_d^-$ (Higgsino)	$\tilde C_1^\pm\ \tilde C_2^\pm$
gluino	1/2	−1	$\tilde g$	(same)
goldstino (gravitino)	1/2 (3/2)	−1	$\tilde G$	(same)

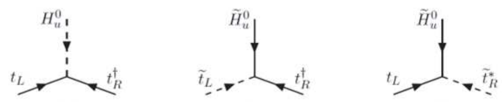
- μ = SUSY version of the SM Higgs mass
- $\tan\beta$ = Ratio of vacuum expectation values of H_u/H_d
- m_h = Mass of h^0 $m_h^2 \le M_Z^2 + \Delta m_{rad}^2\,(A_t,\tan\beta,\mu,m_{\tilde t_{1,2}},m_t,v^{**})$
- m_A = Mass of A^0 $\frac{1}{2}M_Z^2 = \frac{m_{H_d}^2 - m_{H_u}^2\tan^2\beta}{\tan^2\beta - 1} - \mu^2 \approx -m_{Hu}^2 - \mu^2$
- m_{H^+} = Mass of $H^{+/-}$
- $m_{H_u}^2, m_{H_d}^2$ from SUSY breaking
- M_Q^2 = Squark 3x3 mass term
- M_L^2 = Slepton 3x3 mass term

} $= m_0^2$ at GUT scale*

- M_1 = Bino mass term
- M_2 = Wino mass term
- M_3 = gluino mass term

} $= m_{1/2}$ at GUT scale*

- $A_{u,d,e}$ ~Yukawa-like 3x3 matrix $= A_o$ at GUT scale*



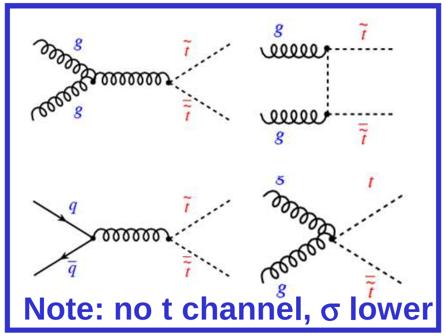
Need some pragmatic approach to scan these huge phase space (see later) !

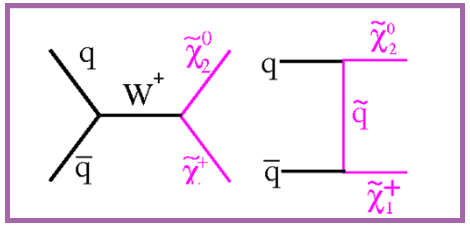
* In Planck scale-mediated SUSY breaking models like mSUGRA, ** $v=\sqrt{(v_u^2+v_d^2)}$

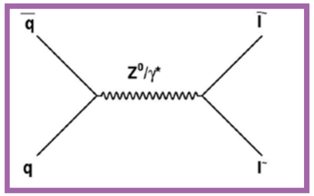
SUSY @ LHC (1)

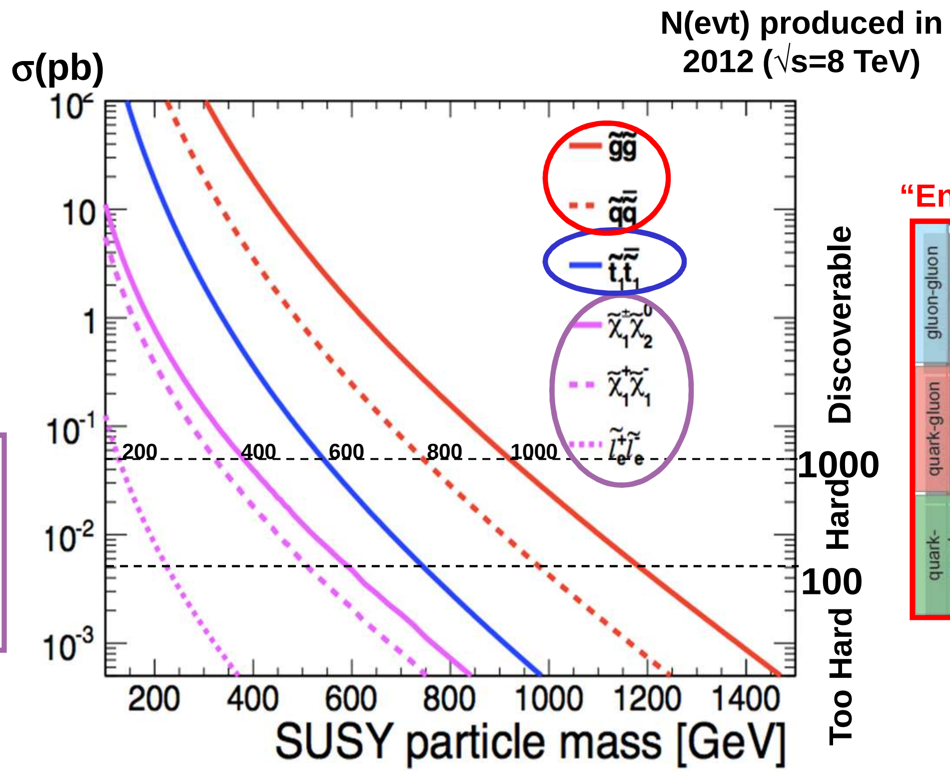
❑ **Sparticles are pair produced at LHC** (R-Parity conserved)

"Dedicated" searches

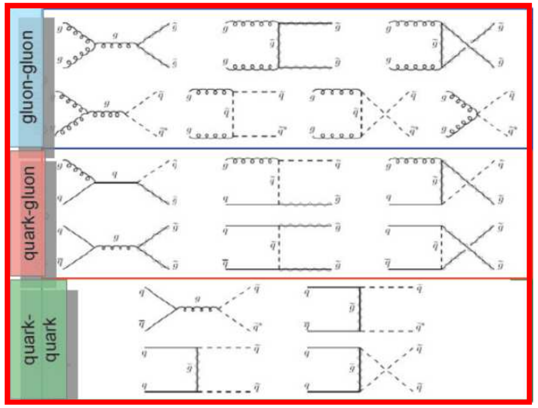








"Energy frontier/generic" searches

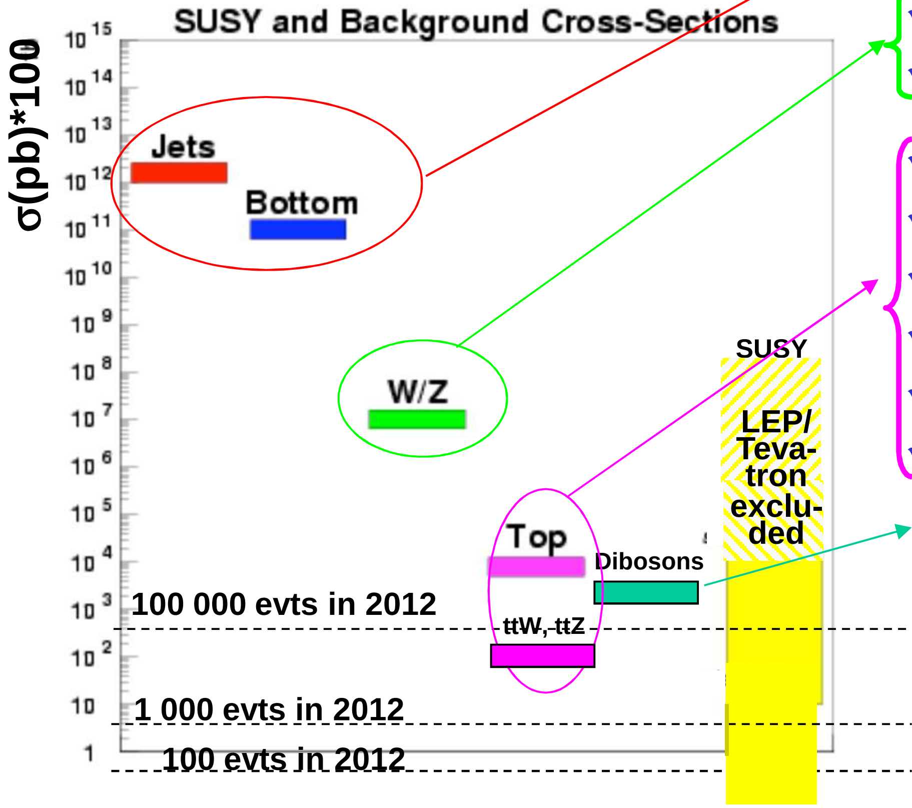


➔ Searching for SUSY often means building dedicated/refined analyses

SUSY @ LHC (2)

Part Ib

❑ Background to RPC SUSY searches



- ✓Later called «QCD»: **fake MET (low MET** for bb**)**
- ✓W→lν+jets (ISR/FSR): l=**e,μ**, l=τ→**jet**, ν→**MET***
- ✓Z→νν+jets (ISR/FSR): **MET+jets** irreducible
- ✓tt→bWbW→bqqbqq: **jets** and low **MET** (b-decay)
- ✓tt→bWbW→bqqblν: l=**e,μ**, l=τ→**jet**, ν→**MET**
- ✓tt→bWbW→blνblν: l=**e,μ**, l=τ→**jet**, ν→**MET**
- ✓**tt+jets (ISR,FSR)**
- ✓tt+X with X=bb,Z,W,H, γ : Predicted but not yet discovered!
- ✓Single top: Wt, tb, tbqq
- ✓WW→lνlν, ZZ→llνν, WZ→lνqq: **lept., jets**, **MET**

m(g,q)~ **500** GeV, m(t_1)~ **200** GeV, m($\chi_{1,2}$)~ **100** GeV
Discoverable
m(g,q)~**1000** GeV, m(t_1)~ **600** GeV, m($\chi_{1,2}$)~ **400** GeV
Hard
m(g,q)~**1200** GeV, m(t_1)~ **800** GeV, m($\chi_{1,2}$)~ **600** GeV
Too Hard

➔ Need to suppress QCD / WZ / top by ~ 10^{10} / 10^5 / 10^2 and estimate small remaining quantities

SUSY @ LHC (3)

❑ Once mass spectrum known, theoretically computable decay rate

- Mix of on-shell (2 body decay) and off-shell (3-body decay)

MSSM: 29 sparticles + 4 Higgs undiscovered

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$
squarks	0	−1	$\tilde{u}_L\ \tilde{u}_R\ \tilde{d}_L\ \tilde{d}_R$	(same)
			$\tilde{s}_L\ \tilde{s}_R\ \tilde{c}_L\ \tilde{c}_R$	(same)
			$\tilde{t}_L\ \tilde{t}_R\ \tilde{b}_L\ \tilde{b}_R$	$\tilde{t}_1\ \tilde{t}_2\ \tilde{b}_1\ \tilde{b}_2$
sleptons	0	−1	$\tilde{e}_L\ \tilde{e}_R\ \tilde{\nu}_e$	(same)
			$\tilde{\mu}_L\ \tilde{\mu}_R\ \tilde{\nu}_\mu$	(same)
			$\tilde{\tau}_L\ \tilde{\tau}_R\ \tilde{\nu}_\tau$	$\tilde{\tau}_1\ \tilde{\tau}_2\ \tilde{\nu}_\tau$
neutralinos	1/2	−1	$\tilde{B}^0\ \tilde{W}^0\ \tilde{H}_u^0\ \tilde{H}_d^0$ (Bino) (Wino) (Higgsino)	$\tilde{N}_1\ \tilde{N}_2\ \tilde{N}_3\ \tilde{N}_4$
charginos	1/2	−1	$\tilde{W}^\pm\ \tilde{H}_u^+\ \tilde{H}_d^-$ (Wino) (Higgsino)	$\tilde{C}_1^\pm\ \tilde{C}_2^\pm$
gluino	1/2	−1	$\tilde{g}$	(same)
goldstino (gravitino)	1/2 (3/2)	−1	$\tilde{G}$	(same)

Main decay channels in MSSM

$h \to bb, WW, \tau\tau$; $H^0 \to hh, WW, tt, bb$; $A^0 \to tt, bb$; $H^{+/-} \to \tau\nu, tb$

$\tilde{q} \to q\tilde{g}, q\tilde{\chi}_1^0, q'\tilde{\chi}_1^{+/-}, q'W^{(*)}\tilde{\chi}_1^0$ $\begin{cases} \tilde{q}_L \to q\tilde{\chi}_{1(2)}^0, q'\tilde{\chi}_1^{+/-}\ (\tilde{\chi}_2^0\ \text{wino}) \\ \tilde{q}_R \to q\tilde{\chi}_1^0\ (\tilde{\chi}_1^0\ \text{bino}) \end{cases}$

$\tilde{g} \to q\tilde{q},\ q\bar{q}\tilde{\chi}_1^0, q\bar{q}'\tilde{\chi}_1^{+/-}$

STRONG

$\tilde{l} \to l\tilde{\chi}_{1(2)}^0, \nu\tilde{\chi}_1^{+/-}$ → $\tilde{l}_L \to l\tilde{\chi}_{1(2)}^0, \nu_l\tilde{\chi}_1^{+/-}\ (\tilde{\chi}_2^0\ \text{wino})$

$\tilde{\nu} \to \nu\tilde{\chi}_{1(2)}^0, l\tilde{\chi}_1^{+/-}$ → $\tilde{l}_R \to l\tilde{\chi}_1^0\ (\tilde{\chi}_1^0\ \text{bino})$

$\tilde{\chi}_2^0 \to W^{(*)}\tilde{\chi}_1^{+/-}, Z^{(*)}\tilde{\chi}_1^0, \tilde{l}l, \tilde{\nu}\nu, \tilde{q}q$

$\tilde{\chi}_{1(2)}^{+/-} \to W^{(*)}\tilde{\chi}_1^0, Z^{(*)}\tilde{\chi}_1^{+/-}, l\tilde{\nu}, \nu\tilde{l}, qq'$

Electro-Weak

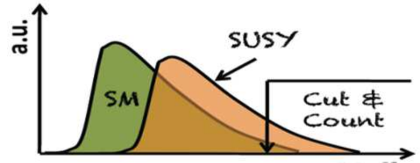
➔ Predictable but huge combinatorics: (Possible decays) x (mass spectrum) !

SUSY @ LHC (4)

Part IIa,b

❑ R-Parity conserved ➔ cascade of particles + Missing Energy

- SUSY appears as excess in tails



MSSM: 29 sparticles + 4 Higgs undiscovered

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
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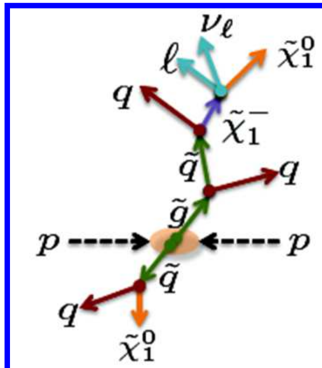
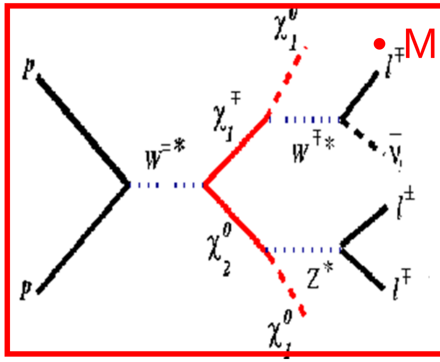
			$\tilde{s}_L\ \tilde{s}_R\ \tilde{c}_L\ \tilde{c}_R$	(same)
			$\tilde{t}_L\ \tilde{t}_R\ \tilde{b}_L\ \tilde{b}_R$	$\tilde{t}_1\ \tilde{t}_2\ \tilde{b}_1\ \tilde{b}_2$
sleptons	0	−1	$\tilde{e}_L\ \tilde{e}_R\ \tilde{\nu}_e$	(same)
			$\tilde{\mu}_L\ \tilde{\mu}_R\ \tilde{\nu}_\mu$	(same)
			$\tilde{\tau}_L\ \tilde{\tau}_R\ \tilde{\nu}_\tau$	$\tilde{\tau}_1\ \tilde{\tau}_2\ \tilde{\nu}_\tau$
neutralinos	1/2	−1	$\tilde{B}^0\ \tilde{W}^0\ \tilde{H}_u^0\ \tilde{H}_d^0$	$\tilde{N}_1\ \tilde{N}_2\ \tilde{N}_3\ \tilde{N}_4$
charginos	1/2	−1	$\tilde{W}^\pm\ \tilde{H}_u^+\ \tilde{H}_d^-$	$\tilde{C}_1^\pm\ \tilde{C}_2^\pm$
gluino	1/2	−1	$\tilde{g}$	(same)
goldstino (gravitino)	1/2 (3/2)	−1	$\tilde{G}$	(same)

@ LHC



- Missing Energy=MET ($\tilde{\chi}_1^0$)
- "Jetty" (some from b)
- Eventually leptons
- Eventually γ

STRONG



- Missing Energy=MET ($\tilde{\chi}_1^0$)
- Jet veto
- 2 or 3 leptons

Electro-Weak (EWK)

➔ Generally signal acceptance quite low (~1% **strong**, ~10% **EWK**)

SUSY @ LHC (5)

Part IIc

❑ R-parity violating search at LHC ➔ ~ background free analyses

$$W = W_{MSSM} + \underbrace{\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k}_{\text{Lepton Number Violation (LFV)}} + \kappa_i L_i H_u + \underbrace{\lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k}_{\text{Baryon Number Violation (BNV)}}$$

- Proton decays only forbids simultaneous violation of lepton and baryon number

From H. Dreiner

Multilepton production (including taus)

Resonances (2jets, 2x2 jets, 2x3 jets, eμ, eτ, mτ)

Note: Absence of Z and Importance of taus

	Signature	Model
1)	4 charged leptons: $e^+e^+\mu^-\mu^-$	χ_1^0–LSP, $LL\bar{E}$, $\tilde{\tau}$–LSP, $LL\bar{E}$
2)	2 leptons, 2 taus: $e^+e^+\tau^-\tau^-$	χ_1^0–LSP, $LL\bar{E}$, $\tilde{\tau}$–LSP, $LQ\bar{D}$
3)	6 jets or 2 w/ substructure	χ_1^0–LSP, $\bar{U}\bar{D}\bar{D}$
4)	like-sign dileptons + jets	χ_1^0–LSP, $LQ\bar{D}$
5)	dilepton resonance	$LL\bar{E} \otimes LQ\bar{D}$
6)	mono lepton	$LL\bar{E} \otimes LQ\bar{D}$
7)	dijet resonance	pure $LQ\bar{D}$
8)	like sign ditau's $\tau^-\tau^-$ + 6jets	$\tilde{\tau}$–LSP, $LQ\bar{D}$

➔ Generally: lower background (no LFV nor BNV in SM) and MET than RPC

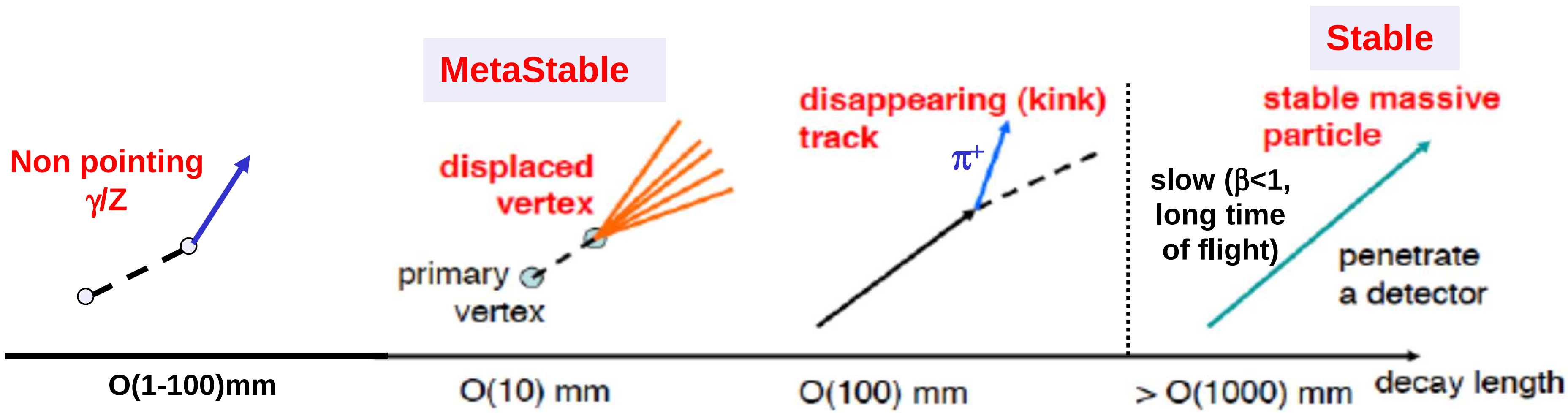
SUSY @ LHC (6)

Part IIc

❑ Long-lived Particles (examples)

- Very weak coupling with $\tilde{G}$=LSP [GMSB] : ➔ Non pointing γ or Z
- Lifetime proportionnal to $\lambda^2, \lambda'^2, \lambda''^2$ [R-Parity violation] ➔ Displaced vertex if $\lambda, \lambda', \lambda'' < 10^{-7}$
- Low mass difference $\Delta M(\chi_1^+ - \chi_1^0) \sim 100$ MeV [AMSB] ➔ Low π emitted, kinked track
- Stable Massive Particle ➔ R-hadron ($\tilde{g}$ or $\tilde{q}$) or sleptons

Note: R-hadrons can stopped in the detector and decay later (stopped gluinos) or change sign



➔ Very detailed understanding of the detector/LHC beams to remove the background

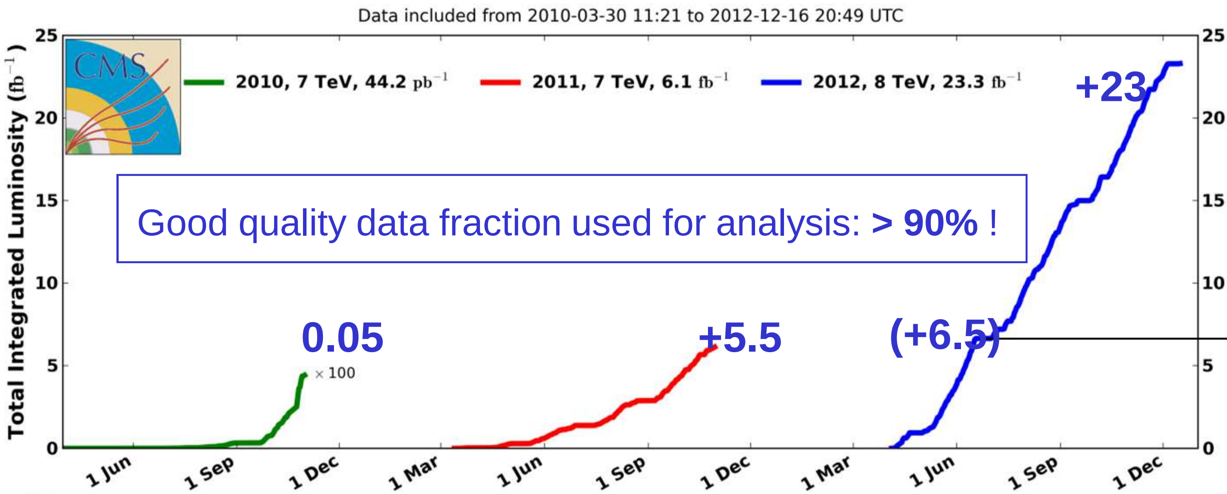
Experimental challenges

- How to find direct evidence of (weak-scale) SUSY at LHC ?
  - SUSY cross-section is weak (pb-fb) and SM background is huge
  - SUSY mass spectrum is a priori unknown (use naturalness guide)
  - SUSY signatures can be numerous and striking

- Experimental challenges = systematics = search sensitivity
  - Changing LHC conditions (especially pile-up) and experiments
  - Trigger can kill the signal …
  - Object reconstruction in hadronic environment
  - Detector understanding (timing, …) crucial for non standard SUSY
  - \+ Data/Monte-Carlo agreement in hadronic environment

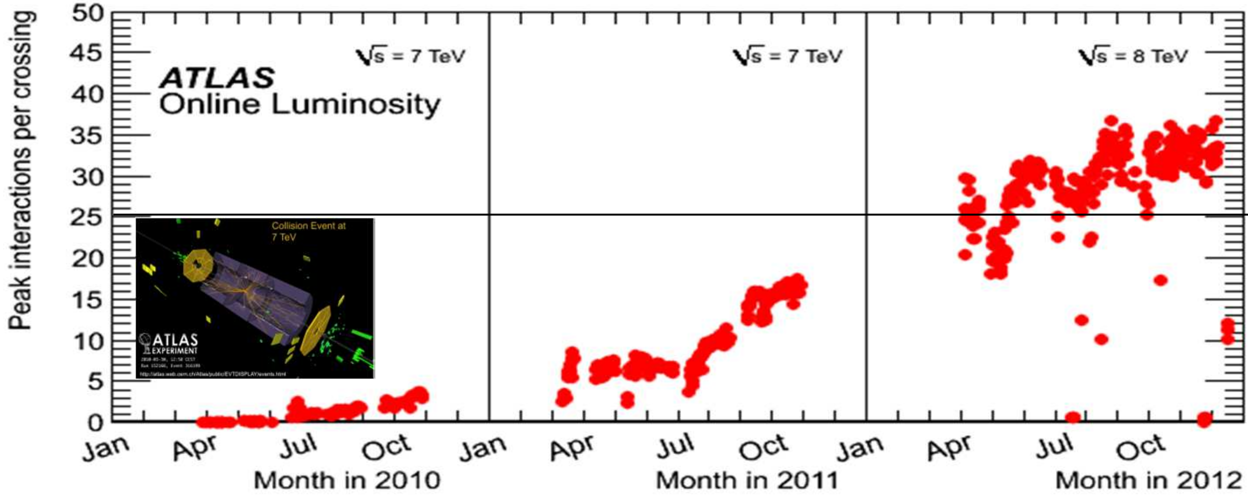
LHC (1)

❑ **LHC pp data : 3 <u>fantastic</u> years with a lot of «pile-up» at the end !**



LHC-RunI (usable): L~28*0.9~25 fb^{-1}

Reach Tevatron final in two years (~11 fb^{-1} in 24 years)

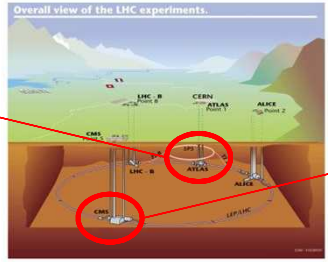


Design LHC value

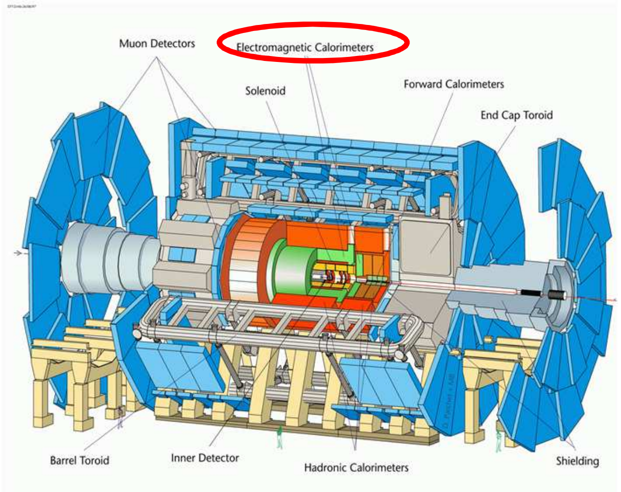
Z→ μμ event with **25**

LHC (2)

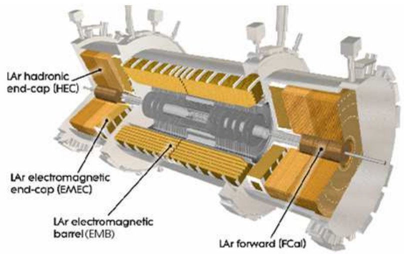
❑ The two general purpose experiments



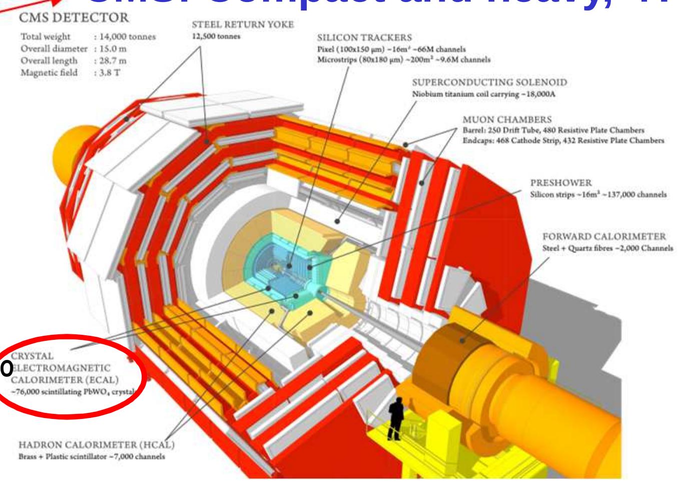
ATLAS: Giant with 2 ≠ magnets



Lead/Liquid Argon sampling EM Calorimeter



CMS: Compact and heavy, 4T



EM Calorimeter : Scintillating PbWO4 Crystals

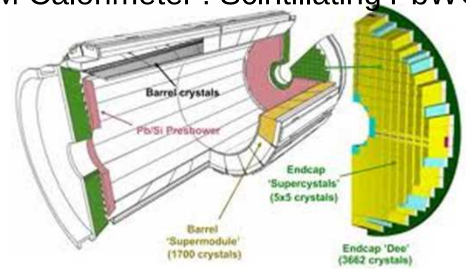


TABLE 2 Main design parameters of the ATLAS and CMS detectors

Parameter	ATLAS	CMS
Total weight (tons)	7000	12,500
Overall diameter (m)	22	15
Overall length (m)	46	20
Magnetic field for tracking (T)	2	4
Solid angle for precision measurements ($\Delta\phi \times \Delta\eta$)	$2\pi \times 5.0$	$2\pi \times 5.0$
Solid angle for energy measurements ($\Delta\phi \times \Delta\eta$)	$2\pi \times 9.6$	$2\pi \times 9.6$
Total cost (million Swiss francs)	550	550

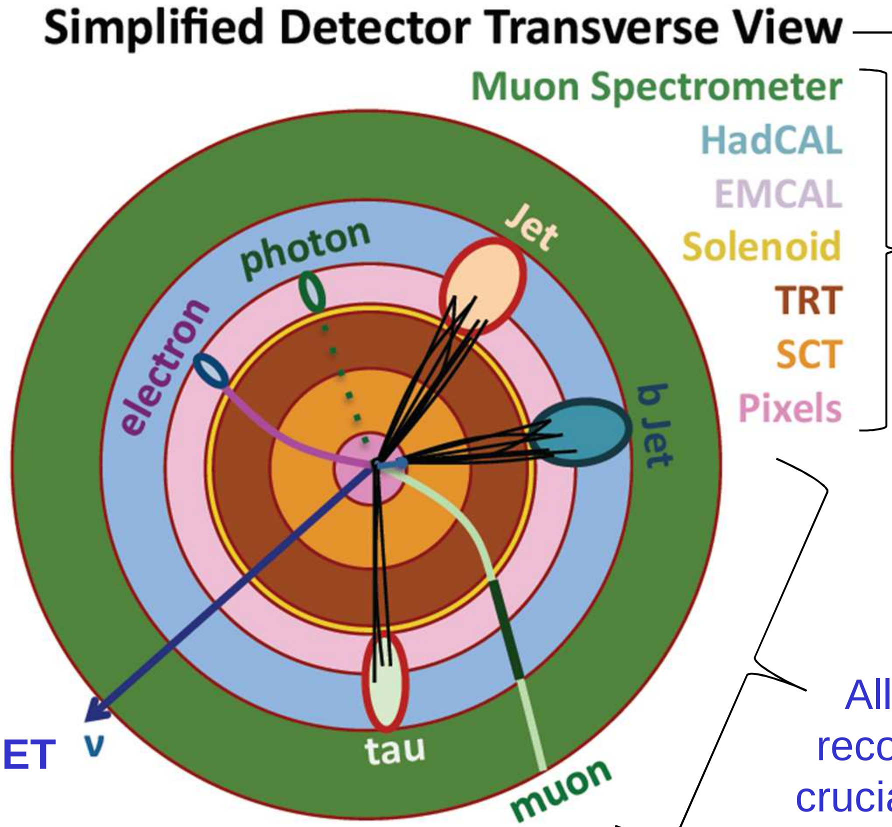
Annu. Rev. Nucl. Part. Sci. 2006. 56:375–440

TABLE 8 Main parameters of the ATLAS and CMS electromagnetic calorimeters

	ATLAS		CMS	
Technology	Lead/LAr accordion		$PbWO_4$ scintillating crystals	
Channels	Barrel	End caps	Barrel	End caps
	110,208	63,744	61,200	14,648
Granularity	$\Delta\eta \times \Delta\phi$		$\Delta\eta \times \Delta\phi$	
Presampler	0.025×0.1	0.025×0.1		
Strips/ Si-preshower	0.003×0.1	0.003×0.1 to 0.006×0.1		32×32 Si-strips per 4 crystals
Main sampling	0.025×0.025	0.025×0.025	0.017×0.017	0.018×0.003 to 0.088×0.015
Back	0.05×0.025	0.05×0.025		
Depth	Barrel	End caps	Barrel	End caps
Presampler (LAr)	10 mm	2×2 mm		
Strips/ Si-preshower	$\approx 4.3\ X_0$	$\approx 4.0\ X_0$		$3\ X_0$
Main sampling	$\approx 16\ X_0$	$\approx 20\ X_0$	$26\ X_0$	$25\ X_0$
Back	$\approx 2\ X_0$	$\approx 2\ X_0$		
Noise per cluster	250 MeV	250 MeV	200 MeV	600 MeV
Intrinsic resolution	Barrel	End caps	Barrel	End caps
Stochastic term a	10%	10 to 12%	3%	5.5%
Local constant term b	0.2%	0.35%	0.5%	0.5%

Complementarity mandatory in case of discovery !

Object reconstruction



MET

→ No access to full energy

Detectors crucial for **Long-Lived particle** searches

All objects (Identification, reconstruction, systematics) crucial for **RPC/RPV** searches
→ data/MC agreement ?

Non collision + cosmic muon

❑ LHC Beam Halo, single bunch, … (esp. early 2010 and monojet-type searches)

- All prompt RPC analysis ask for a reconstructed primary vertex
- Reject very badly reconstructed jets or EM-like jet $f_{em} = p_T^{jet(EM)} / p_T^{jet} > 0.1$
- Use jet charge fraction $f_{ch} = \sum p_T^{track,jet} / p_T^{jet} > 0.02$

❑ Cosmic muons

- Despite underground, reconstruct lots of cosmic muons (few Hz pseudo-projective)
  - ✓ Best measurement of R= μ^+/μ^- (CMS) [PLB 692 (2010) 83] R=1.2766 ± 0.0032 (stat.) ± 0.0032 (syst.)
- Stringent cuts (~0.1-1 mm) on d_0 and z_0 wrt to Primary Vertex remove all of them

➔Well under control. Negligible in all SUSY searches (except stopped R-hadrons)

Trigger

❑ Often drive the main analysis kinematic cuts

- CMS invests in designing one trigger per analysis
- ATLAS put lots of bandwith in single trigger

Object	Offline Selection
j	$p_T > 360$ GeV
MET	MET>150 GeV
e	$p_T > 25$ GeV
μ	$p_T > 25$ GeV
γ	$p_T > 140$ GeV

➔

j + MET

p_T^{jet}>130 GeV + MET>150 GeV

- 0lepton + MET + ≥2-6jets
- 0lepton + MET + 1-3bjets + jets
- 1-2Taus + MET + jets
- …

e OR μ OR τ τ

e μ OR e e OR μ μ

Symmetric & Asymmetric

- 2leptons + MET
- 3leptons + MET
- 4leptons + MET

j j j j (j j)

4 (5, 6) jets p_T> 80 (60, 50) GeV

- 2x2jets
- 0lepton + MET/$\sqrt{H_T}$ + 7-10jets

γ γ

2 photons p_T^{γ}>25 GeV

- 2photons + MET

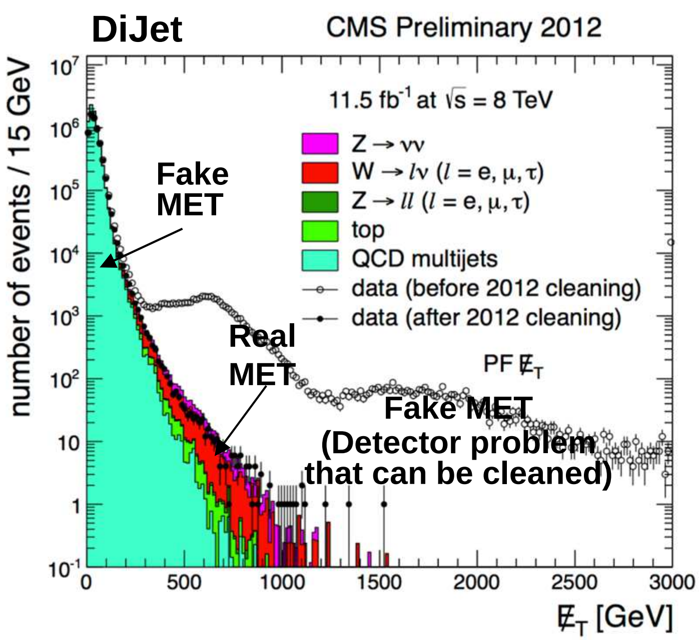
+ Dedicated SUSY triggers for low beta particles, stopped gluinos (out of collision).

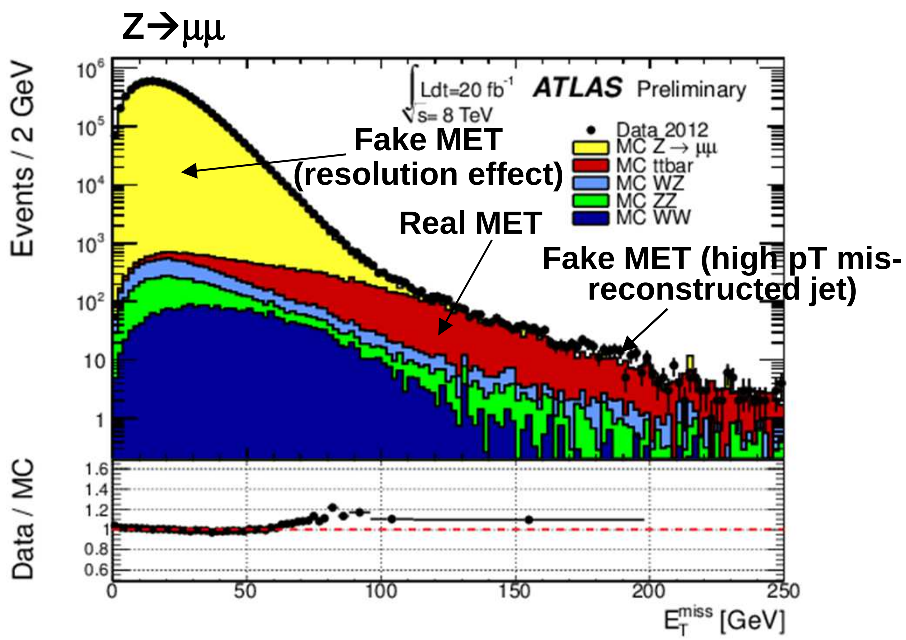
➔ Triggering is really challenging and may limit what we can do : soft MET, soft jet, …

MET reconstruction (1)

❑ **Crucial for all SUSY searches** (and experimentally very challenging)

- Energy conservation (transverse plane) : $\vec{MET} = \vec{E}_T^{\text{non-int}} = -\Sigma \vec{E}_T$ (calo) - $\Sigma \vec{E}_T$ (muon)
  - ✓ If calorimeter not enough use also tracker (Particle Flow a la CMS)
- Real MET : Presence of a neutral weakly interacting particle in the event (i.e. ν)
- Fake MET : Mismeasurement + detector malfunctions, poorly instrumented regions





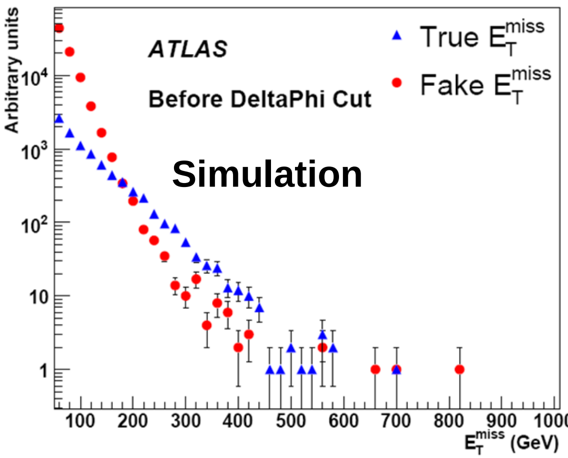
➔ Agreement data – Monte Carlo key for SUSY searches (systematics no dominant)

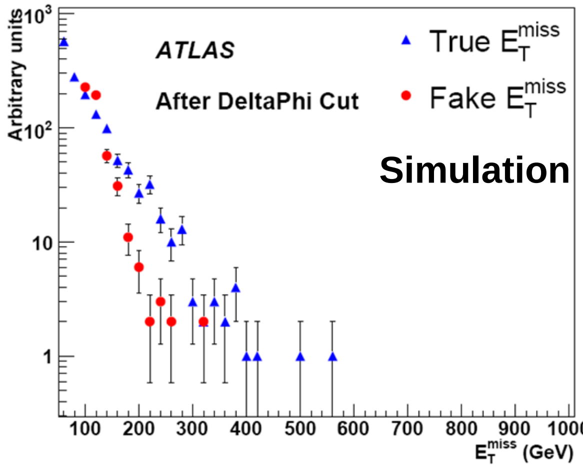
MET reconstruction (2)

❑ SUSY ~ high MET : Need to remove efficiently high pT 'fake' jets/lepton

- Simpliest is to cut on $\Delta\phi(\text{jet,MET})_{min}$: $\Delta\phi(\text{jet, MET})_{min}>0.2\text{-}0.4$ **[0-lepton events]**
  - ✓ Reverting this cut provides a very nice QCD enriched sample

QCD sample ($0.5<p_T<1.1$ TeV)





- Can also use "relative" MET **[2-lepton events]**
  - ✓ Can reduce MET contribution for process with real MET ..
  - ✓ … but efficiently reduce fake MET in Z→ll events

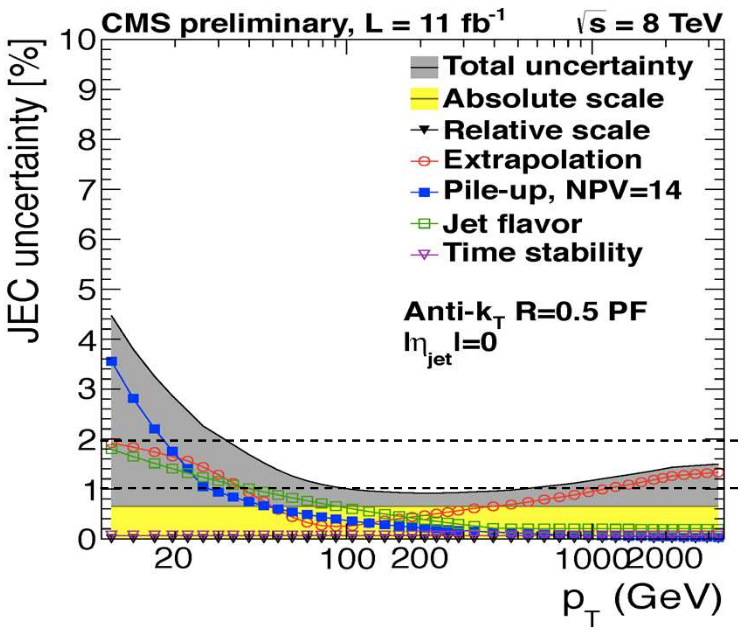
$$E_T^{\text{miss,rel}} = \begin{cases} E_T^{\text{miss}} & \text{if } \Delta\phi_{\ell,j} \geq \pi/2 \\ E_T^{\text{miss}} \times \sin\Delta\phi_{\ell,j} & \text{if } \Delta\phi_{\ell,j} < \pi/2 \end{cases}$$

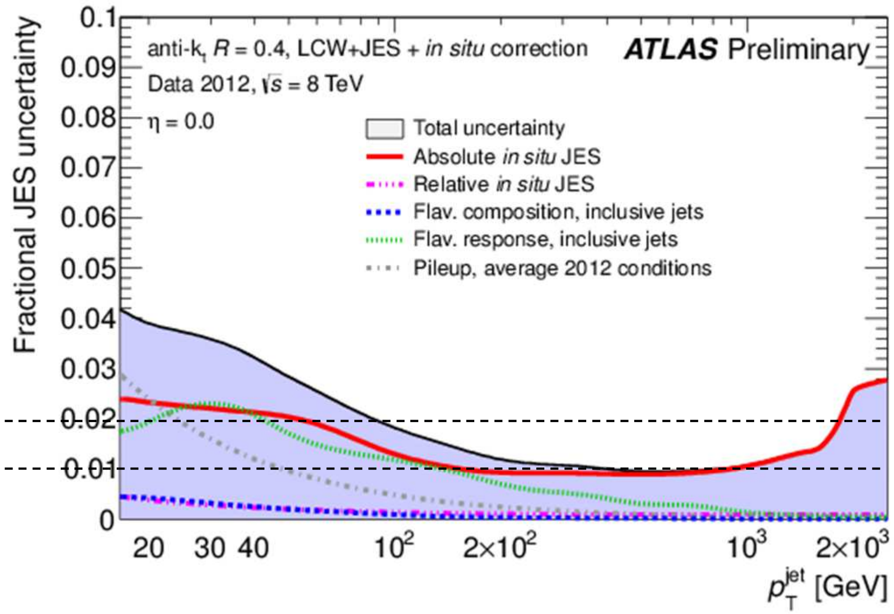
$[\phi_{l,j} = \Delta\phi(\vec{MET},\vec{l})$ or $\Delta\phi(\vec{MET},\vec{j})]$

Jet Reconstruction

❑ Central for SUSY searches

- Anti-kt Jet with Radius R=0.4/0.5 (ATLAS/CMS)
- Several technics to remove pile-up dependence
- Uncertainties on Jet Energy Scale (JES) ~ 1-2 % for ATLAS and CMS

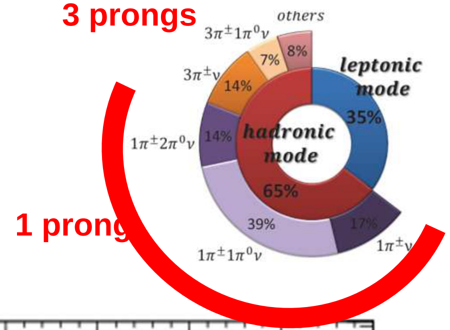




➔ Generally the dominant systematics for SUSY searches !

b and τ tagging

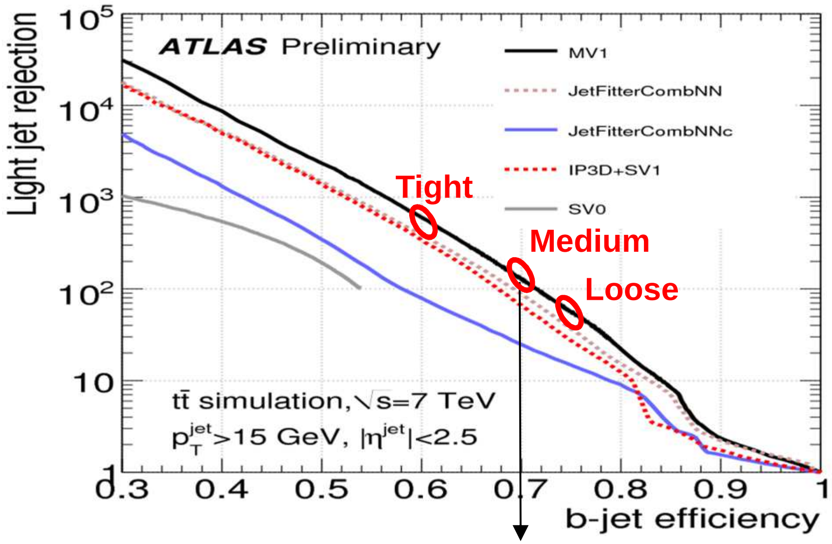
ATLAS-CONF-2012-043



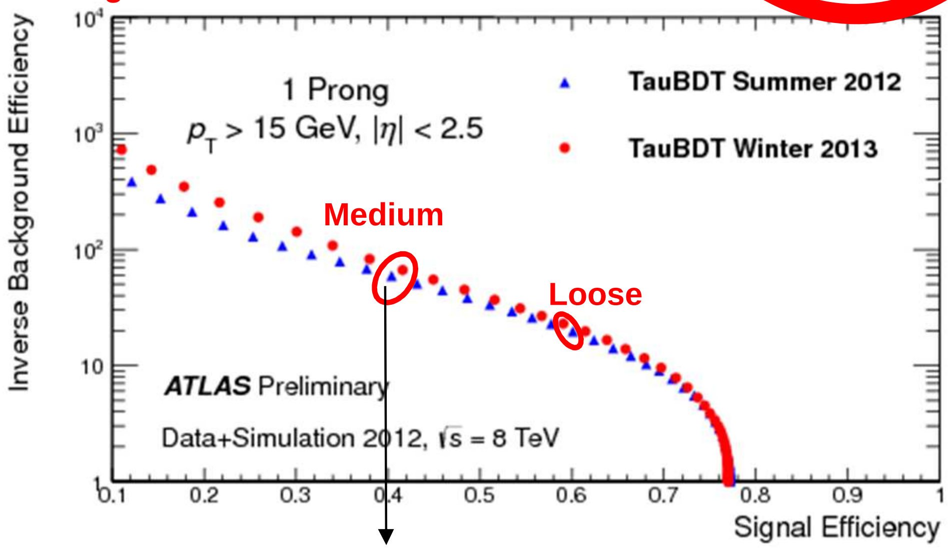
❑ Crucial for 3rd generation studies !

- Combined many inputs in a likelihood/BDT to increase light jet rejection
  - ✓ b : Impact parameter, secondary vertex information
  - ✓ τ (hadronic): seeded from jet, 11 shower shape + tracker variables

SUSY Working Points



Rejection c-jet/light-jet/τ = 5/135/13



Rejection hadronic-jet/τ = 50

➔ Compete with JES systematics in b/τ enriched analyses

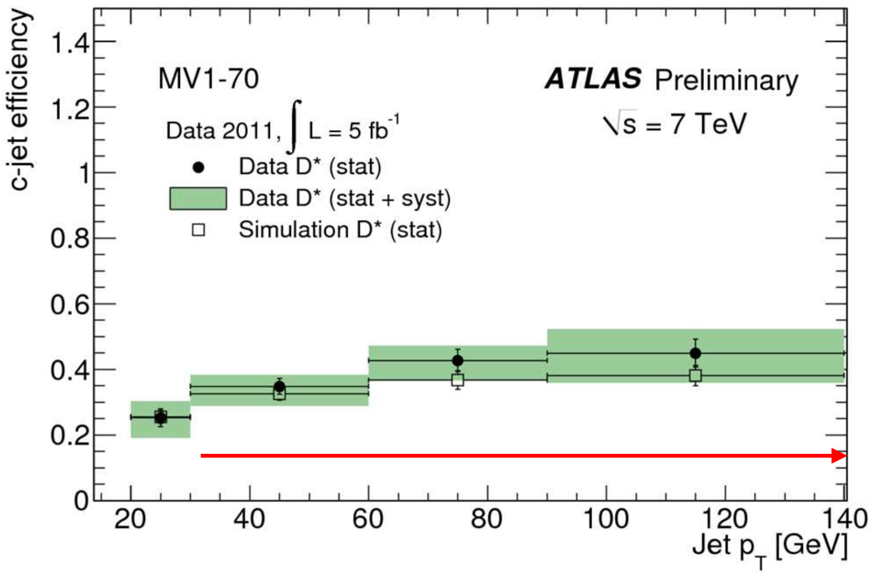
➔ Final states with had. τ (eg, tt➔τ+X) are often the main SM background

And also c-tagging !

ATLAS-CONF-2012-039

❑ Very useful in some corners of SUSY parameter space

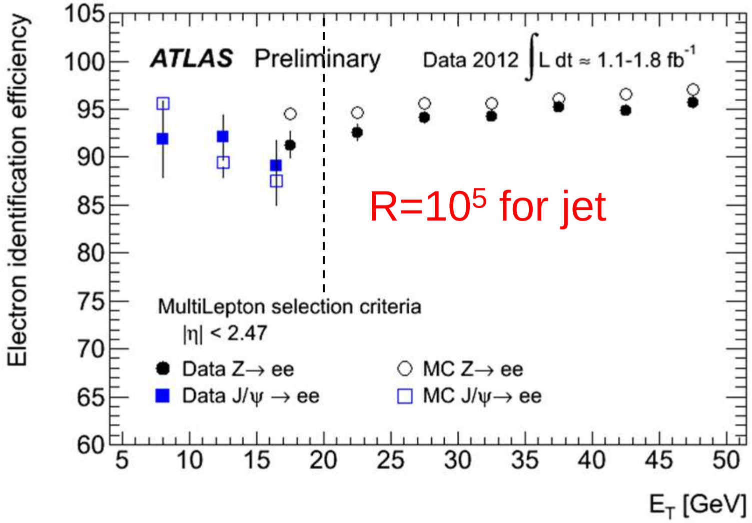
- Combined many inputs in a likelihood/BDT to increase b-jet, light and τ jet rejection
  - ✓ Loose selection: $\varepsilon(c)$= 95%, R(b/light/τ) = 2/~1/~1
  - ✓ Medium selection: $\varepsilon(c)$= 20%, R(b/light/τ) = 5/140/10

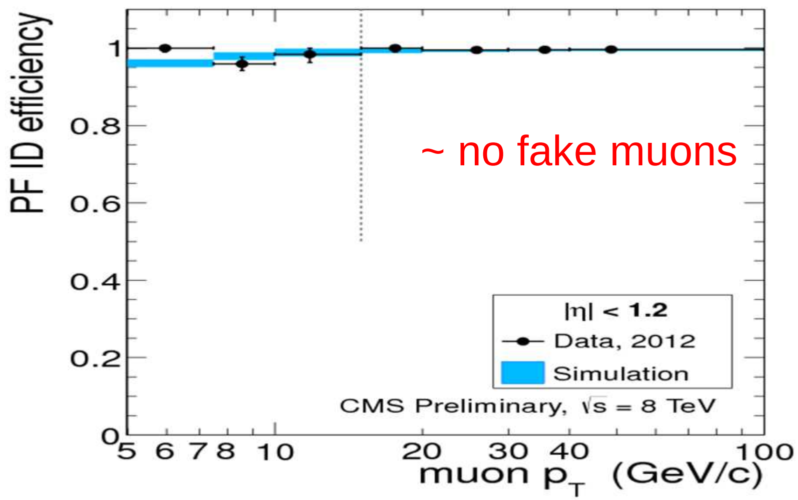


Leptons (e, μ)

❑ Useful for compressed SUSY spectra, SUSY Weak searches

- Ask for isolated leptons (can be tuned per analysis) → SUSY Strong, Weak
- Identification & Reconstruction down to very low pT (5-7 GeV) → Compressed specta
- Multilepton signal benefit from high efficiency / high coverage → RPV
- Experimental challenge: charge determination, fake leptons





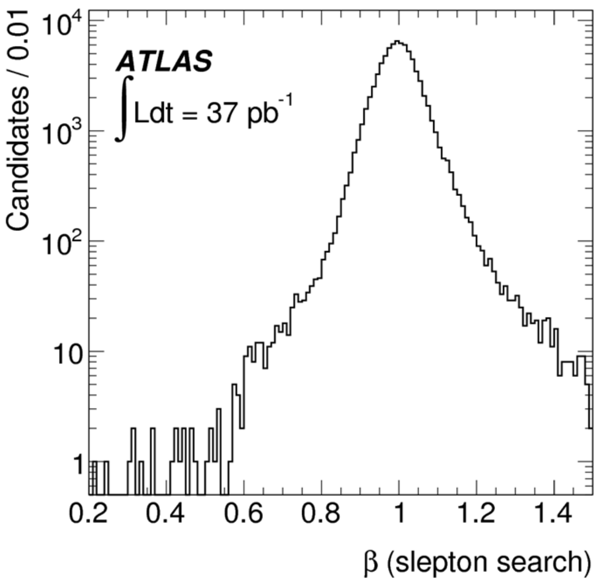
→ Systematics from Lepton energy scale and resolution small in SUSY

Speed measurement of muons

❑ Crucial for long-lived particles

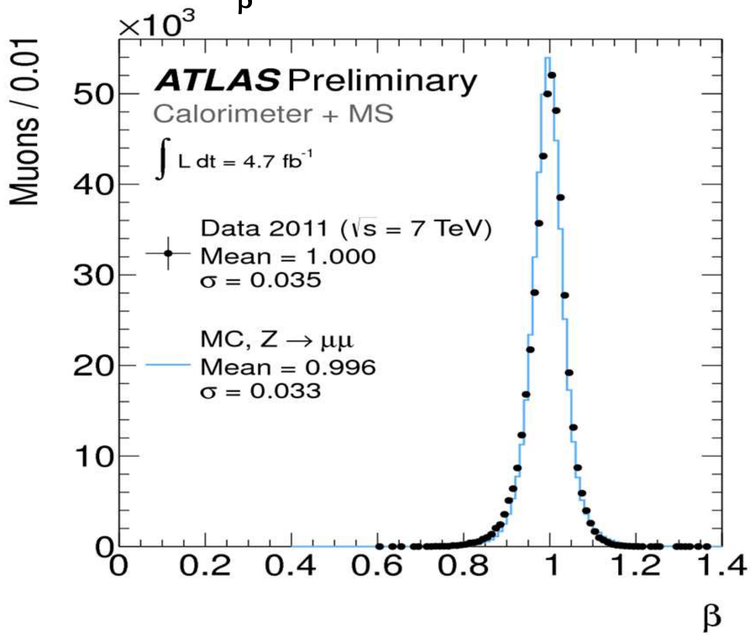
- Test on a (pure) Z→μμ samples
- Combine Muon Spectrometer + Calorimeter

2010 : σ_β~4.8% + tails



- Improve RPC and calo combination
- Include all calorimeters
- Check consistency between detector measurement

2011 : σ_β~3.5% + smaller tails

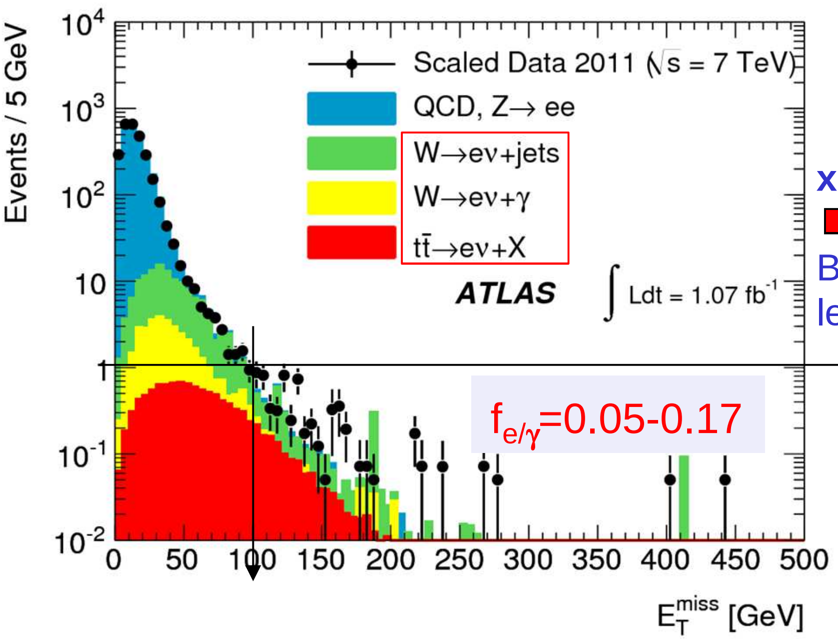


→Also good description by Monte-Carlo. A great achievement !

Photon

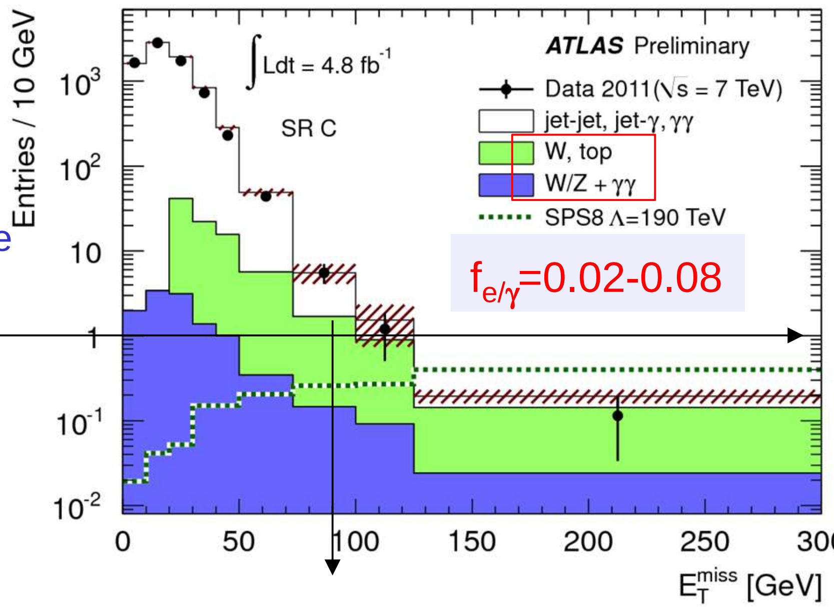
❑ A typical signature for GMSB models

- Ex: ATLAS γγ + MET $1 fb^{-1} \rightarrow 5 fb^{-1}$
- Improve $f_{e/\gamma}$ by categorising, e.g. γ conv. and unconv., barrel vs endcap reconstruction
  - ✓ Reduce the (dominant) electron background



x8 stat/bins

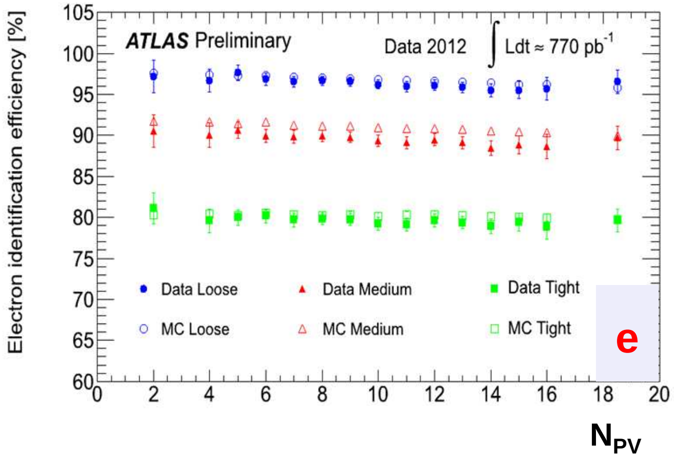
But keep same level as $1 fb^{-1}$

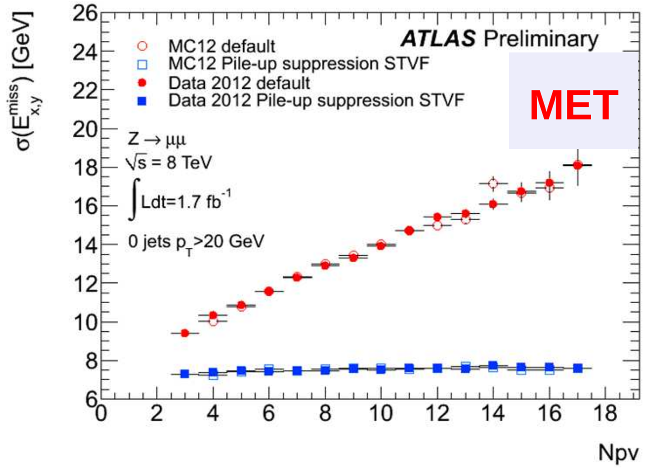


➔ A nice example of object implication on SUSY Sensitivity

Pileup

❑ **Object Id./Reconstruction robust against pile-up (check with data)**

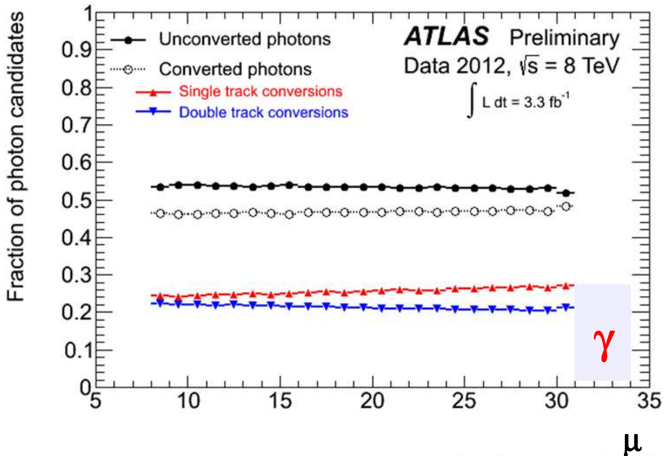


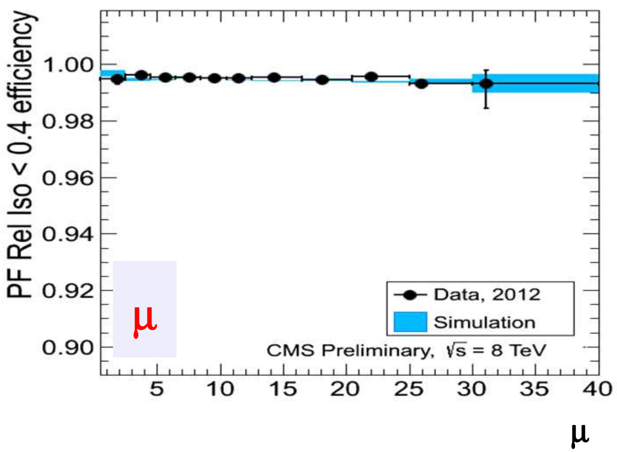


Average interactions per bunch crossing

$\mu \sim 1.4 * N_{PV}^{rec}$

Number of reconstructed primary vertex





➔Also good description by Monte-Carlo. A great achievement !

Monte Carlo (1)

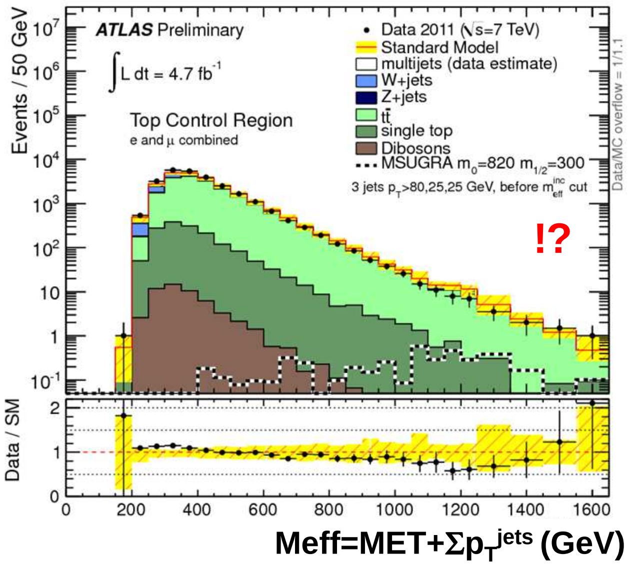
❑ Challenging to model SM processes with high jet mulitplicities

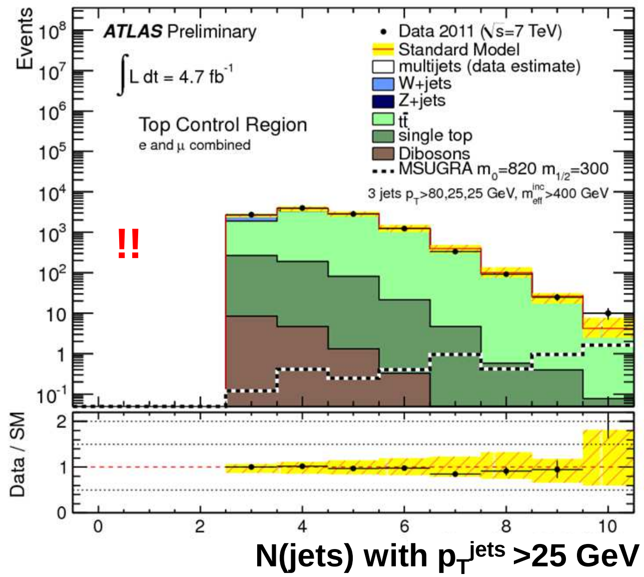
- Parton Shower (PS) : PYTHIA, HERWIG
- Matrix Element (ME) + PS : MADGRAPH, ALPGEN

Note: SHERPA, HERWIG++, NLO+PS (MC@NLO, POWHEG) also used

➔'Best' to describe large-angle emissions beyond the hardest jet (jets well separated)

SUSY -1lepton Top Control Region



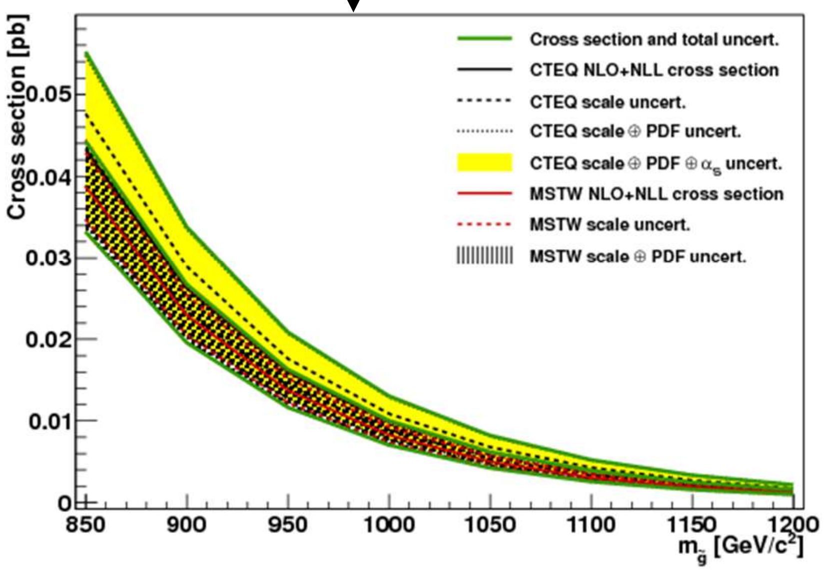


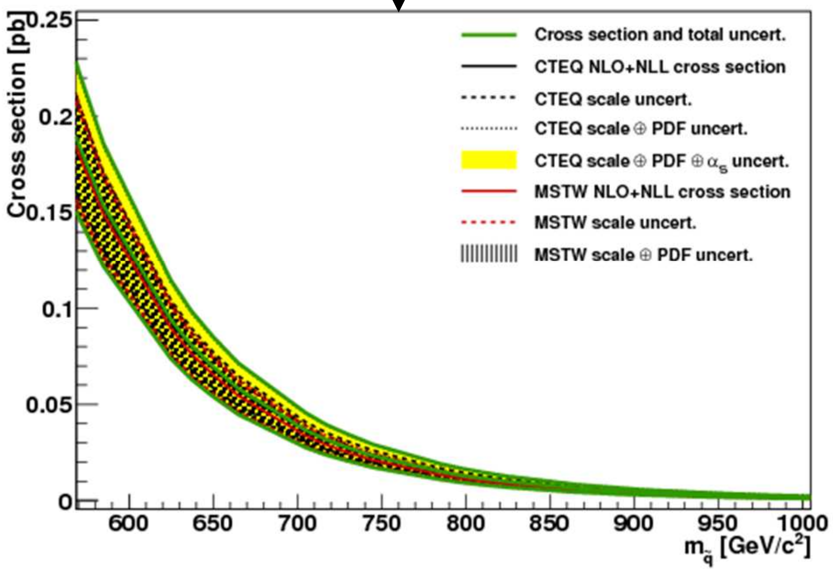
➔ Yellow band = k_T scale variation barely cover data-MC discrepancy in Meff

Monte Carlo (2)

❑ SUSY Signal: standard for ATLAS/CMS for 5 fb^{-1} results (1206.2892)

- Cross-section from Prospino: NLO (EWK), NLO+NNLL (Strong)
- Systematics: PDF4LHC and factorisation/renormalisation scale variation
- Example: **$\tilde{g}\tilde{g}$ with $\tilde{q}$ decoupled** **$\tilde{q}\tilde{q}^*$ with $\tilde{g}$ decoupled**





➔ Typical systematics (scale + PDF) = 20-30 % for $m_{\tilde{g},\tilde{q}}$<1 TeV

➔ Initial/Final State Radiation for compressed spectra (up to 30%)

Object Summary

- ❑ **Need to fill the following table per analysis**

	Systematics	SM background estimate	SUSY Signal <1 TeV	Comments
Experimental	Pile-up			Negligible or Small
	Trigger			Small
	Jet Energy scale (JES)	.		Generally dominates exp
	Jet Energy resolution (JER)	Less than JES (apart Z+jets)	Less than JES	
	b/τ-tagging			Take over for ≥ 2 b/τ
	Lepton/γ energy scale			Small (even for multilep.) except τ
	Lepton/γ energy resolution			negligible
Theory	Scale, PDF uncertainties	Not for data-driven methods	~20% for NLO+NLL	Depend on many parameters
	Generators+Showering	Poor man's method	N.A.	
	ISR/FSR	Generally important for ttbar	Up to 30% for Compressed spectra	
	MC stat			Depend on grid computing !
	Total (indicative)	**~20-100%**	**~20-50%**	

(Bracket spanning Jet Energy scale through Lepton/γ energy resolution:) Fully **correlated** between signal & backgrd

➔ Will give some concrete examples tomorrow !

Summary of Part Ia

❑ Historical period for SUSY searches

- Naturalness predicts new EW-scale particles (Nx, Cx, stop, sbottom_L, gluino)
- 2012 @ LHC: N(SUSY) = 1000 for mC1=mN2 ~ 0.4, m(stop) ~ 0.6, m(gluino) ~ 1 TeV
- General Decay (spart → SM part + N1) and final states (Jets, MET, leptons/photon)

➔ LHC is an ideal place to discover Natural Weak scale SUSY !

❑ Theory unknowns → Drive experimental SUSY searches [Part II]

- R-Parity (RPC, RPV) ?
- SUSY Breaking (SUGRA, GMSB, AMSB) ?
- Open/compressed spectra ?

MSSM: 29 sparticles + 4 Higgs undiscovered

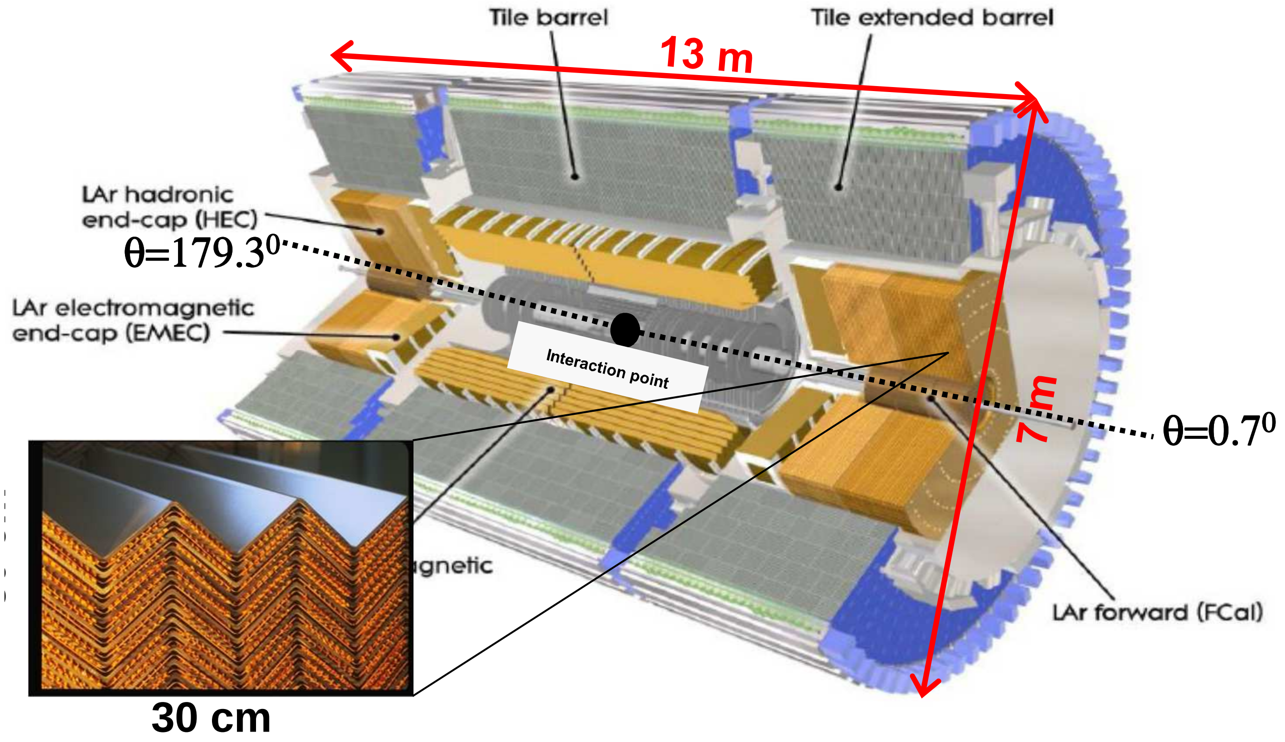
Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$
squarks	0	−1	$\tilde{u}_L\ \tilde{u}_R\ \tilde{d}_L\ \tilde{d}_R$	(same)
			$\tilde{s}_L\ \tilde{s}_R\ \tilde{c}_L\ \tilde{c}_R$	(same)
			$\tilde{t}_L\ \tilde{t}_R\ \tilde{b}_L\ \tilde{b}_R$	$\tilde{t}_1\ \tilde{t}_2\ \tilde{b}_1\ \tilde{b}_2$
sleptons	0	−1	$\tilde{e}_L\ \tilde{e}_R\ \tilde{\nu}_e$	(same)
			$\tilde{\mu}_L\ \tilde{\mu}_R\ \tilde{\nu}_\mu$	(same)
			$\tilde{\tau}_L\ \tilde{\tau}_R\ \tilde{\nu}_\tau$	$\tilde{\tau}_1\ \tilde{\tau}_2\ \tilde{\nu}_\tau$
neutralinos	1/2	−1	$\tilde{B}^0\ \tilde{W}^0\ \tilde{H}_u^0\ \tilde{H}_d^0$	$\tilde{N}_1\ \tilde{N}_2\ \tilde{N}_3\ \tilde{N}_4$
charginos	1/2	−1	$\tilde{W}^\pm\ \tilde{H}_u^+\ \tilde{H}_d^-$	$\tilde{C}_1^\pm\ \tilde{C}_2^\pm$
gluino	1/2	−1	$\tilde{g}$	(same)
goldstino (gravitino)	1/2 (3/2)	−1	$\tilde{G}$	(same)

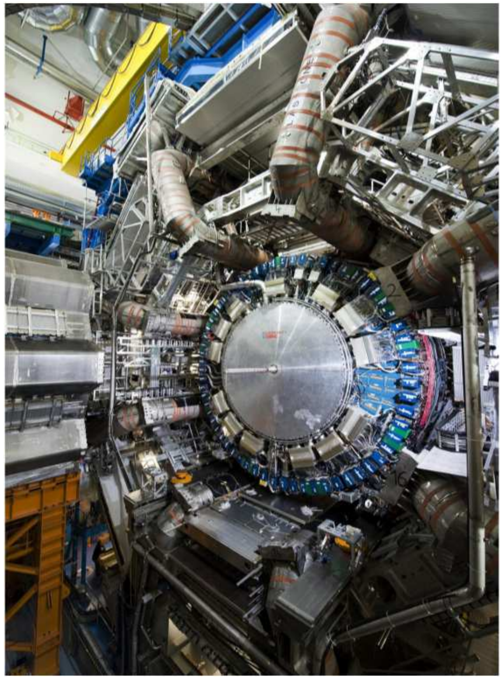
❑ How to find SUSY at LHC?

- Well understood reconstructed objects

SPARE

ATLAS Calorimetry





- **Very granular :** EM (173 500), HAD (14000 = 5 000 Tile + 5500 HEC + 3500 FCal)
- **Hermetic :** EM (22-35 X_0), EM+HAD (11-15 λ), $0.7^o<\theta<179.3^o$

➔ Measure electrons/photons/jets, missing transverse momentum (MET)

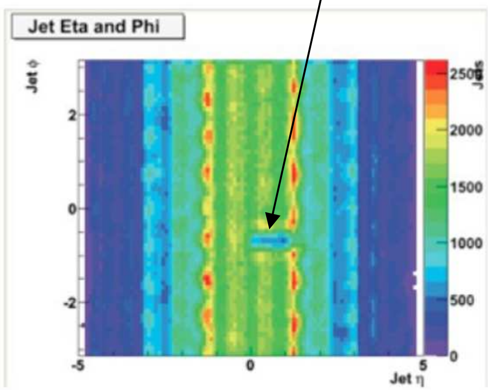
MET reconstruction

❑ **To identify weakly interacting particle, avoid «holes» in the detector !**

- Extracted from an ATLAS SUSY papers

During a fraction of the data-taking period (about 20% of the total integrated luminosity), a localised electronics failure in the LAr barrel calorimeter created a dead region in the second and third calorimeter layers ($\Delta\eta \times \Delta\phi \simeq 1.4 \times 0.2$) in which on average 30% of the incident jet energy is not measured. Negligible impact is found on the reconstruction efficiency for jets with $p_{\mathrm{T}} > 20$ GeV. For events selected during this data period, if any jet with $p_{\mathrm{T}} > 50$ GeV falls in the aforementioned region, the event is rejected. The loss in signal acceptance is smaller than 10% in the affected period for the models considered.

- Reminder: 187500 cells in ~3000 Front-End boards on the ATLAS EM calorimeter cryostat
- 1rst may 2011: 6 boards lost their 25 ns clock (power glitch)
  ➔ Dip in the number of reconstructed jets, E_T^{miss} tail



Take out **Plug in**

- Successful repair «acrobatique/téléguidé» during the shutdown early July 2011

➔ Affected ~1fb-1 of 2011 data (an offline fix was applied)

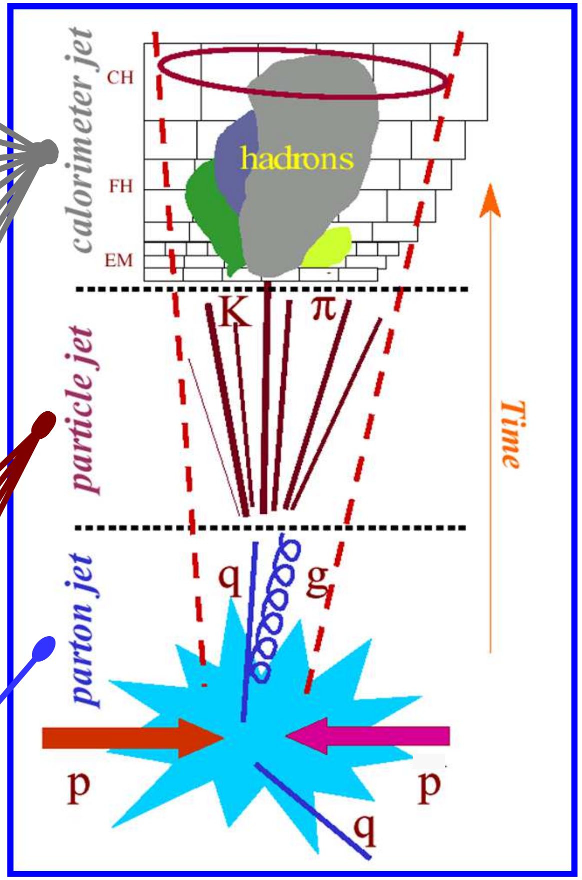
Calorimeter : Jet

❑ **Application : Measure the energy of non interacting particle ($E^{non-int}$)**

longitudinal energy leakage
detector signal inefficiencies (dead channels, HV…)
pile-up noise from (off-time) bunch crossings
calo signal definition (clustering, noise suppression ,…)
electronic noise
dead material losses (front, cracks, transitions…)
detector response characteristics (e/h ≠ 1)
jet reconstruction algorithm efficiency

jet reconstruction algorithm efficiency
added tracks from in-time (same trigger) pile-up event
added tracks from underlying event
lost soft tracks due to magnetic field

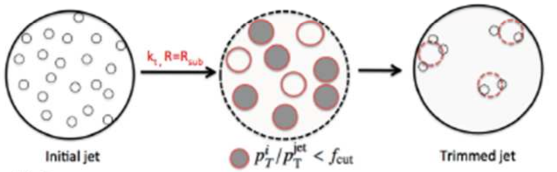
physics reaction of interest (parton level)



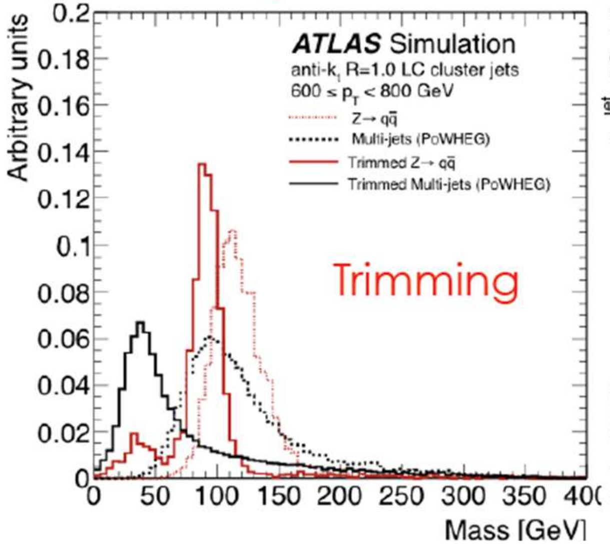
➔ **Not so easy to reconstruct jet … Need lots of LHC data to check**

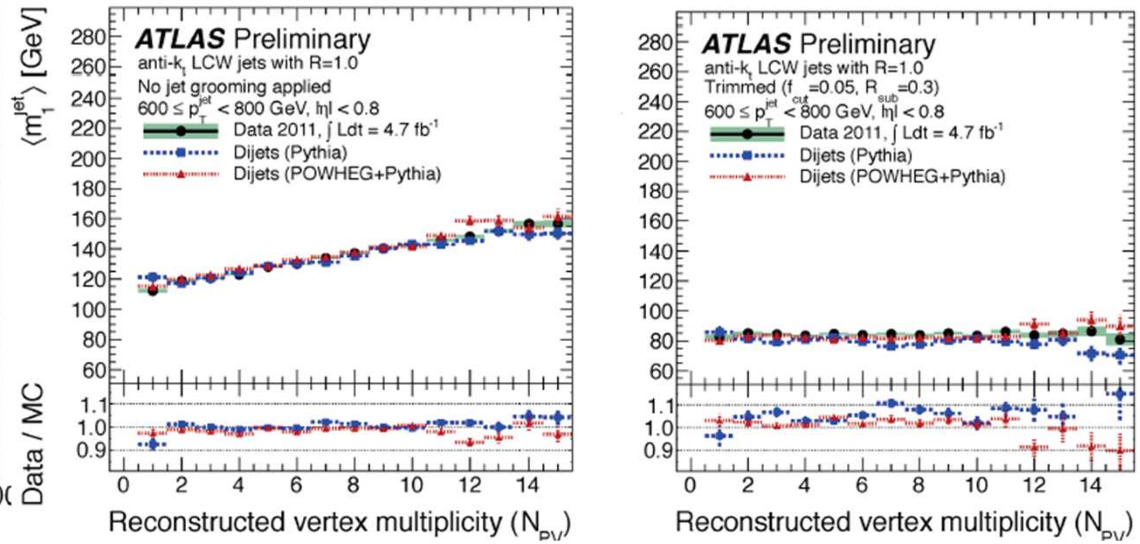
Jet Grooming

- **Distinguish jets from the decay of massive objects from massive QCD jets by removing soft wide angle radiation:**
  - Improve large-R jet mass resolution
  - Increase S/B
  - Remove pile-up effects on jet mass (reduced area)

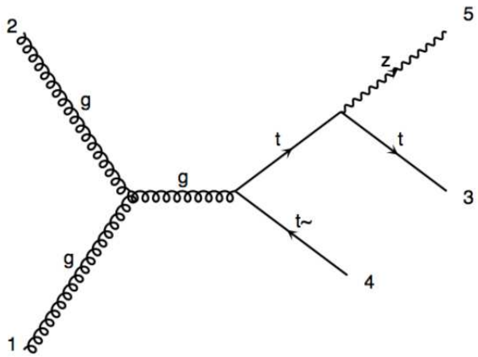


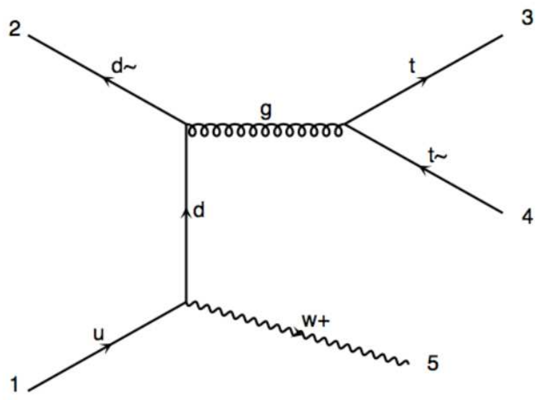
- ATLAS has commissioned three grooming algorithms: **trimming, pruning, filtering**

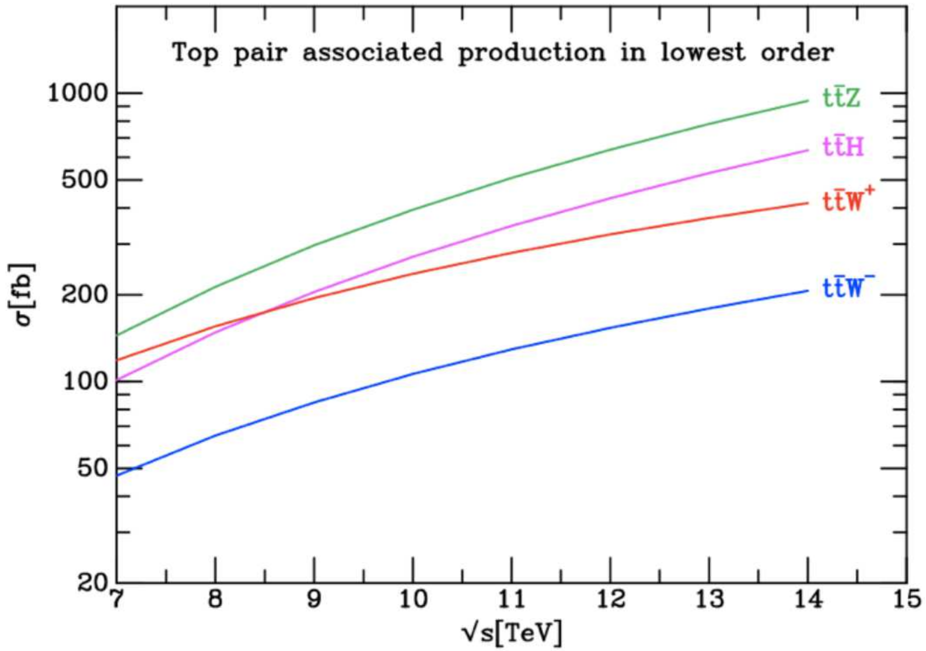




Ttbar+X







σ (ttbb) ~ 1 pb