Recherche directe de nouvelle physique au LHC

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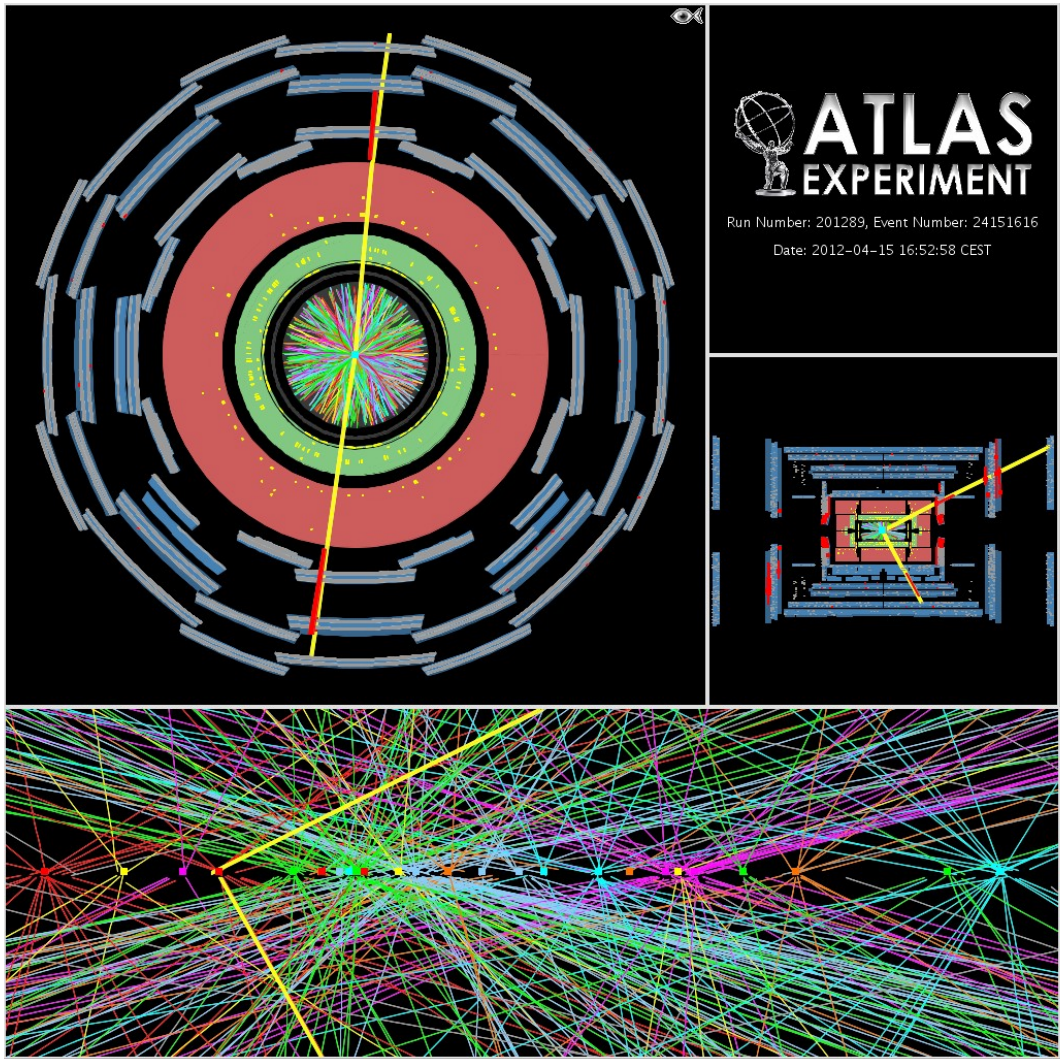


Recherche directe de nouvelle physique au LHC

- Focus on ATLAS and CMS direct searches
- Apologies for the strong ATLAS bias...
- Not a comprehensive overview: I chose a few themes
- Much more information available here:
  - → https://twiki.cern.ch/twiki/bin/view/AtlasPublic
  - → https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults
- See other lectures on related topics:
  - → SM and BSM theories
  - → Heavy Flavour
  - → SM and MSSM Higgs

Outline

- Introduction
  - → The Standard Model and its limitations
  - → The main Beyond-Standard-Model candidates to cope with the SM limitations
  - → General methodology at the LHC
  - → The LHC and the ATLAS and CMS detectors
- Supersymmetry *
  - → "standard" SUSY: MSUGRA/CMSSM
  - → "compressed" SUSY
  - → "natural" SUSY: dedicated stop/sbottom/gaugino searches

} today

- Long-lived particles (not only SUSY)
- Extra-dimensions and heavy resonances
- 4^{th} generation and heavy quarks
- Model-independent searches
- Outlook and conclusions

} tomorrow

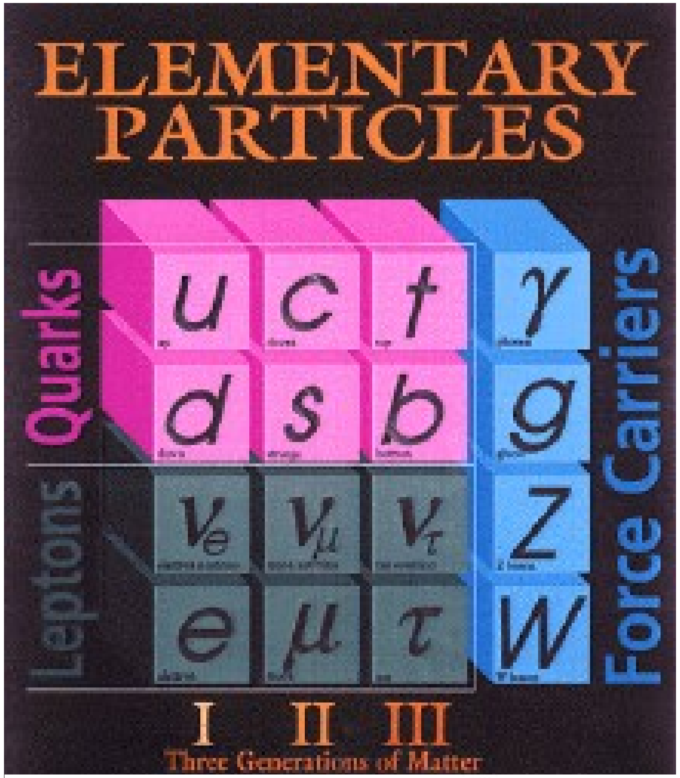
* Thanks to P. Pralavorio for help with SUSY

Introduction

- The Standard Model and its limitations
- The main Beyond-Standard-Model candidates to cope with the SM limitations
- General methodology at the LHC
- The LHC and the ATLAS and CMS detectors

The Standard Model in 1 slide: 3 forces, 3 generations, 1 Higgs boson

- Strong, Weak, and Electromagnetic forces described by gauge theory:
  - → $SU(3)_{QCD} \times SU(2)_L \times U(1)$
- Force carriers: photon, gluons, W and Z bosons
- $SU(2)_L \times U(1)$ spontanously broken by Higgs mechanism to give mass to W and Z bosons
- CKM matrix describes mixing of quarks
- Incredible success of the SM: explains (almost) all phenomena of particle physics from 0 to 1 TeV !

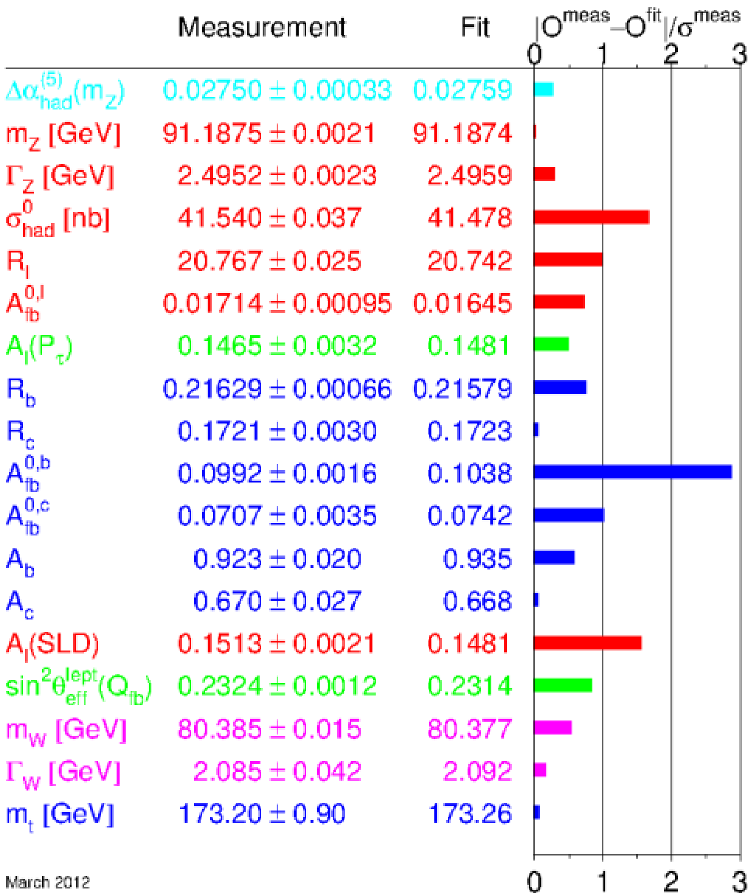


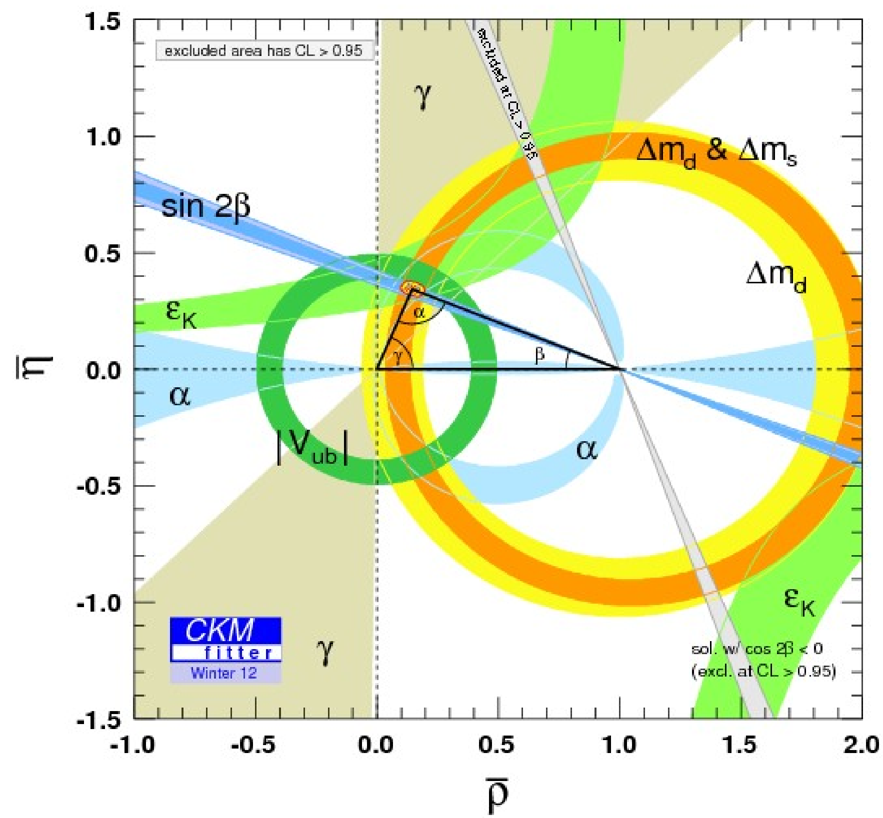
$$V(\Phi^+\Phi) = \mu^2 \Phi^+\Phi + \frac{\lambda}{2}(\Phi^+\Phi)^2$$

$$v = \sqrt{\frac{-\mu^2}{\lambda}} = 246\ \text{GeV}$$

Success of the Standard Model: EW and CP-violation Precision Measurements

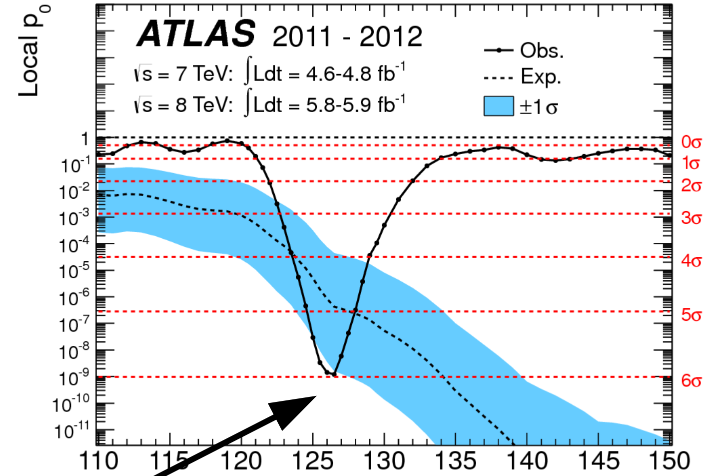
- Electroweak measurements at LEP, SLD, and Tevatron
- CP-violation at B-factories, K-factories



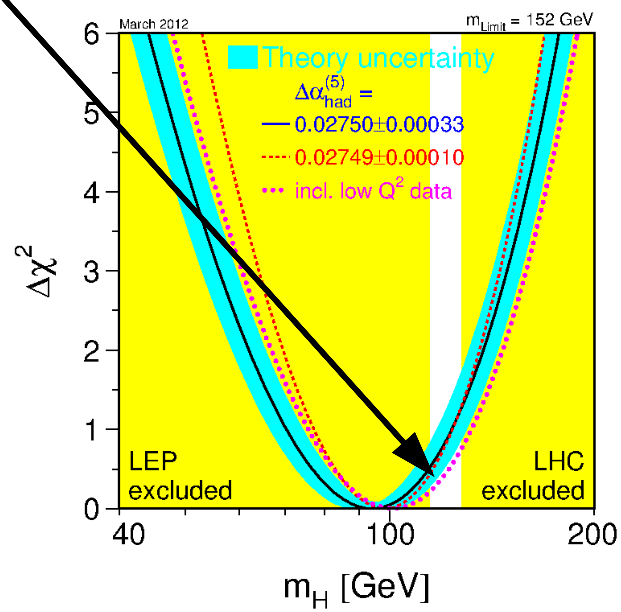


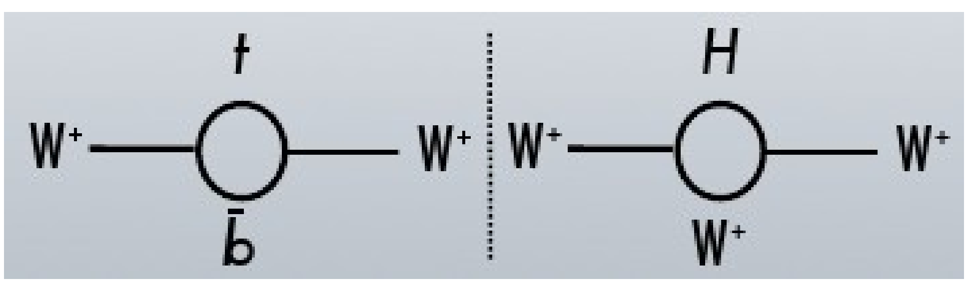
Latest Success of the Standard Model: The Higgs Boson !

- Precision measurements at LEP, SLD, and Tevatron (Z pole, W mass, top mass) → constraint on Higgs mass
- A light Higgs is preferred
- LHC Higgs(-like) discovery at ~126 GeV is compatible with precision measuremens



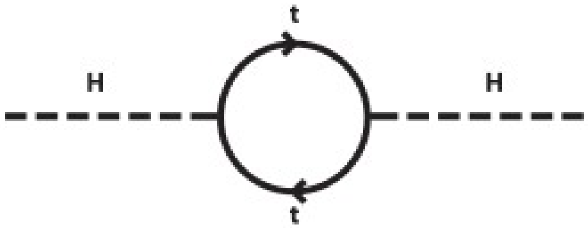
126 GeV

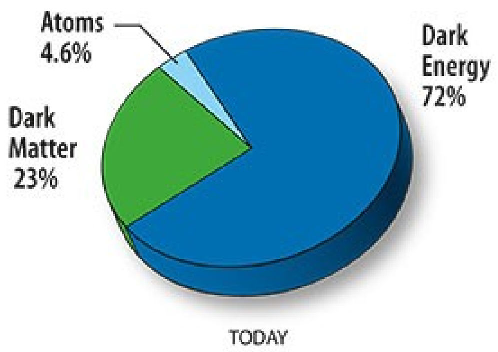


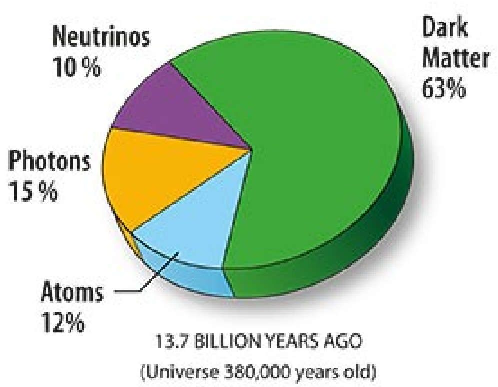


Why look "beyond" the Standard Model? Some limitations of the Standard Model

- The Standard Model is an effective theory that must break down at a certain scale
  - → Hierarchy: quadratic divergence of the Higgs mass, extremely fine-tuned
  - → What is the underlying nature of EWSB?
- Dark Matter and Dark Energy
  - → cannot be explained by SM
- Neutrinos have mass
  - → where are the right-handed neutrinos?
- How to include gravitation?
- How to produce enough CP-violation to explain the Universe matter-antimatter asymmetry? 4th generation of fermions?
- BSM models try to answer limitations of the SM

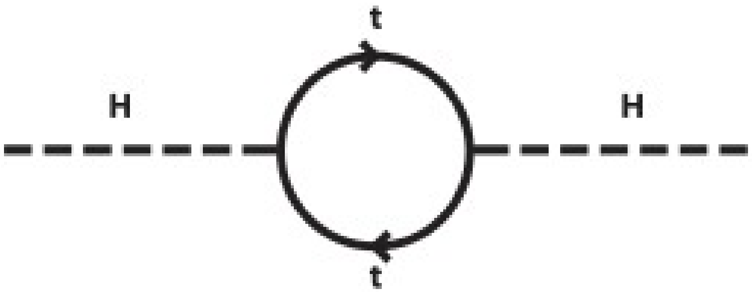






Why look "beyond" the Standard Model? The Hierarchy Problem

- Loop corrections to Higgs mass lead to quadratic divergences



$\Delta m_H^2 \sim y_t^2 \, \Lambda^2$

- Hierarchy problem:

  Electroweak scale ~ 100 GeV

  Plank scale ~ 10^{19} GeV

  17 orders of magnitude!

- Fine tuning:

  bare mass (very large)

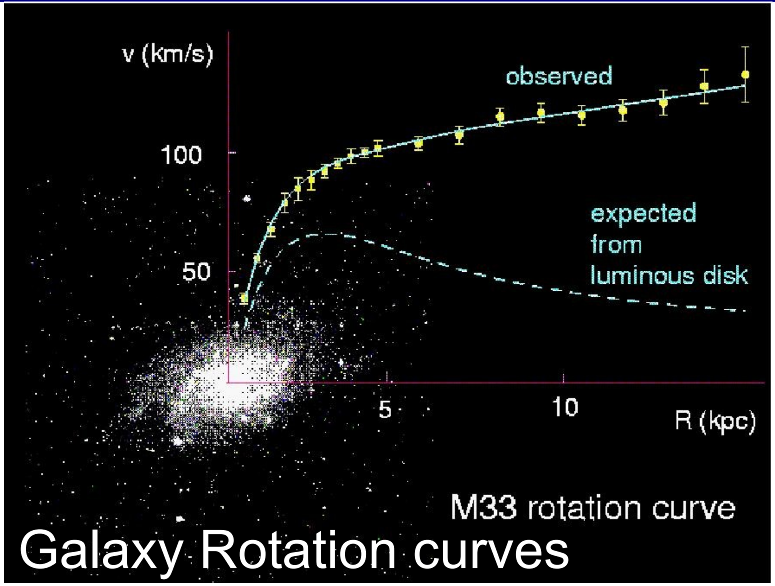
  – radiative corrections (very large)

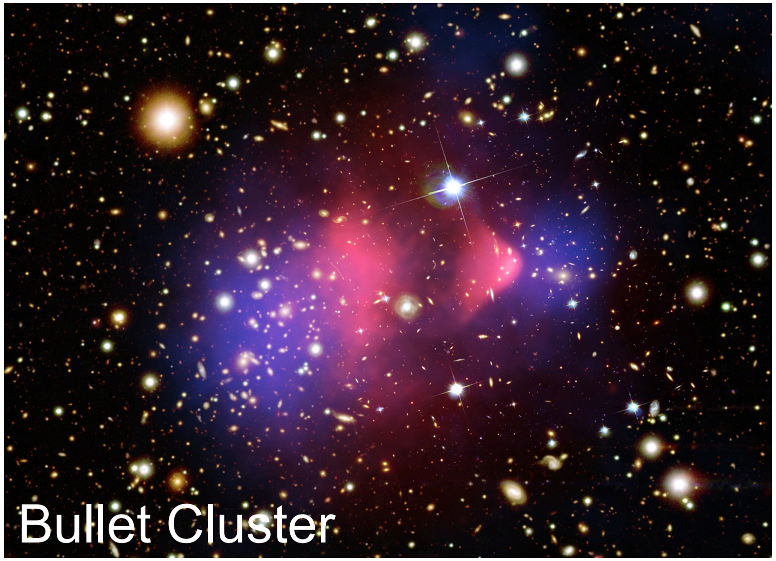
  = 126 GeV

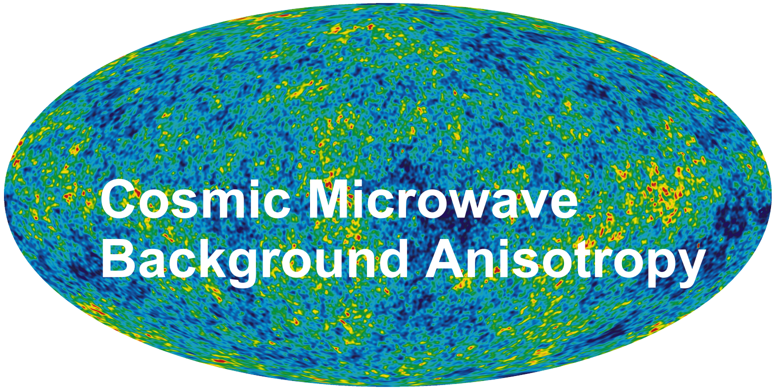
- Can new physics cancel the quadratic divergences?

Why look "beyond" the Standard Model? Dark Matter

- Dark Matter has been observed in several ways:
  - → Galaxy rotation curves
  - → Gravity lensing
  - → CMB anisotropy
- BSM phenomena have already been observed!

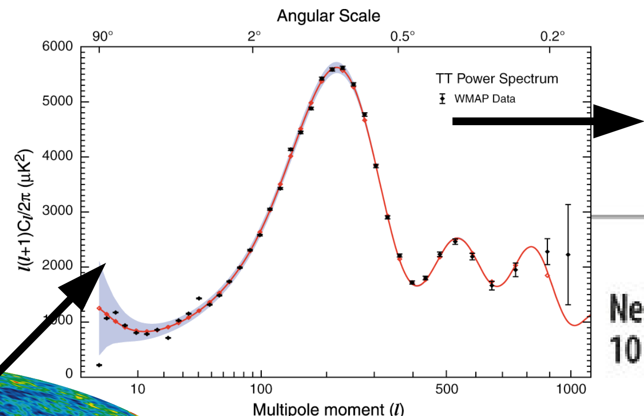


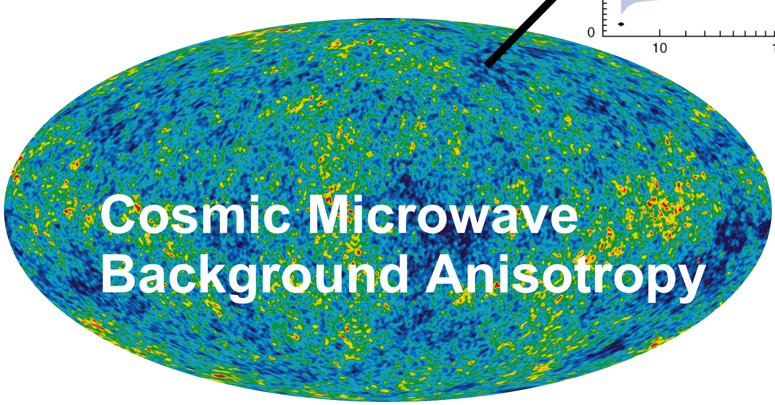


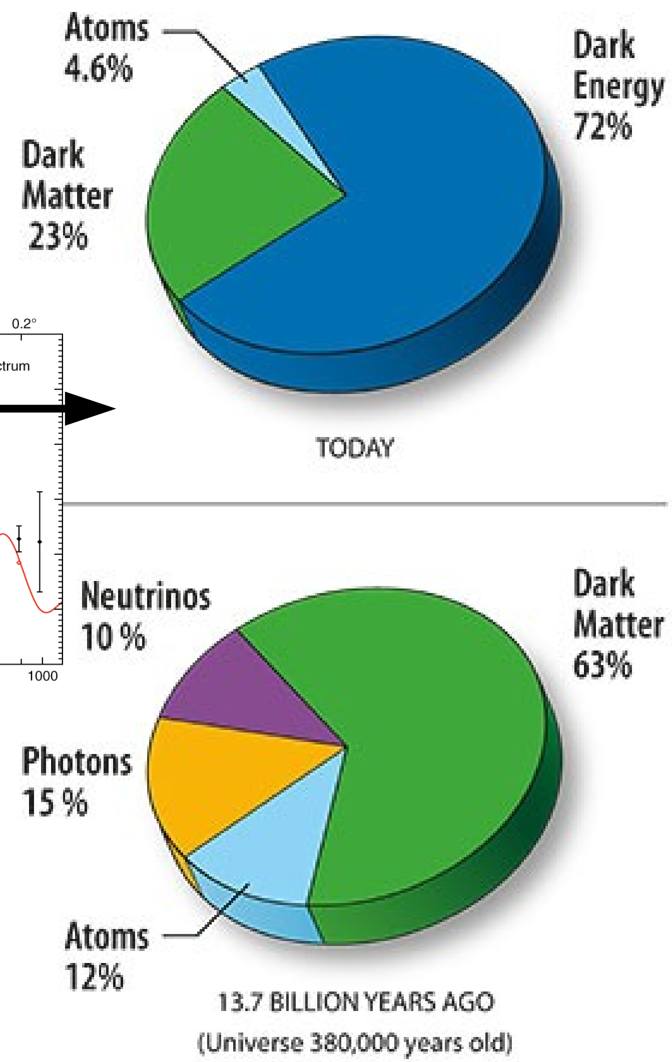


Why look “beyond” the Standard Model?
Dark Matter

- ~ 80% of matter is Dark Matter
- Weakly Interacting Massive Particles? (WIMPS)



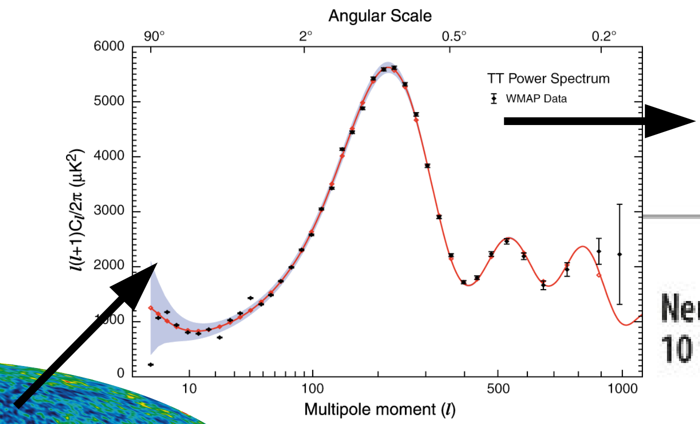


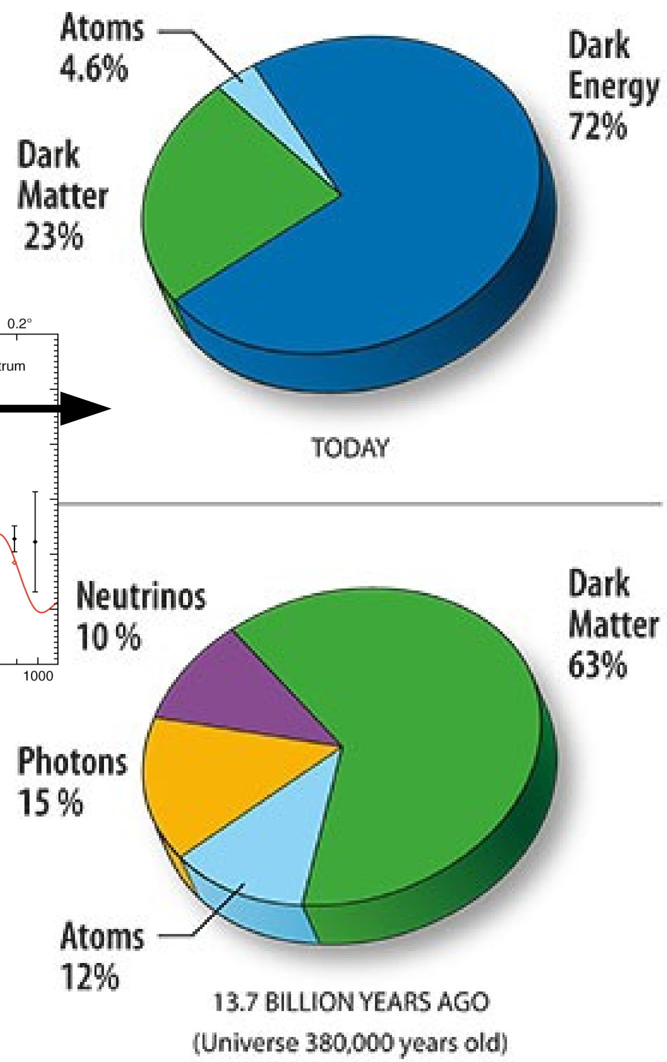


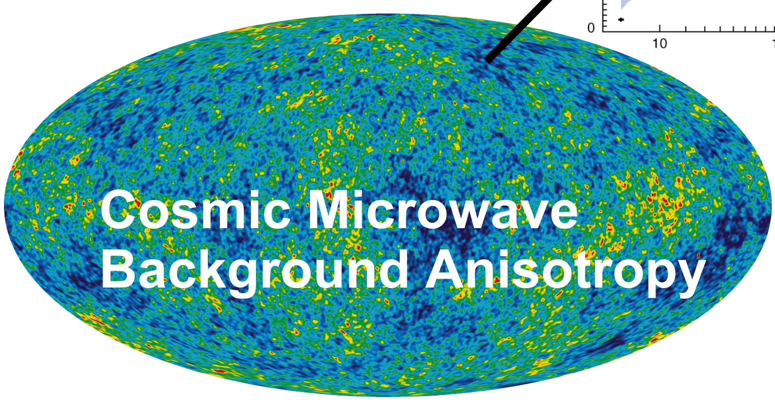
Why look "beyond" the Standard Model?
Dark Energy

- ~ 70% of energy is Dark Energy

???







Why look "beyond" the Standard Model? The main candidates

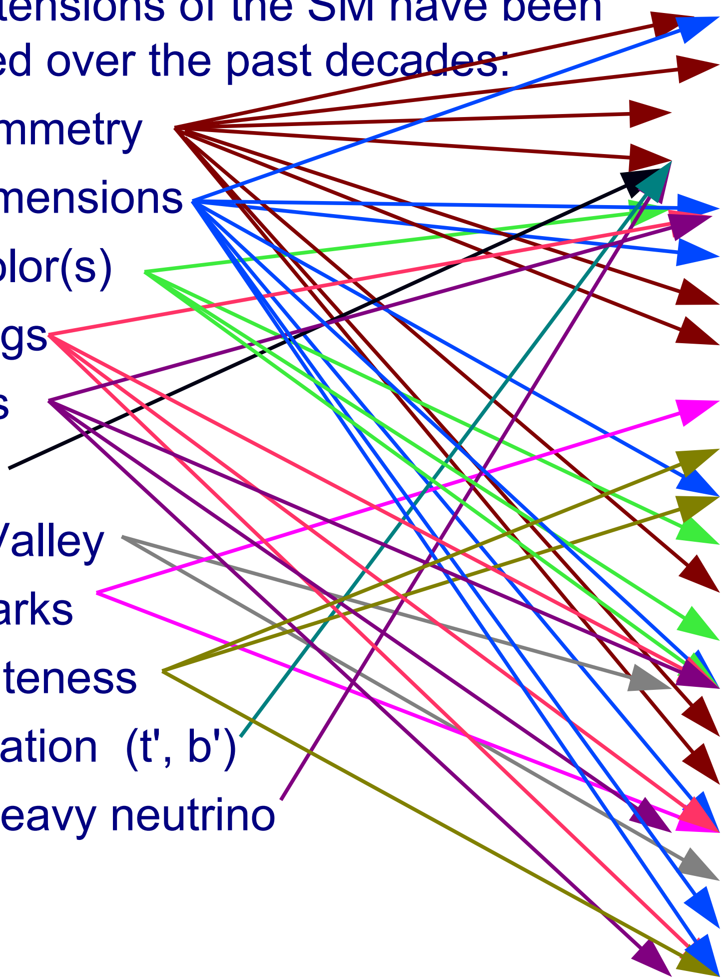
- Many BSM models developped to answer SM limitations:

- Supersymmetry: addresses Hierarchy Problem, offers good Dark Matter candidates
- Technicolor: explains underlying nature of EW SB through strong interaction *
- Extra-dimensions: addresses Hierarchy Problem by bringing the Plank scale down to TeV (i.e. explains why gravity is so weak)
- 4th generation models: new source of CP-violation capable of explaining Matter-Antimatter asymmetry *
- Etc...

* but have a hard time explaining the recent observation at 126 GeV

How do we look for BSM at the LHC? A very long list of models x signatures

- Many extensions of the SM have been developed over the past decades:
- Supersymmetry
- Extra-Dimensions
- Technicolor(s)
- Little Higgs
- No Higgs
- GUT
- Hidden Valley
- Leptoquarks
- Compositeness
- 4^{th} generation (t', b')
- LRSM, heavy neutrino
- etc...



- 1 jet + MET
- jets + MET
- 1 lepton + MET
- Same-sign di-lepton
- Dilepton resonance
- Diphoton resonance
- Diphoton + MET
- Multileptons
- Lepton-jet resonance
- Lepton-photon resonance
- Gamma-jet resonance
- Diboson resonance
- Z+MET
- W/Z+Gamma resonance
- Top-antitop resonance
- Slow-moving particles
- Long-lived particles
- Top-antitop production
- Lepton-Jets
- Microscopic blackholes
- Dijet resonance
- etc...

(for illustration only)

Many models leading to many signatures!

Must proceed methodically (?)

How do we look for BSM at the LHC?
A very long list of models x signatures

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- Dijet resonance
- etc...

A complex 2D problem

Experimentally, a **signature standpoint** makes a lot of sense:

→ Practical

→ Less model-dependent

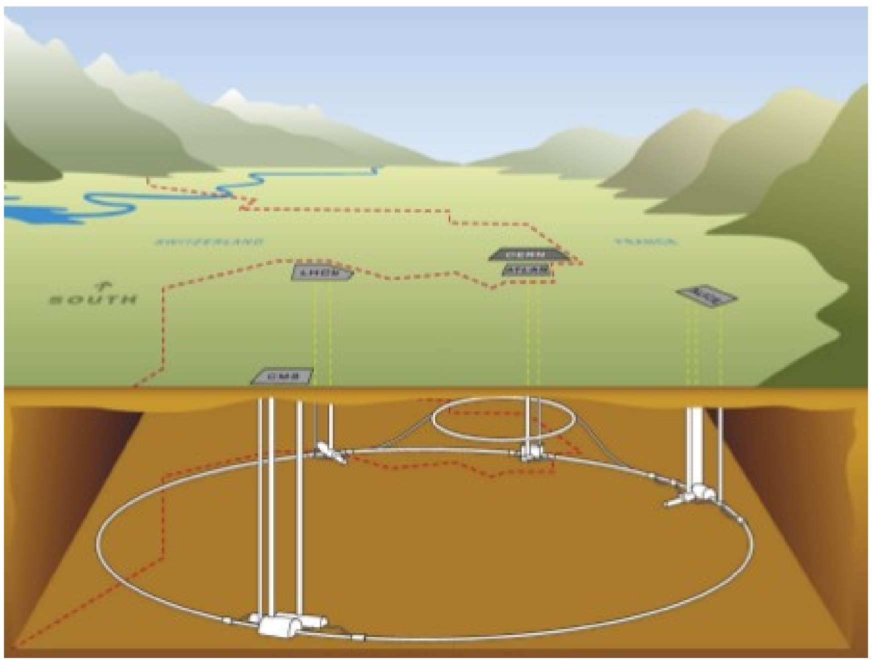
→ Important to cover every possible signature

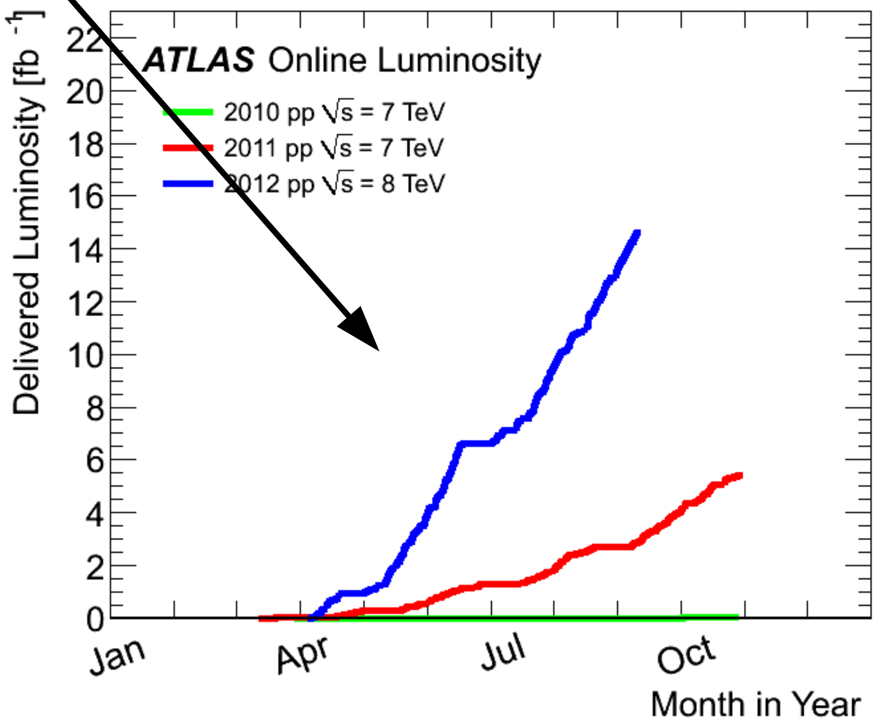
How do we look for BSM at the LHC? Looking for models or for signatures?

- Several types of searches:
- Very model-specific:
  - → Ex: monopole search
  - → Look for highly-ionizing particle that bends in the wrong direction
- Very model-independent:
  - → Ex: inclusive search for same-sign leptons
- Somewhere In-between (most analyses):
  - → motivated by a particular model, but tries to remain inclusive
  - → Ex: SUSY analysis looking for final state with jets and missing ET

The Large Hadron Collider (LHC)

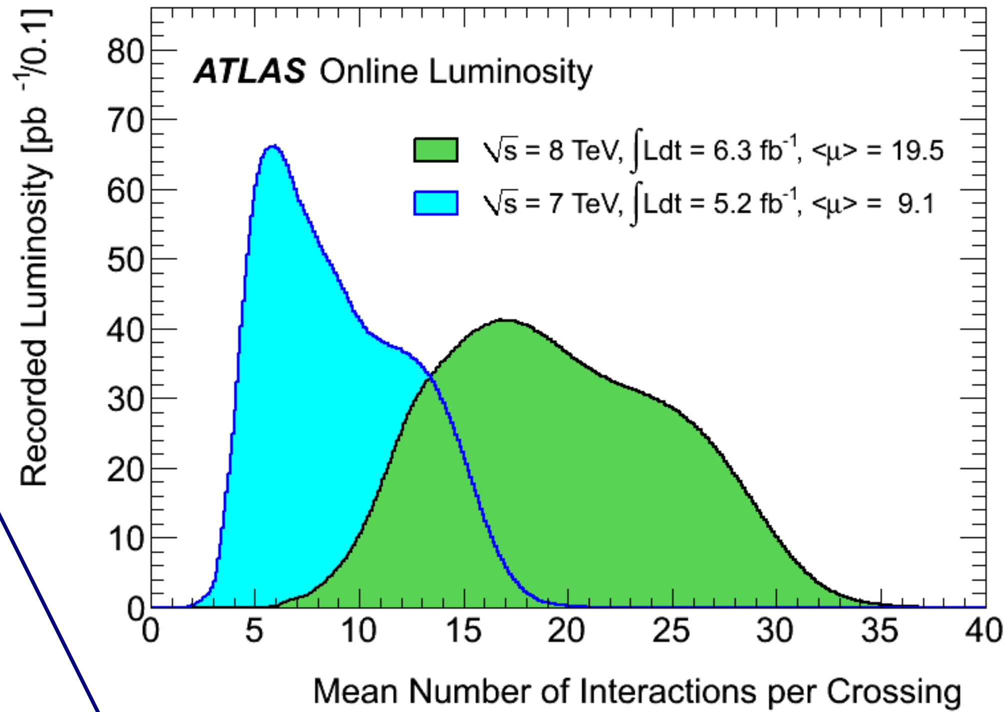
- LHC has performed extremely well:
  - → 5.3 fb^{-1} at $\sqrt{s}$ = 7 TeV delivered in 2011
  - → Already ~ 15 fb^{-1} at $\sqrt{s}$ = 8 TeV delivered in 2012, expect close to 30 fb^{-1} by the end of the the year!
- Past 2 years: significant gain every 6 months: difficult to keep up!

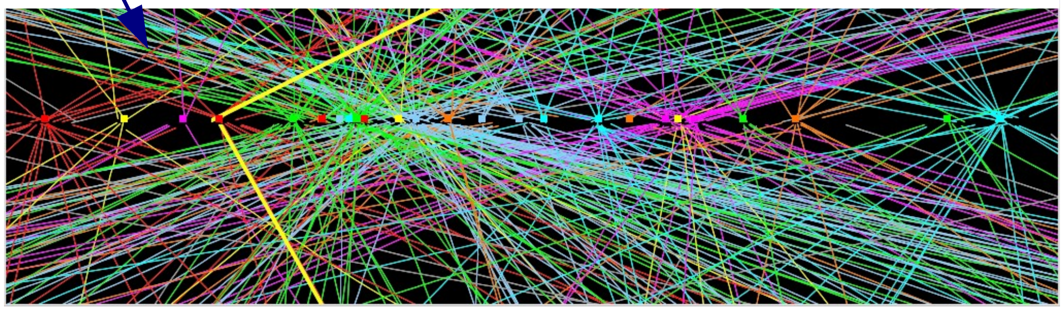




Pile-up: several proton-proton interactions in each bunch-crossing

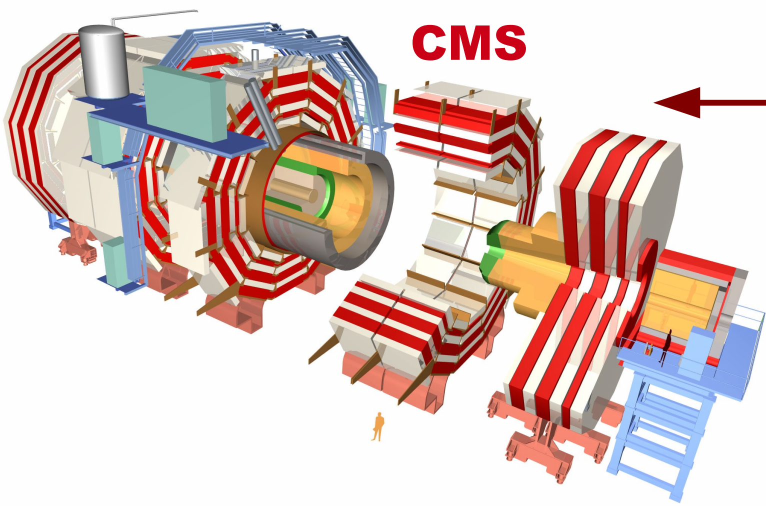
- $Z \rightarrow$ mu mu event... and 24 other collisions from the same bunch-crossing (a.k.a. “in-time pile-up”)





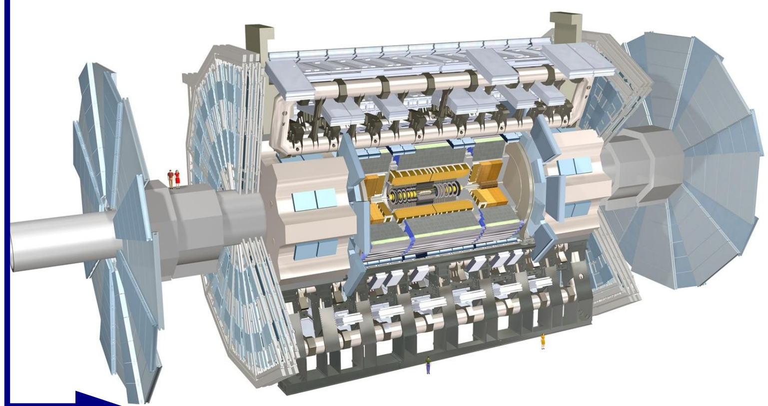
- Due to small bunch spacing (50 ns), also effect from collisions from previous and next crossings (a.k.a. “out-of-time pile-up”)

The ATLAS and CMS Detectors: same goals, different choices

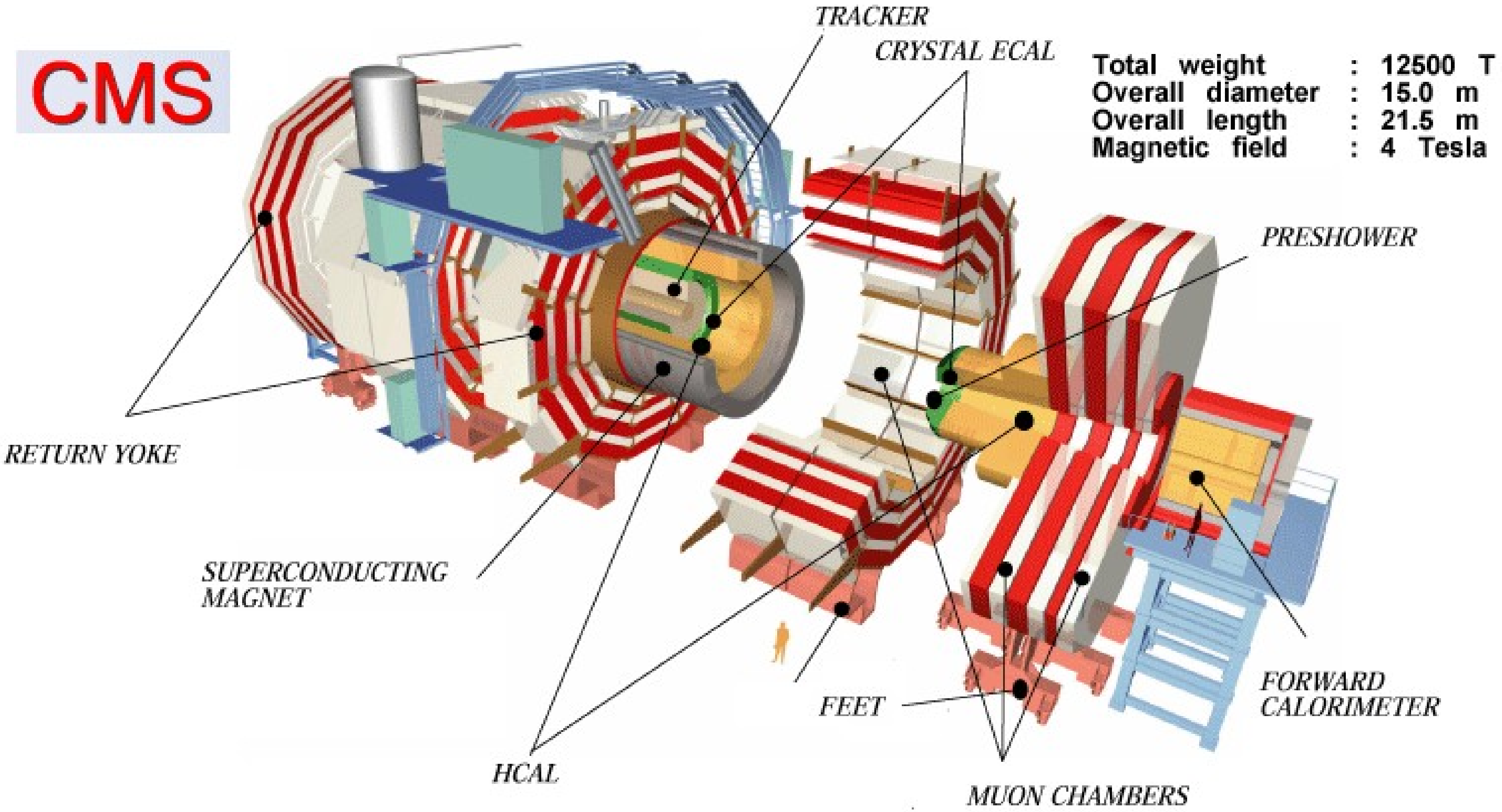


- 3.8T solenoid containing calorimeters
- Silicon tracker: $\sigma(p_T)/p_T \sim 15\%$ at 1TeV
- EM cal: homogeneous Lead-Tungstate crystal, $\sigma_E/E \sim 3\%/\sqrt{E[GeV]} \oplus 0.5\%$
- HAD cal: Brass-scint., $\geq 7\lambda_0$
  $\sigma_E/E \sim 100\%/\sqrt{E[GeV]} \oplus 5\%$
- Iron return yoke muon spectrometer

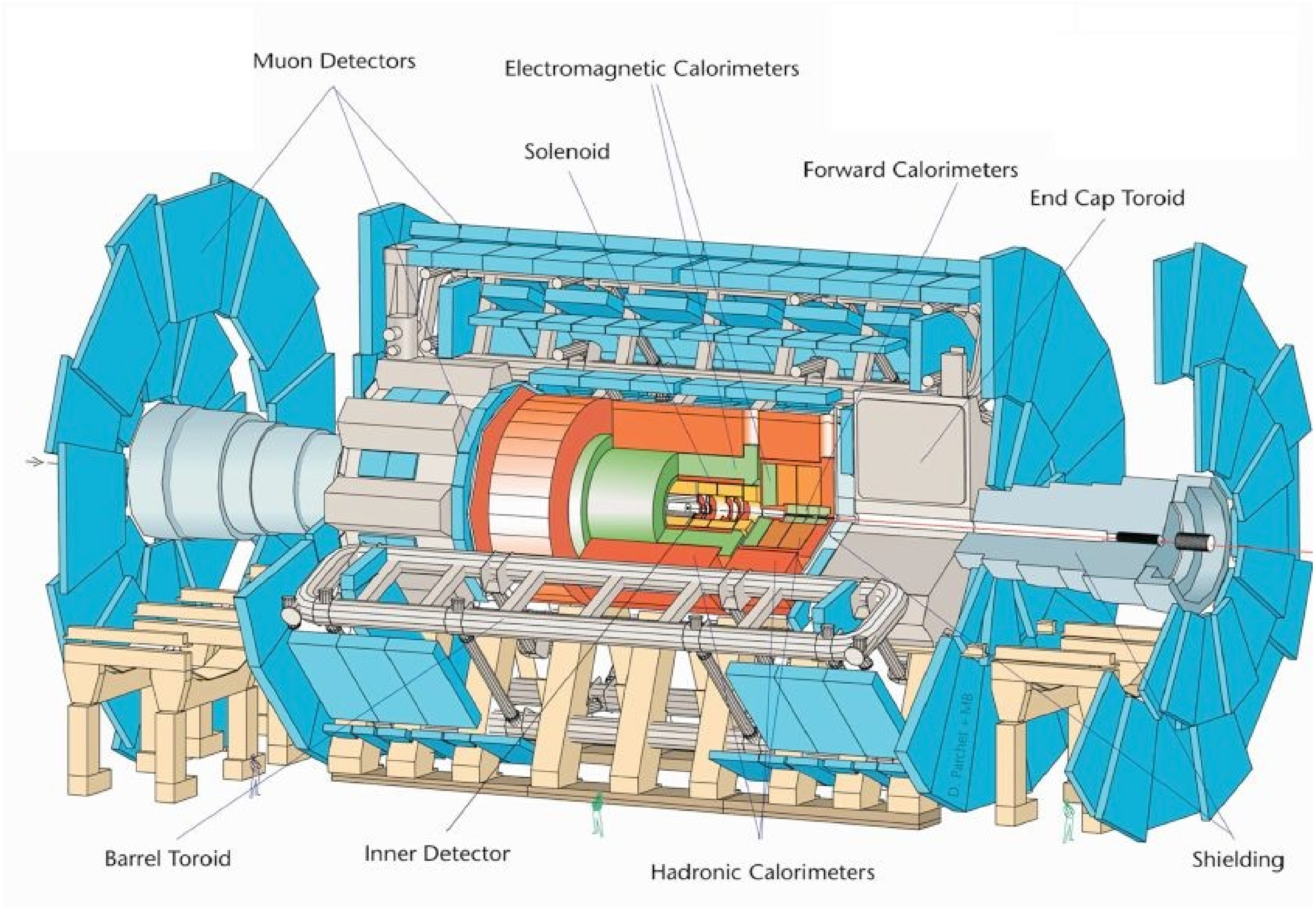
- 2T solenoid inside calorimeters
- Silicon+TRT tracker + electron ID
- EM cal: Longitudinally segmented Lead-Ar:
  $\sigma_E/E \sim 10\%/\sqrt{E[GeV]} \oplus 0.7\%$
- HAD cal: Fe-scint + Cu-Ar, $\geq 11\lambda_0$
  $\sigma_E/E \sim 50\%/\sqrt{E[GeV]} \oplus 3\%$
- Air-toroid muon sp.: $\int \sqrt{B}.dl = 1$ to 7 T.m



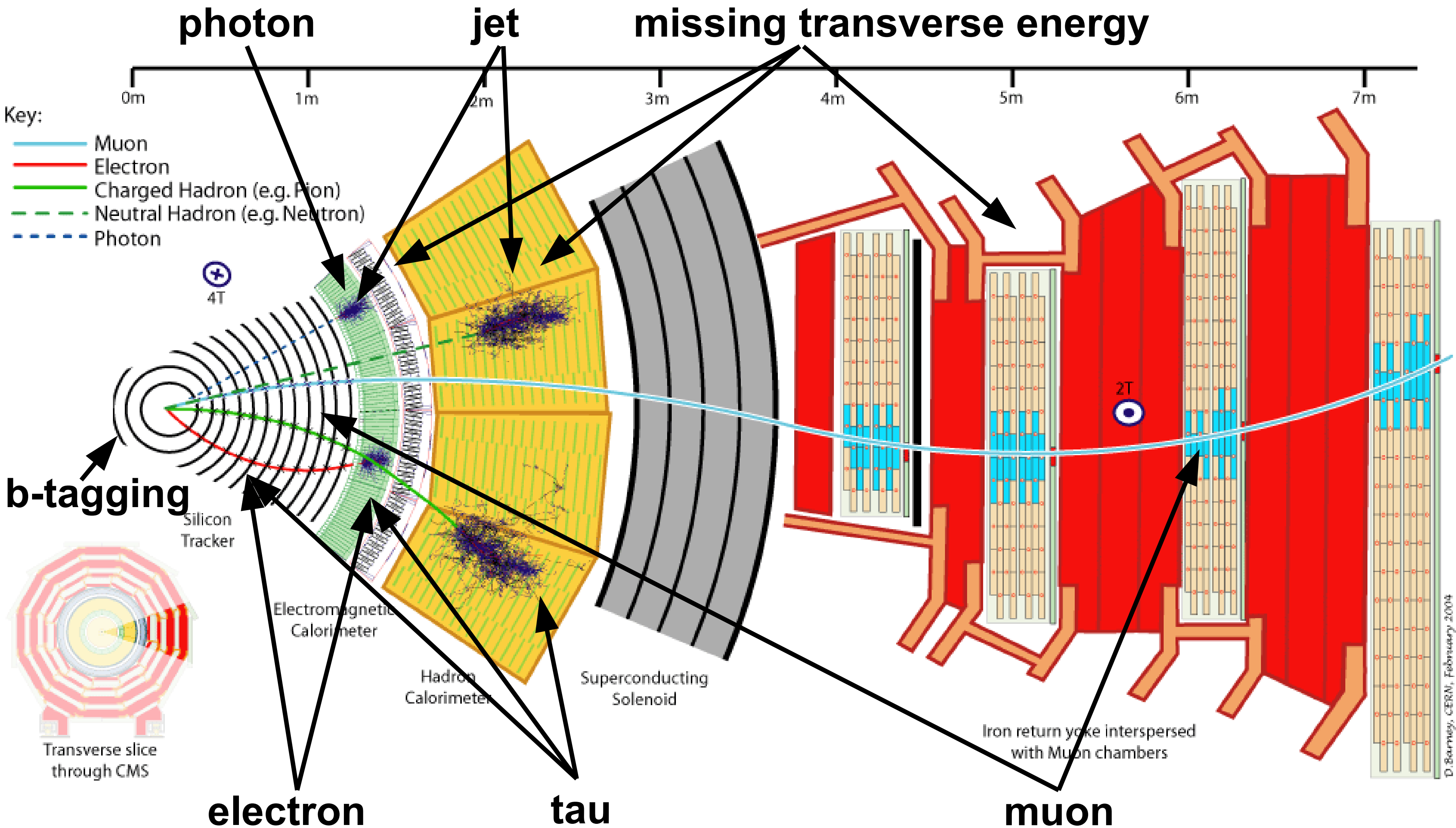
The CMS Detector



The ATLAS Detector



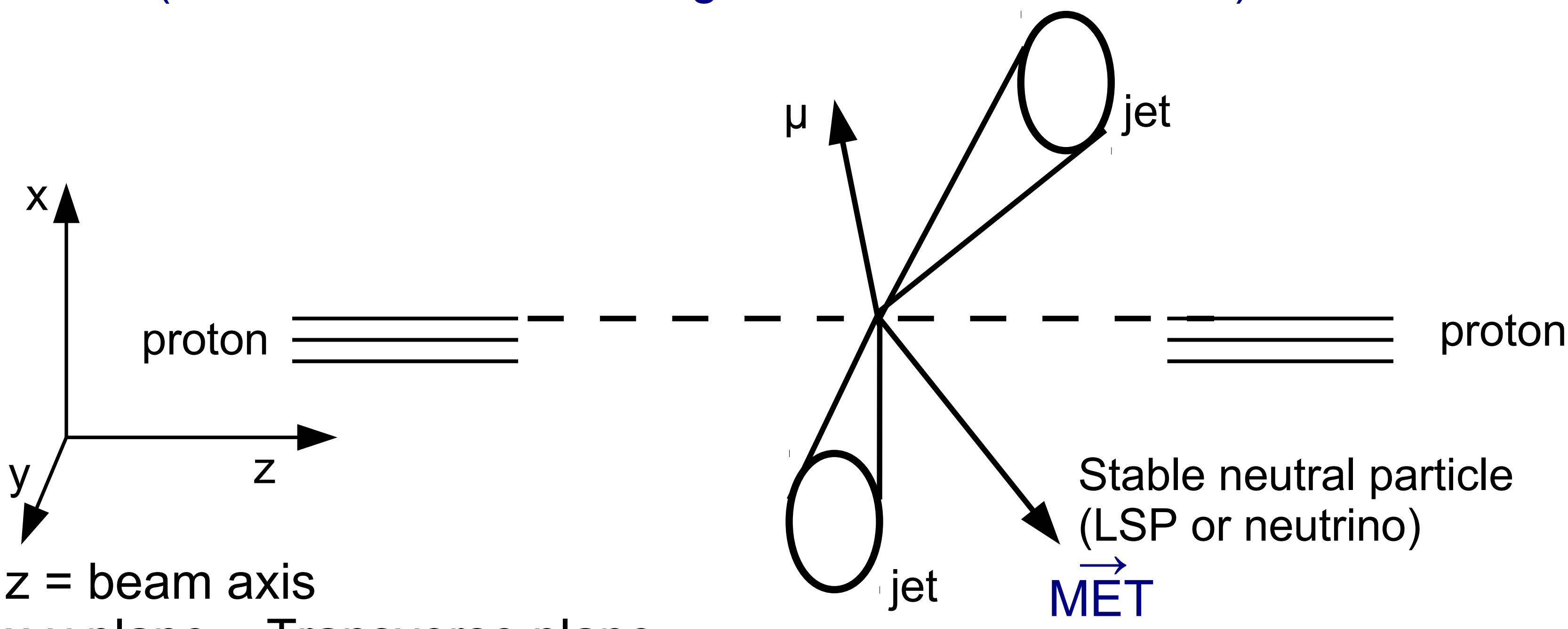
A word about Object Reconstruction



A word about Object Reconstruction

Missing Transverse Energy = $-\Sigma \vec{p}_T(\text{calo}) - \Sigma \vec{p}_T(\text{muon}) = p_T$ (undetected)

(should be called missing transverse momentum)



z = beam axis

x-y plane = Transverse plane

p_z(proton) = 4 TeV

p_z(parton) = ? TeV

p_T(parton) = 0 Tev

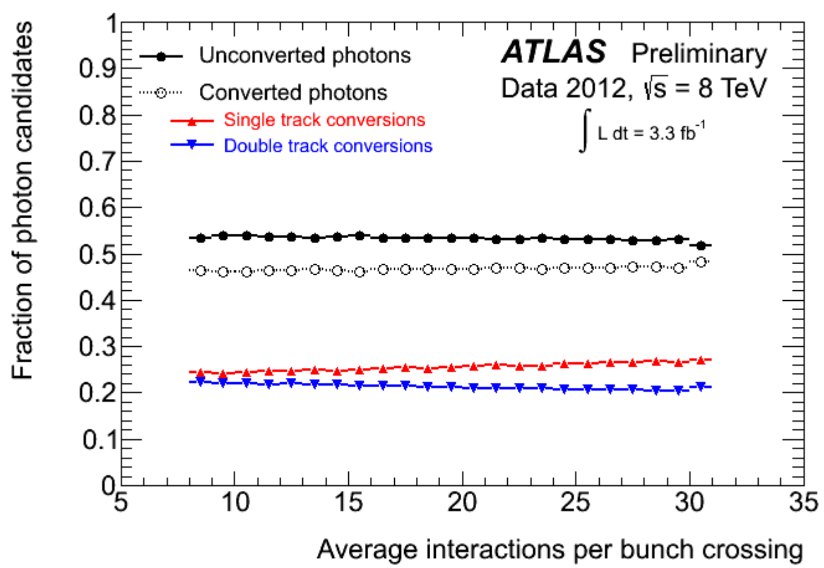
Momentum conservation:

$\Sigma \vec{p}_T$ (final state) = $\vec{p}_T$(partons) = $\vec{0}$

A word about Object Reconstruction

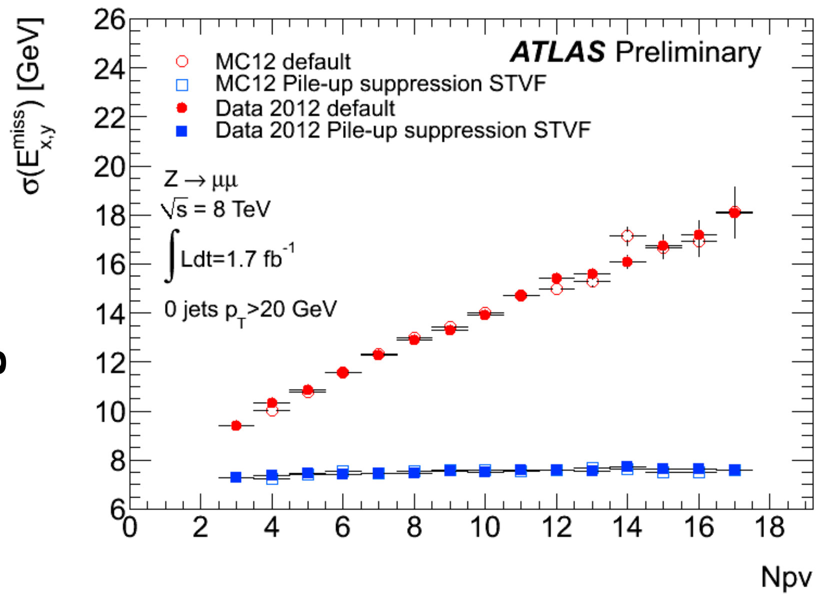
- A lot of work put into coping with pile-up

Photon efficiency

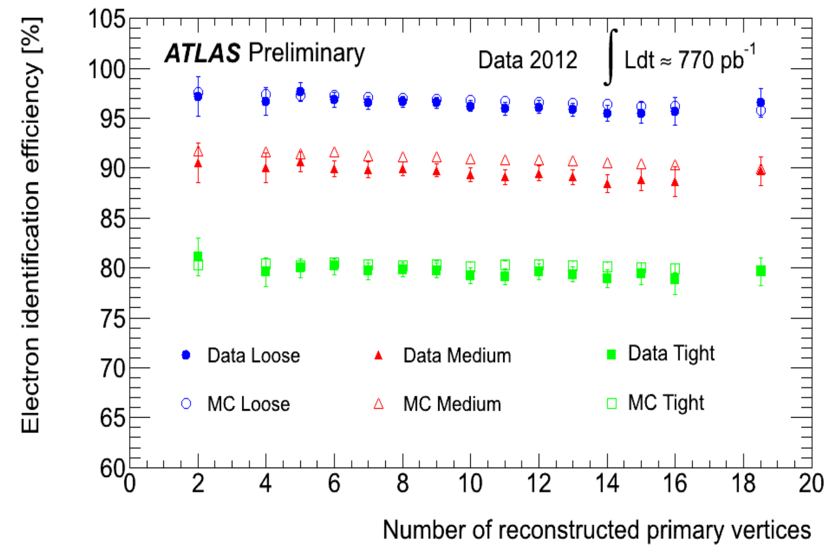


Number of events per crossing

Missing ET Resolution

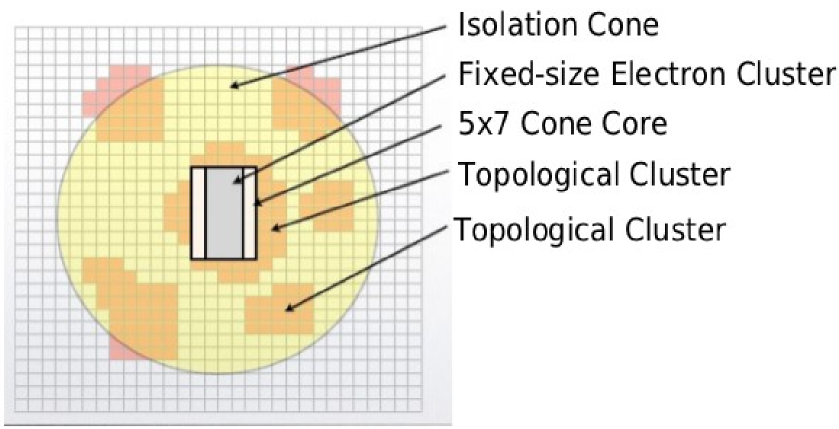


Electron efficiency

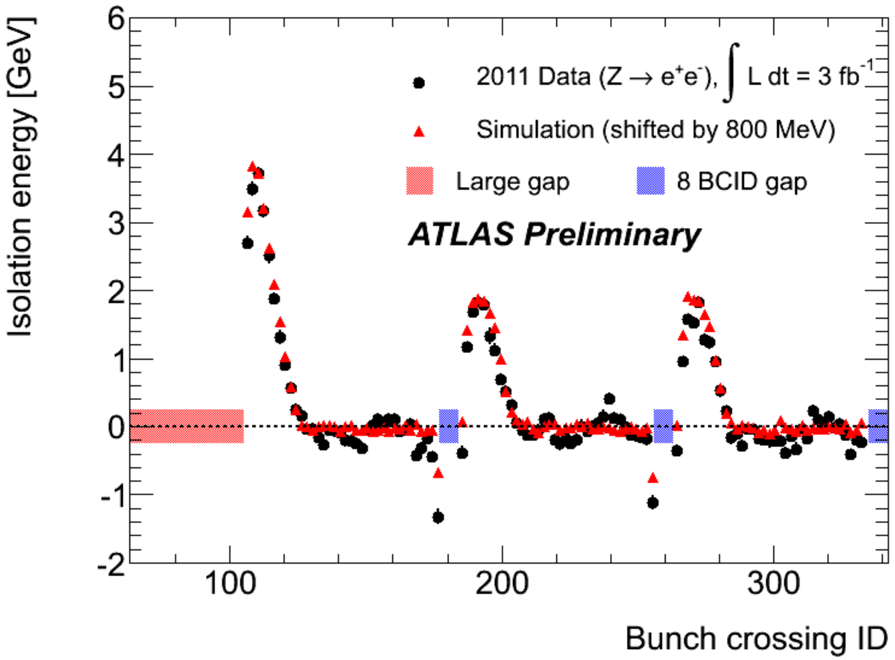


Pile-up and Calorimeter Isolation

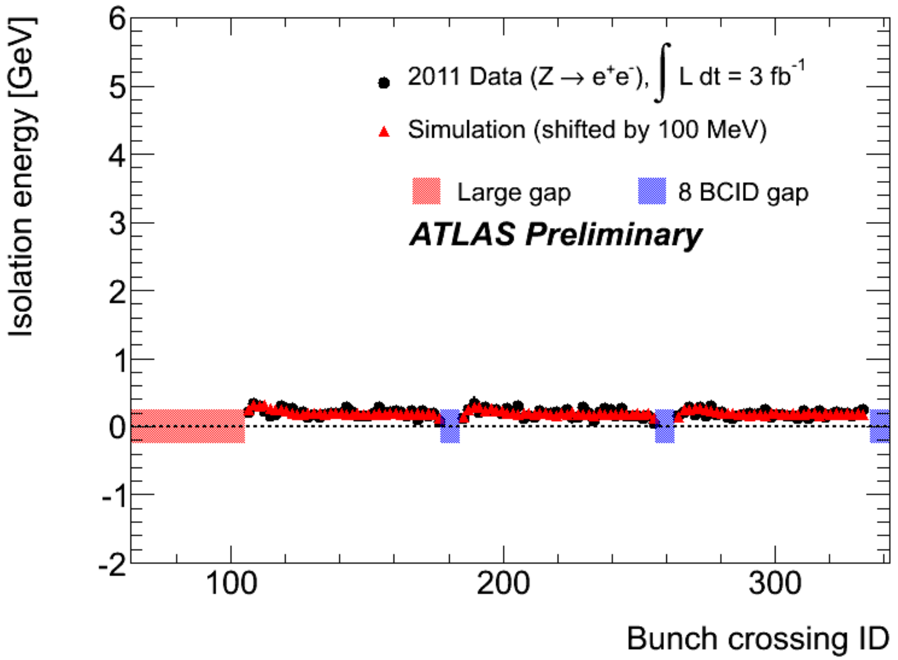
- "Isolation": amount of energy surrounding a lepton
- Crucial variable to reject fake leptons



Cell-based isolation:

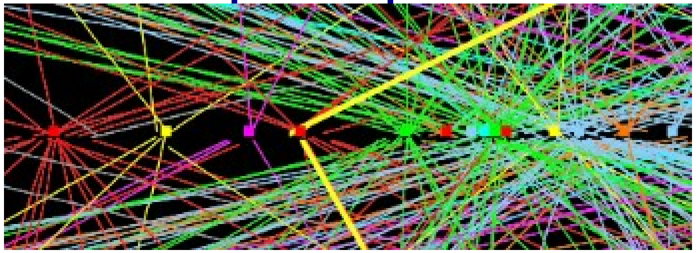


Topo-Cluster isolation:

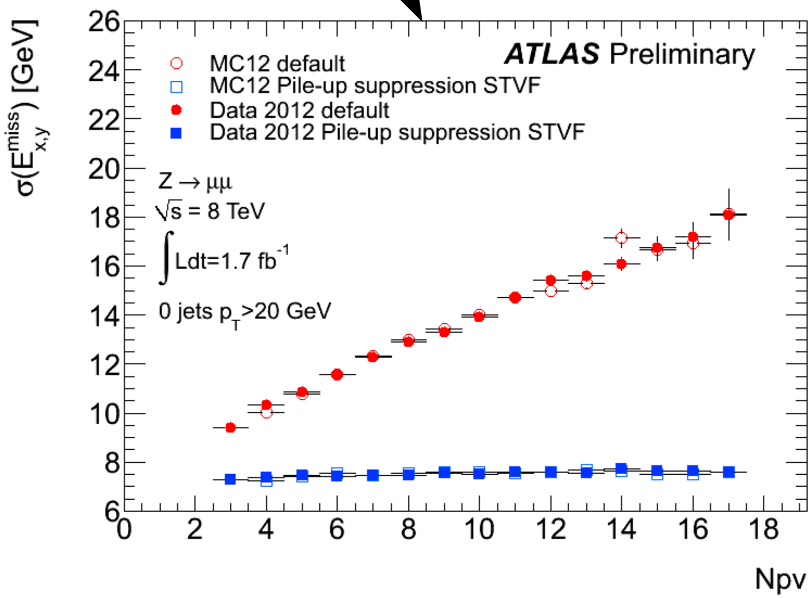


Missing ET and pile-up

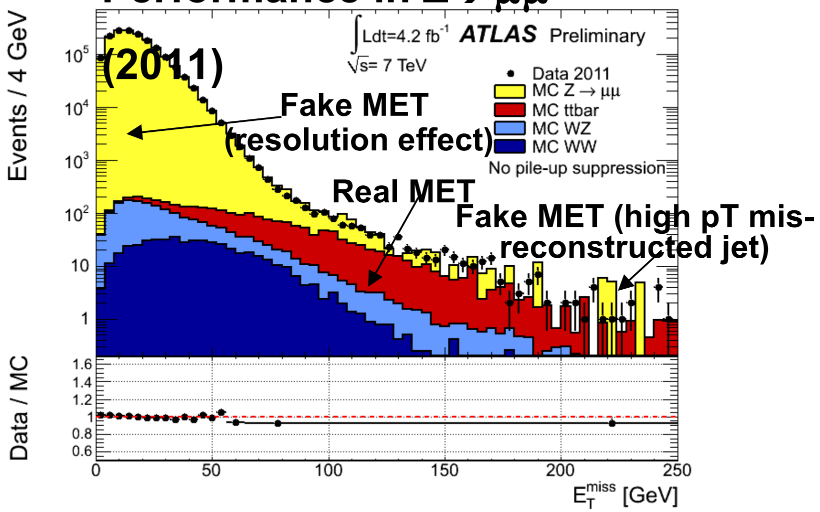
- Use fraction of tracks from the Primary Vertex associated to a jet (a.k.a Jet Vertex Fraction) to correct for pile-up:
- Similarly, correct energy not associated with jets (a.k.a. Soft Term Vertex Fraction)



$$\sum_{\text{track,PV}} p_T / \sum_{\text{track}} p_T$$



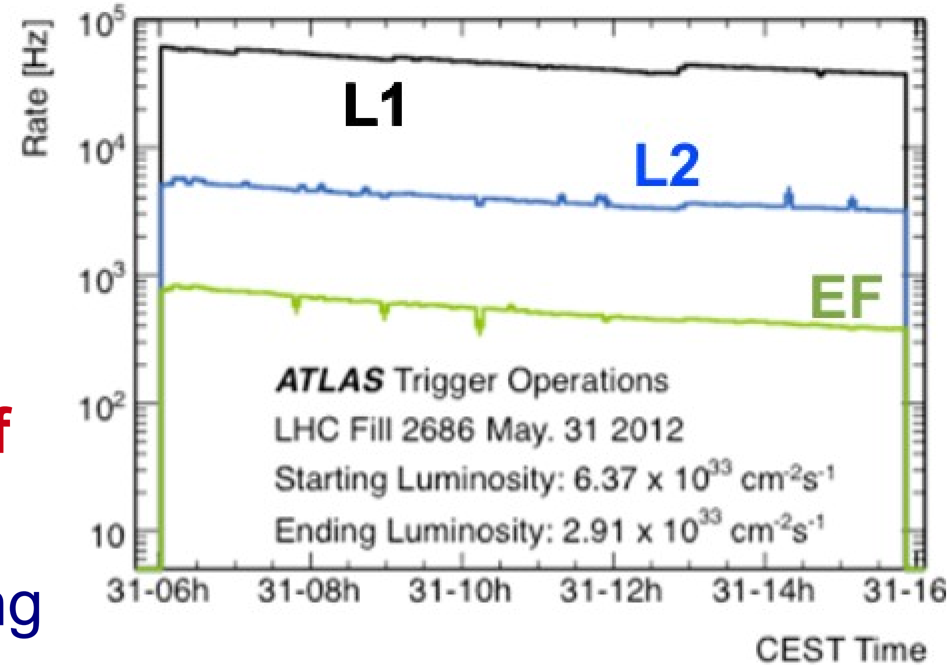
Performance in Z→μμ



A word about Trigger

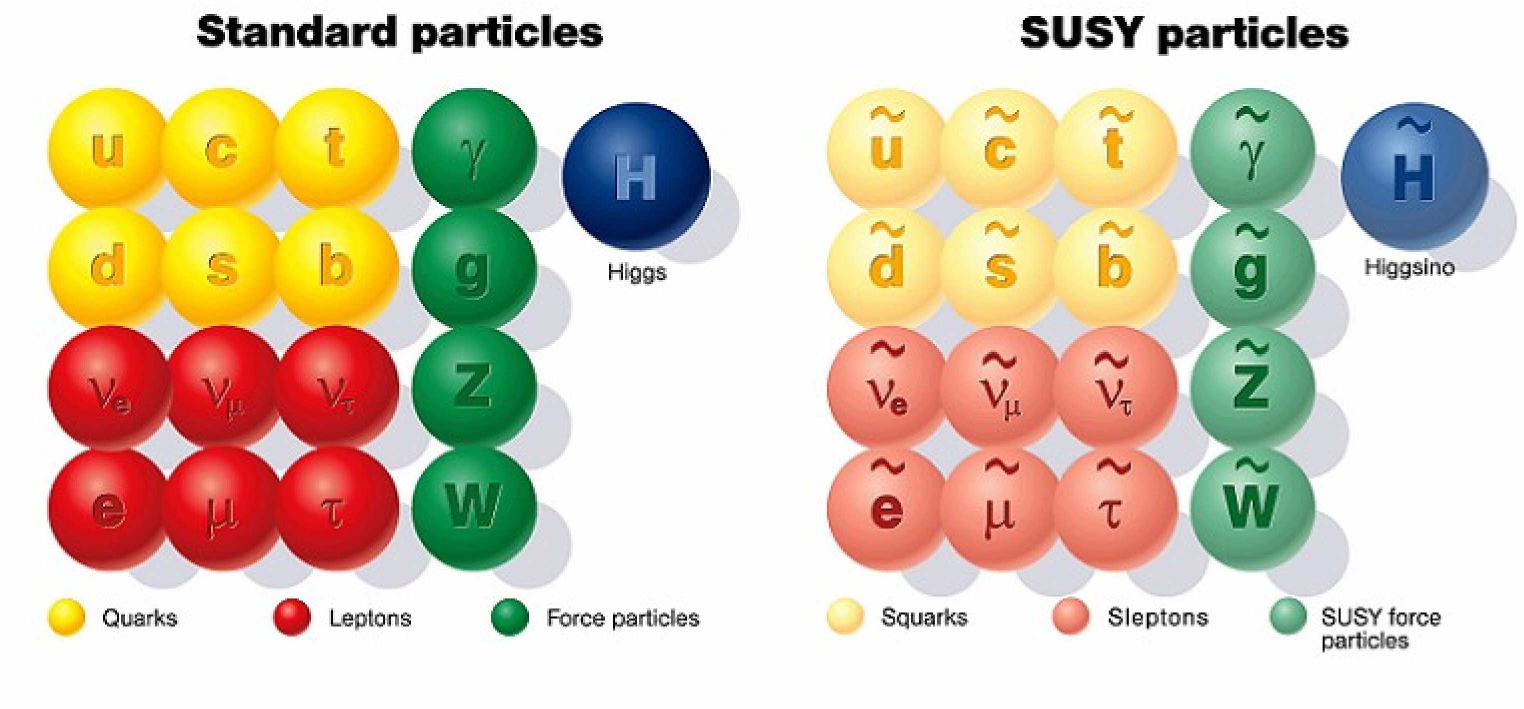
- Bunch spacing = 50 ns → collision rate = 20 MHz
- Recording events on disc at 400 Hz only

  → **We record only ~ 1 out of 100000 events!**
- In ATLAS, 3 levels of triggering
- Maximum rates:



collisions	Level 1	Level 2	Event Filter	Reconstruction (average rate)
20 MHz	75 MHz	6 kHz	900 Hz	400 Hz

Supersymmetry



Supersymmetry

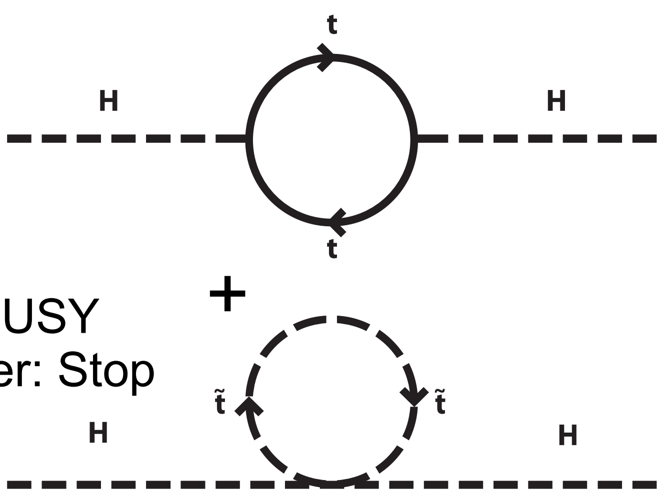
- Extension of the Poincaré algebra
- Fermion ↔ Boson symmetry
- Predicts new spectrum of supersymmetric particles

<u>The pro's:</u>

- Theoretically pleasing
  - → Ingredient to string theory
- Solves many problems of the SM. Ex: stabilizes Higgs sector
- Excellent Dark Matter candidate

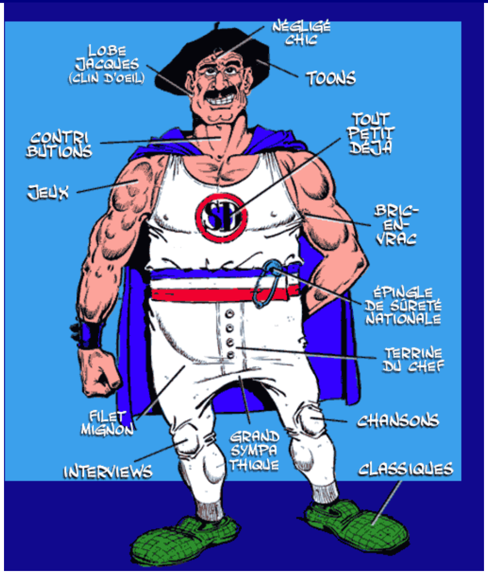
Top

Top SUSY Partner: Stop



≈ 0 (if $\tilde{t}$ is light)

Supersymmetry

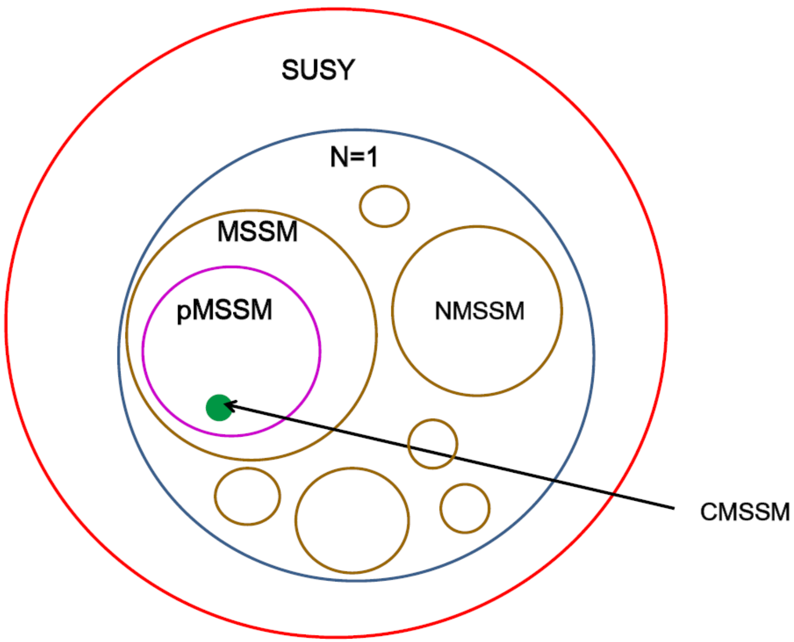


- Extension of the Poincaré algebra
- Fermion ↔ Boson symmetry
- Predicts new spectrum of supersymmetric particles

<u>The con's:</u>

- It has not been seen yet:
  - → Must be seriously broken: m(selectron) >> m(electron)
  - → To avoid lepton/baryon # violation, must add R-parity: $R = (-1)^{3(B-L)+2s}$ (spin)
    Side effect: Lightest SUSY Particle (LSP) is stable → Excellent Dark Matter candidate
- Many free parameters

Which Supersymmetry?
SUSY Phenomenology is <u>Very</u> Diverse



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

SUSY

N = 1 → Minimal SUSY SM (MSSM)
2 Higgs doublets
105 free parameters

N > 1 → Ex: scalar gluon search

MSSM →

R-parity cons.
LSP is Dark Matter candidate

R-parity violation
add 48 free parameters
Lepton/Baryon # violation
Resonances
Long-lived particles

R-parity cons. →

Constrained models. 5 free parameters:
- Minimal SUperGRAvity / CMSSM
- Gauge-Mediated SUSY-breaking
Cascades with large missing energy
- AMSB: long-lived particles

Split SUSY
Long-lived Particles

Stealth SUSY: compressed spectrum
No missing energy
Long-lived Particles

The MSSM and the Constrained MSSM

- MSSM: N=1 and 2 Higgs Doublets. 105 free parameters
- CMSSM / mSUGRA: down to 5 parameters
  - → Strong assumptions, esp. on universality of the 3 generations

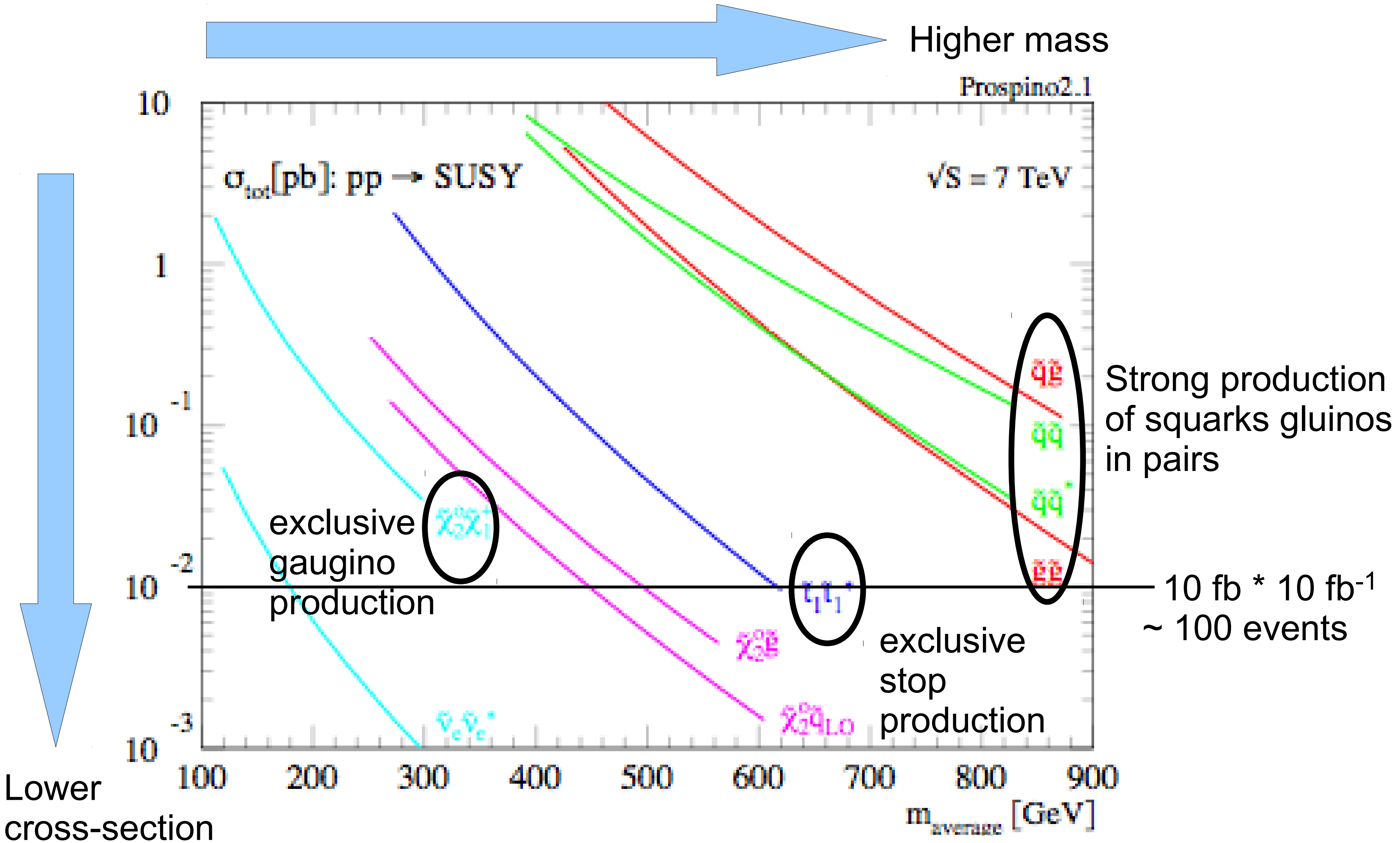
MSSM: 29 sparticles + 5 Higgs

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	$\widetilde{u}_L\ \widetilde{u}_R\ \widetilde{d}_L\ \widetilde{d}_R$	(same)
			$\widetilde{s}_L\ \widetilde{s}_R\ \widetilde{c}_L\ \widetilde{c}_R$	(same)
			$\widetilde{t}_L\ \widetilde{t}_R\ \widetilde{b}_L\ \widetilde{b}_R$	$\widetilde{t}_1\ \widetilde{t}_2\ \widetilde{b}_1\ \widetilde{b}_2$
sleptons	0	−1	$\widetilde{e}_L\ \widetilde{e}_R\ \widetilde{\nu}_e$	(same)
			(Bino) $\widetilde{\mu}_L$ (Wino) $\widetilde{\mu}_R\ \widetilde{\nu}_\mu$ (Higgsino)	(same)
			(Wino) $\widetilde{\tau}_L\ \widetilde{\tau}_R\ \widetilde{\nu}_\tau$ (Higgsino)	$\widetilde{\tau}_1\ \widetilde{\tau}_2\ \widetilde{\nu}_\tau$
neutralinos	1/2	−1	$\widetilde{B}^0\ \widetilde{W}^0\ \widetilde{H}_u^0\ \widetilde{H}_d^0$	$\widetilde{N}_1\ \widetilde{N}_2\ \widetilde{N}_3\ \widetilde{N}_4$
charginos	1/2	−1	$\widetilde{W}^\pm\ \widetilde{H}_u^+\ \widetilde{H}_d^-$	$\widetilde{C}_1^\pm\ \widetilde{C}_2^\pm$
gluino	1/2	−1	$\widetilde{g}$	(same)
goldstino (gravitino)	1/2 (3/2)	−1	$\widetilde{G}$	(same)

MSUGRA parameters:

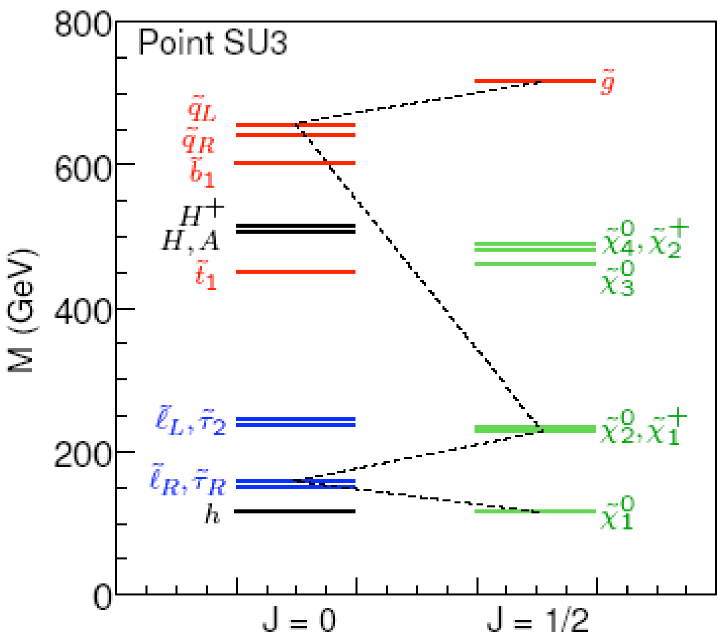
- m_0 : mass of scalars (squarks and sleptons) at GUT scale
- $m_{1/2}$: mass of fermions (gluinos and gauginos) at GUT scale
- A_0 : trilinear couplings
- $\tan\beta = \langle H_u \rangle / \langle H_d \rangle$
- Sign of μ

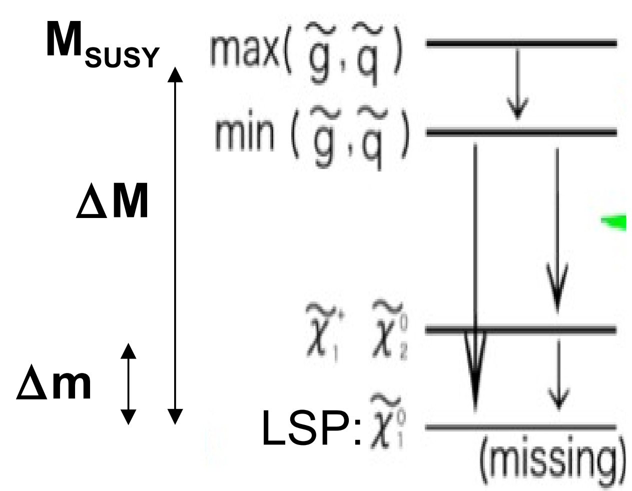
Supersymmetry: Production at LHC



Supersymmetry: Cascades at the LHC

- Cascade depends on SUSY mass spectrum
- Missing ET caused by LSP escaping detector
  - → Larger Missing ET if ΔM is large
  - → “compressed” SUSY: small ΔM and ~ no missing ET



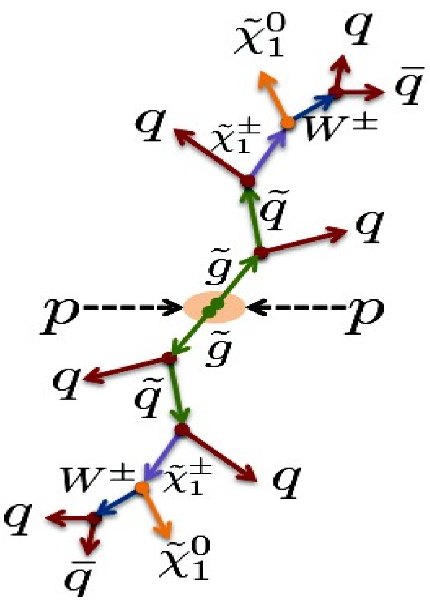


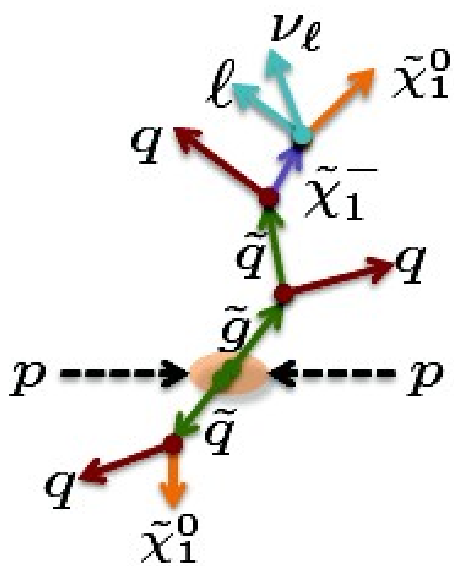
Missing ET ~ ΔM
Total event energy ~ $2M_{SUSY}$

Supersymmetry: Cascades at the LHC

- Some typical cascades:

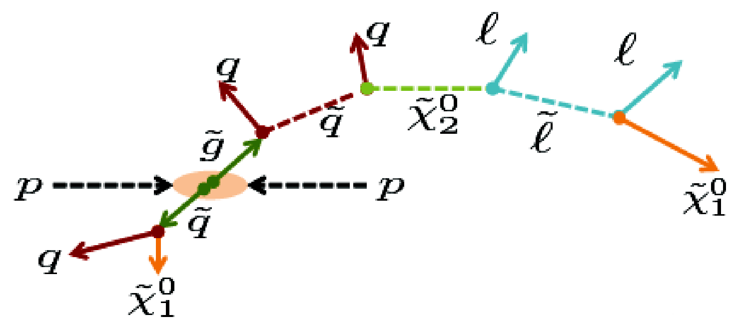
Many jets and missing ET





Jets and missing ET
and one lepton (e or mu or tau)

Jets and missing ET
and two or more leptons
(possibly of same sign)



Looking for squarks and gluinos Jets + Missing E_T (a.k.a. "0-lepton")

$\tilde{q} \rightarrow q\tilde{\chi}_1^0$

$\tilde{g} \rightarrow qq\tilde{\chi}_1^0$

- "Workhorse" analysis of SUSY+MET searches
- Several analyses developped by ATLAS and CMS. Use the ATLAS analysis as an example:
- Select events with 2 to 6 jets
- Veto leptons and events with > 6 jets (left to dedicated high-multiplicity analysis)
- Trigger: Jet p_T > 75 GeV and Missing E_T > 55 GeV

  ε > 98% above turn-on
- Discriminant variables:
  - → H_T = sum of jet p_T (including jets with p_T > 40 GeV and $|\eta| < 2.8$)
  - → $m_{eff} = H_T$ + Missing E_T
- Optimize cut on m_{eff} and Missing ET for each jet multiplicity

SUSY: Jets + Missing E_T

$\tilde{q} \rightarrow q\tilde{\chi}_1^0$

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ATLAS 7 TeV analysis selection: 11 signal regions
(re-optimized a bit for 8 TeV)

above trigger turn-on

Cut-and-count in each signal region

Requirement	Channel					
	A	A'	B	C	D	E
E_T^{miss}[GeV] >	160					
$p_T(j_1)$ [GeV] >	130					
$p_T(j_2)$ [GeV] >	60					
$p_T(j_3)$ [GeV] >	–	–	60	60	60	60
$p_T(j_4)$ [GeV] >	–	–	–	60	60	60
$p_T(j_5)$ [GeV] >	–	–	–	–	40	40
$p_T(j_6)$ [GeV] >	–	–	–	–	–	40
$\Delta\phi(\text{jet}, E_T^{miss})_{min}$ >	0.4 ($i = \{1, 2, (3)\}$)			0.4 ($i = \{1, 2, 3\}$), 0.2 (p_T > 40 GeV jets)		
$E_T^{miss}/m_{eff}(Nj)$ >	0.3 (2j)	0.4 (2j)	0.25 (3j)	0.25 (4j)	0.2 (5j)	0.15 (6j)
m_{eff}(incl.) [GeV] >	1900/1400/–	–/1200/–	1900/–/–	1500/1200/900	1500/–/–	1400/1200/900

Jet p_T

ETmiss and m_{eff}

2 jets 3 4 5 6

SUSY: Jets + Missing E_T

$$\tilde{q} \rightarrow q\tilde{\chi}_1^0$$
$$\tilde{g} \rightarrow qq\tilde{\chi}_1^0$$

- Low jet-multiplicity: sensitive to squark production
- High jet-multiplicity: sensitive to gluino production

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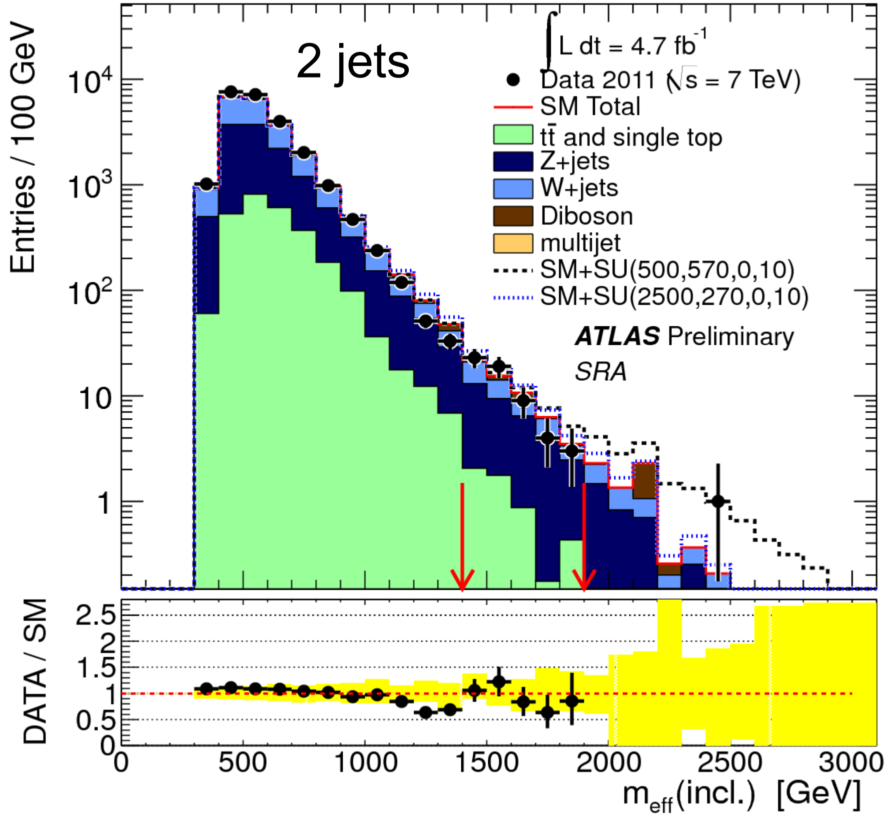

m_{eff} = H_T + Missing E_T

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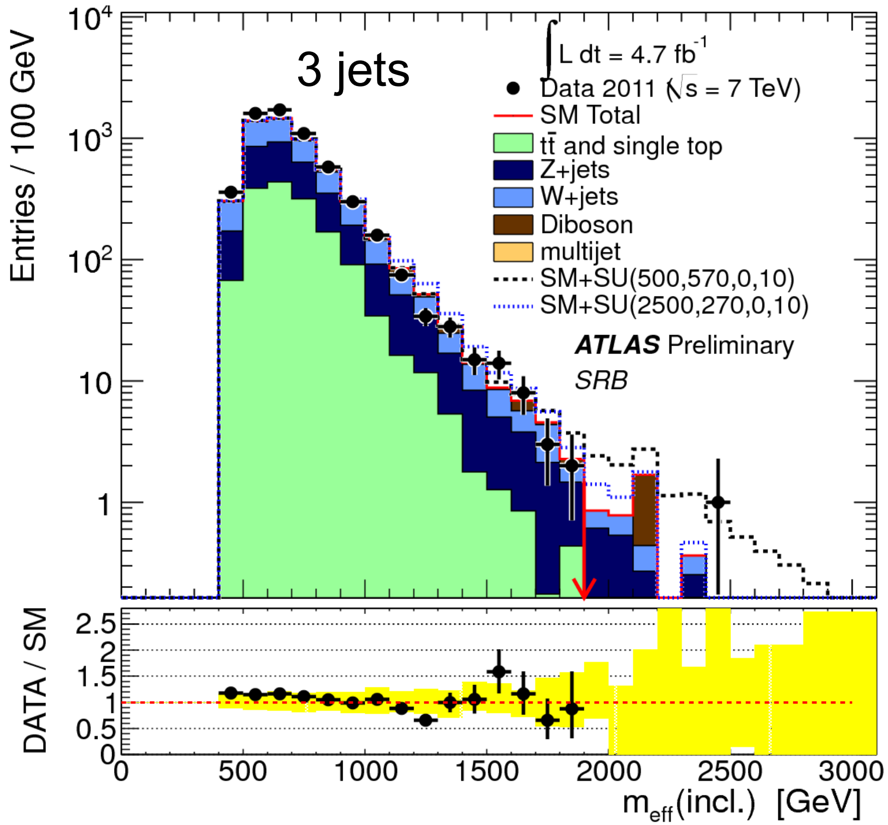

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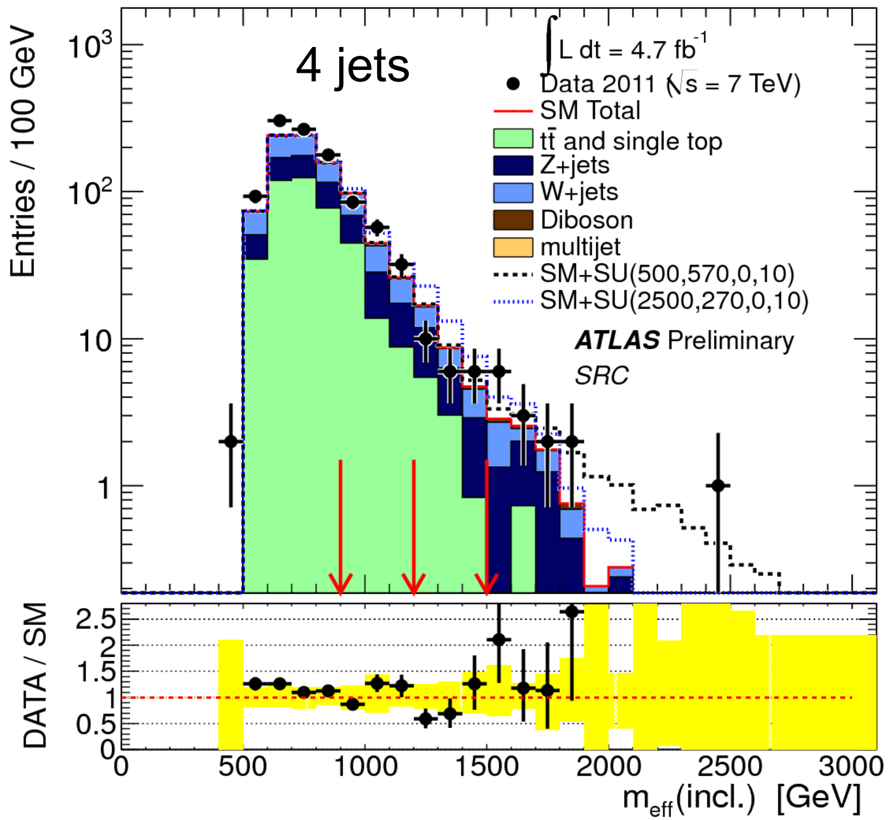

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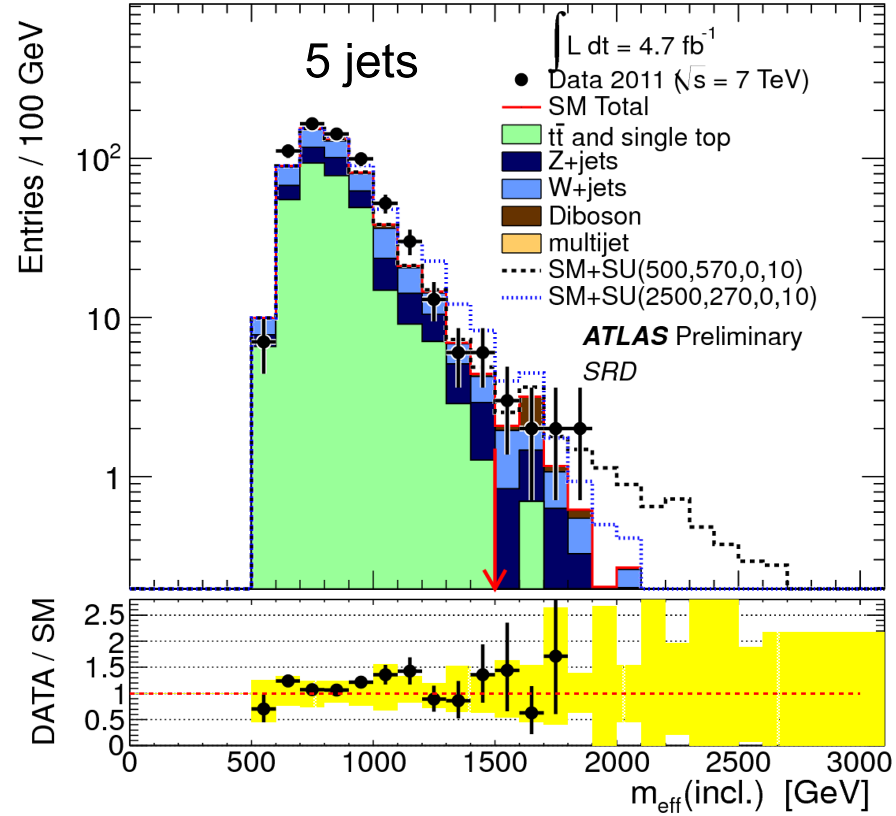

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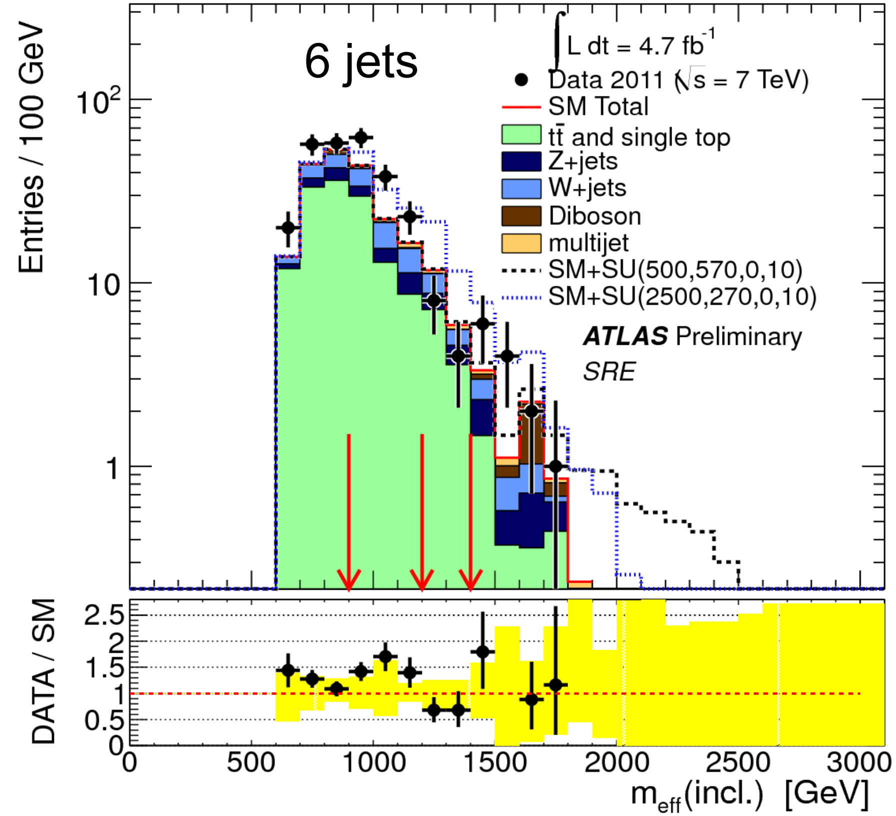


m_{eff} = H_T + Missing E_T

SUSY: Jets + Missing E_T

$\tilde{q} \to q\tilde{\chi}_1^0$

$\tilde{g} \to qq\tilde{\chi}_1^0$

- Background estimation is (mostly) data-driven
- Define control regions with enhanced background:

CR	SR background	CR process	CR selection
CRY	$Z(\to \nu\nu)$+jets	γ+jets	Isolated photon
CRQ	QCD jets	QCD jets	Reversed $\Delta\phi(\text{jet}, \mathbf{E}_\mathrm{T}^\mathrm{miss})_\mathrm{min}$ and $E_\mathrm{T}^\mathrm{miss}/m_\mathrm{eff}(Nj)$ cuts
CRW	$W(\to \ell\nu)$+jets	$W(\to \ell\nu)$+jets	30 GeV $< m_T(\ell, E_\mathrm{T}^\mathrm{miss}) <$ 100 GeV, b-veto
CRT	$t\bar{t}$ and single-t	$t\bar{t} \to bbqq'\ell\nu$	30 GeV $< m_T(\ell, E_\mathrm{T}^\mathrm{miss}) <$ 100 GeV, b-tag

- Calibrate backgrounds to control regions:

$$N(\text{SR, scaled}) = N(\text{CR, obs}) \times \left[\frac{N(\text{SR, unscaled})}{N(\text{CR, unscaled})}\right]$$

from Monte-Carlo

SUSY: Jets + Missing E_T

$\tilde{q} \rightarrow q\tilde{\chi}_1^0$

$\tilde{g} \rightarrow qq\tilde{\chi}_1^0$

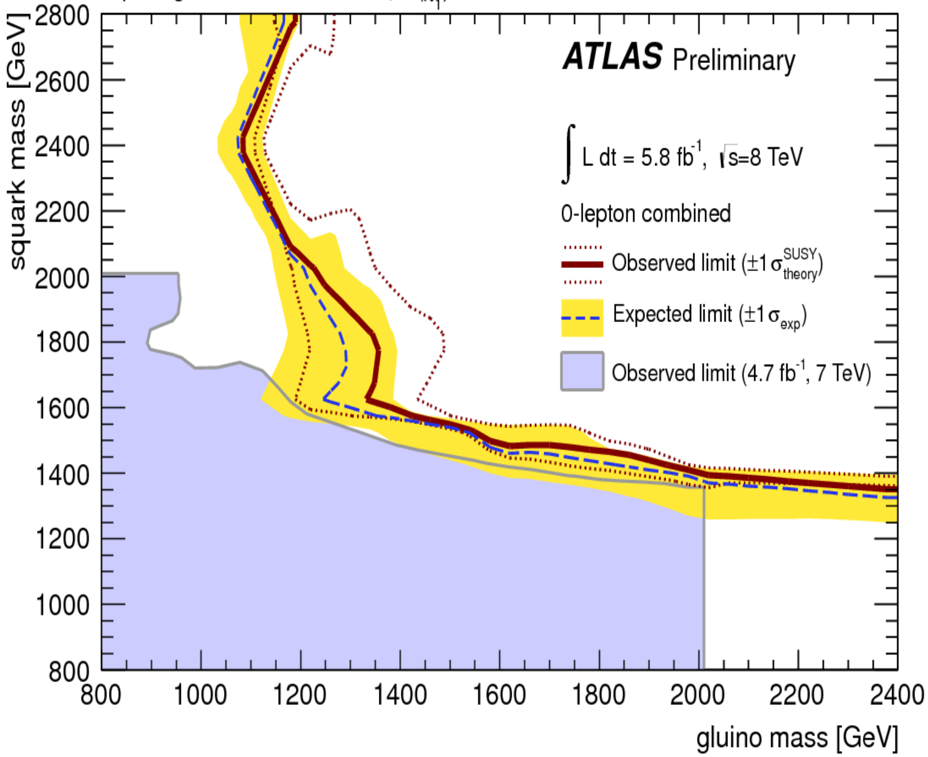
- Background estimation is (mostly) data-driven
- Result for the 8 TeV "tight selection" Signal Regions:

Signal Region	**A-tight**	**B-tight**	**C-tight**	**D-tight**	**E-tight**
MC expected events					
Diboson	3.3	0.2	0.0	0.8	2.6
W+jets	6.6	5.6	2.1	3.4	3.3
Z/γ^*+jets	7.4	4.5	1.9	1.3	1.3
$t\bar{t}$ + single top	1.0	1.1	0.6	1.8	2.7
Fitted background events					
Diboson	3.3 ± 3.1	0.2 ± 1.4	–	0.8 ± 0.4	2.6 ± 2.0
Multi-jets	–	–	–	0.4 ± 0.5	0.1 ± 0.2
W+jets	3 ± 4	2.7 ± 3.4	0.3 ± 0.5	–	0.8 ± 1.3
Z/γ^*+jets	6.8 ± 2.2	5.1 ± 1.7	2.0 ± 1.1	2.5 ± 1.1	1.2 ± 0.7
$t\bar{t}$ + single top	0.8 ± 0.8	0.8 ± 0.9	0.6 ± 0.5	2.6 ± 1.6	5.1 ± 3.3
Total bkg	14 ± 5	8.7 ± 3.4	2.8 ± 1.2	6.3 ± 2.1	10 ± 4
Observed	10	7	1	5	9
p_0	0.499	0.500	0.499	0.500	0.499
UL on N_{BSM}	8.9	7.3	3.3	6.0	9.3
UL on σ_{BSM} (fb)	1.53	1.26	0.57	1.03	1.60

SUSY: Jets + Missing E_T

$$\tilde{q} \rightarrow q\tilde{\chi}_1^0$$
$$\tilde{g} \rightarrow qq\tilde{\chi}_1^0$$

- Limit on simplified model: consider only squark and gluino pair production decaying to squarks, gluinos, quarks, and Lightest SUSY Particle (LSP)
- m(squark) > 1.4 TeV, m(gluino) > 1.1 TeV

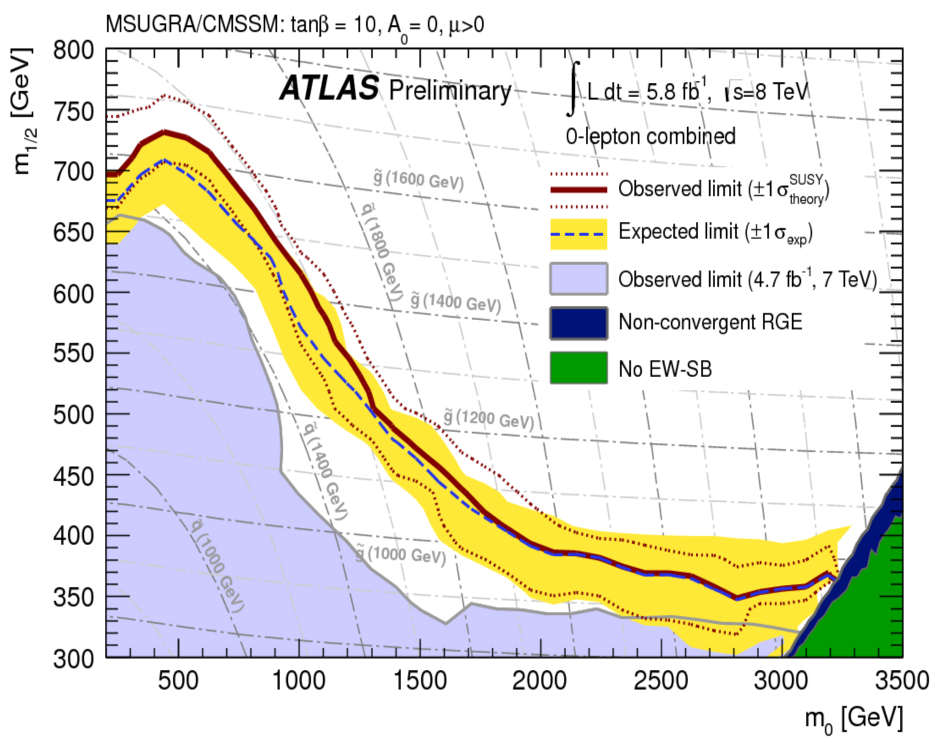


SUSY: Jets + Missing E_T

$\tilde{q} \to q\tilde{\chi}_1^0$

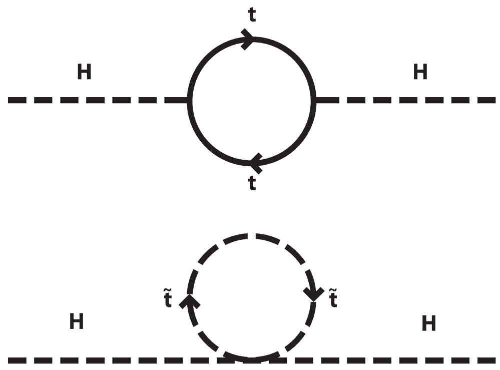
$\tilde{g} \to qq\tilde{\chi}_1^0$

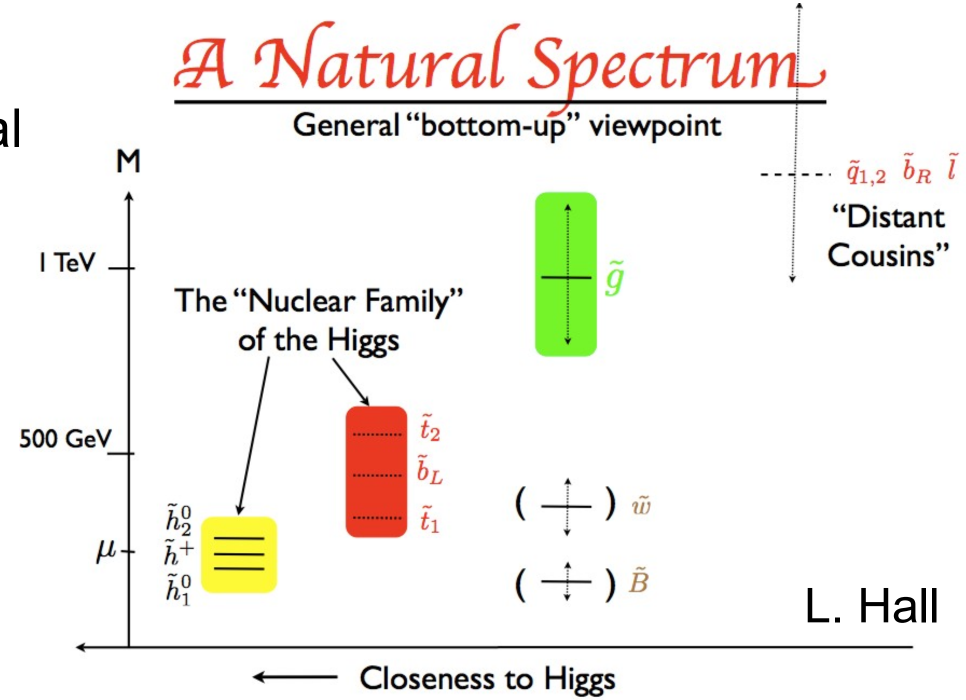
- Limits on MSUGRA/CMSSM:
  m(squark) = m(gluino) > 1.5 TeV
- MSUGRA limits in $m_0 - m_{1/2}$ plane:



"Natural" SUSY: a lighter 3rd generation?

- SUSY solves Hierarchy Problem only if 3rd generation is "light" i.e. m(stop) ~ m(top)
  - → Other gen. can be heavier
- What if 3rd generation lighter than others?
  - → Remove constraint of universal of mSUGRA/CMSSM
- Look specifically for stop and sbottom:
  - → Direct production
  - → Through gluino decays





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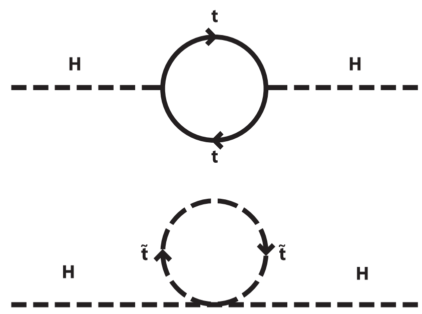
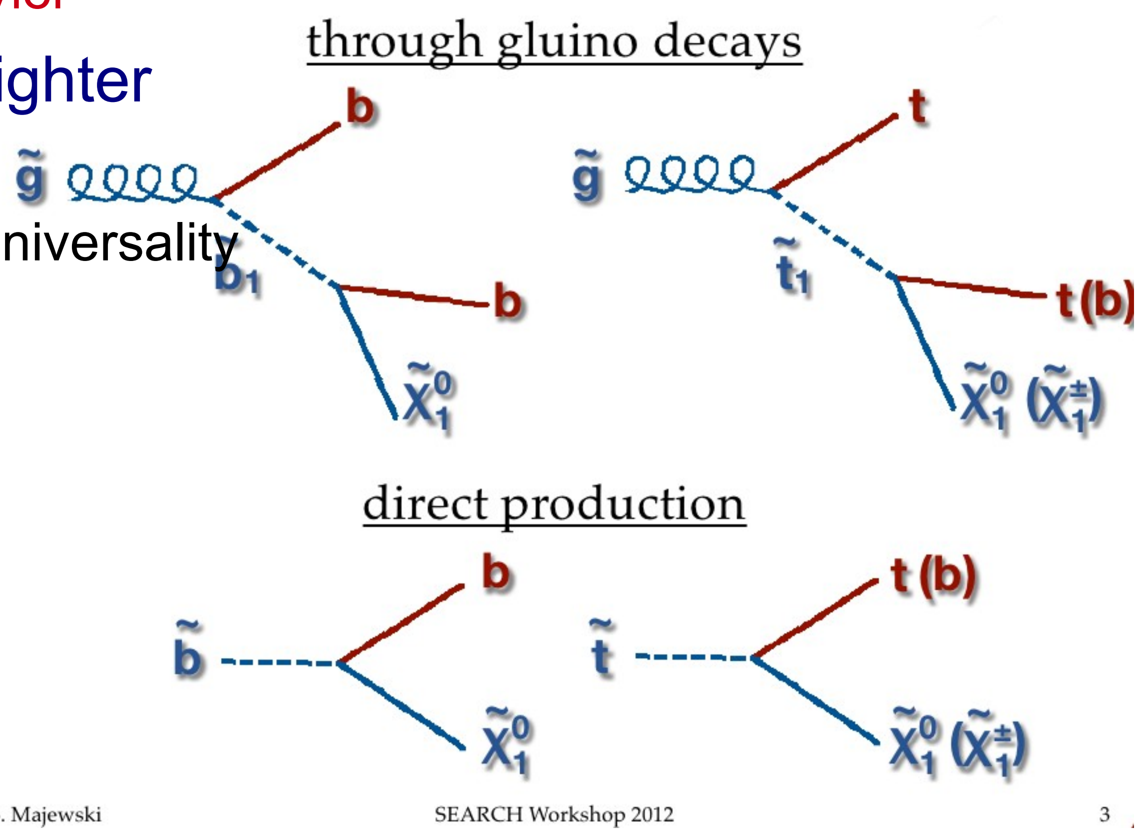
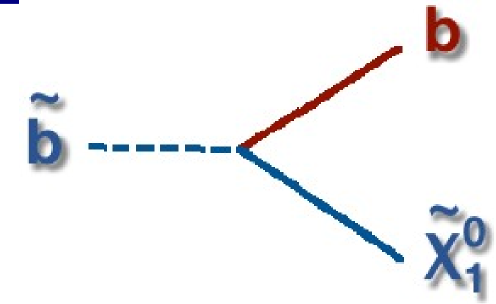




"Natural" SUSY: a lighter 3rd generation? Direct Sbottom Production

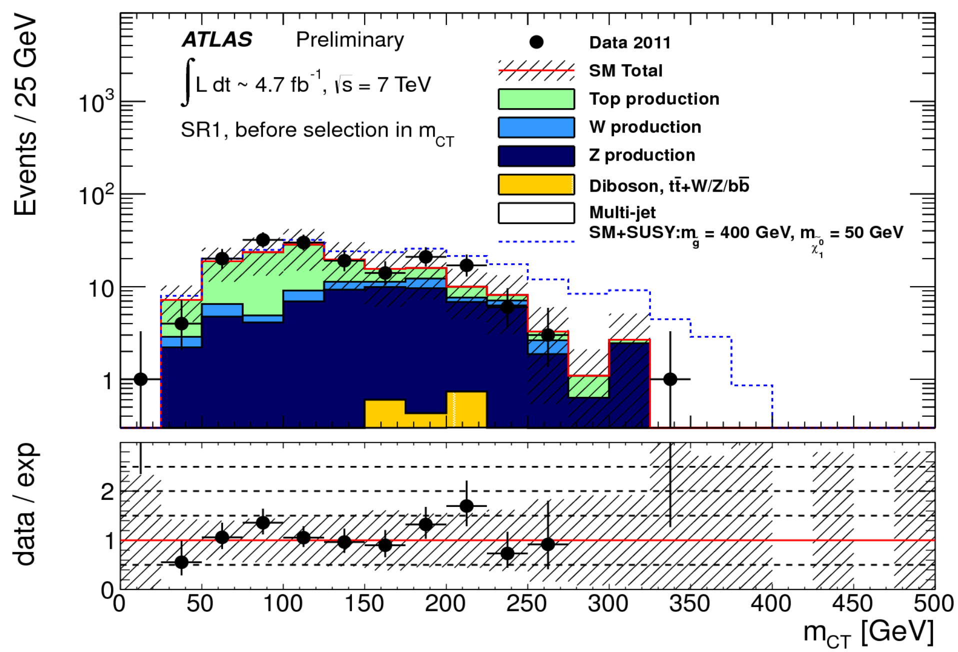
- 2 b-jets + Missing ET
- Use "contransverse mass":

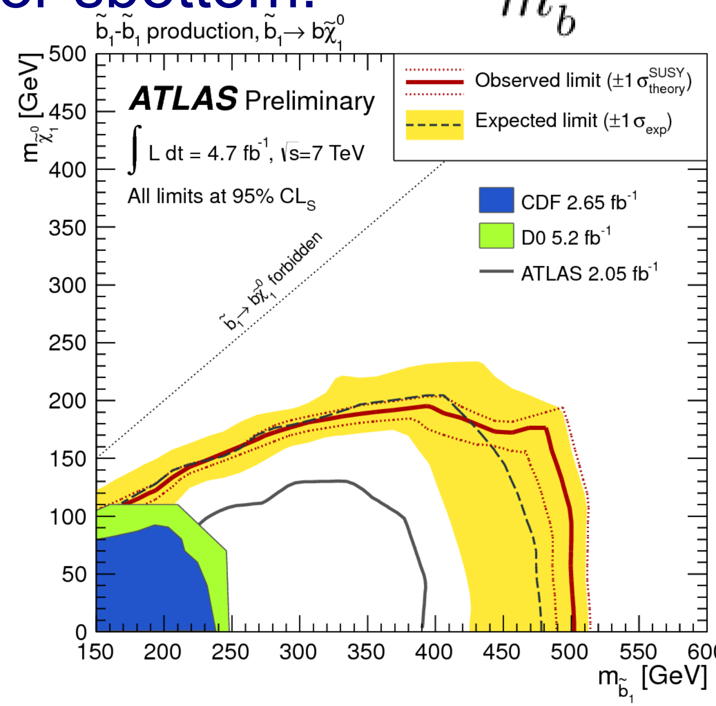
$$m_{\mathrm{CT}} = \sqrt{[E_T(b_1) + E_T(b_2)]^2 - [p_T(b_1) - p_T(b_2)]^2}$$



- Endpoint at: for ttbar ~ 135 GeV, for sbottom:

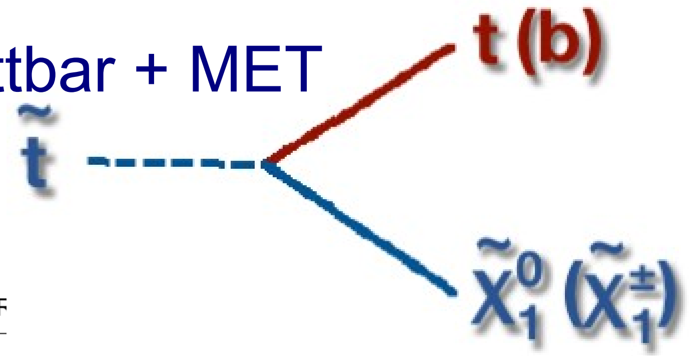
$$\frac{m_{\tilde{b}}^2 - m_{\tilde{\chi}_1^0}^2}{m_{\tilde{b}}}$$

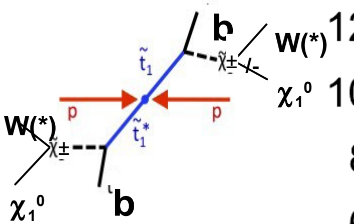


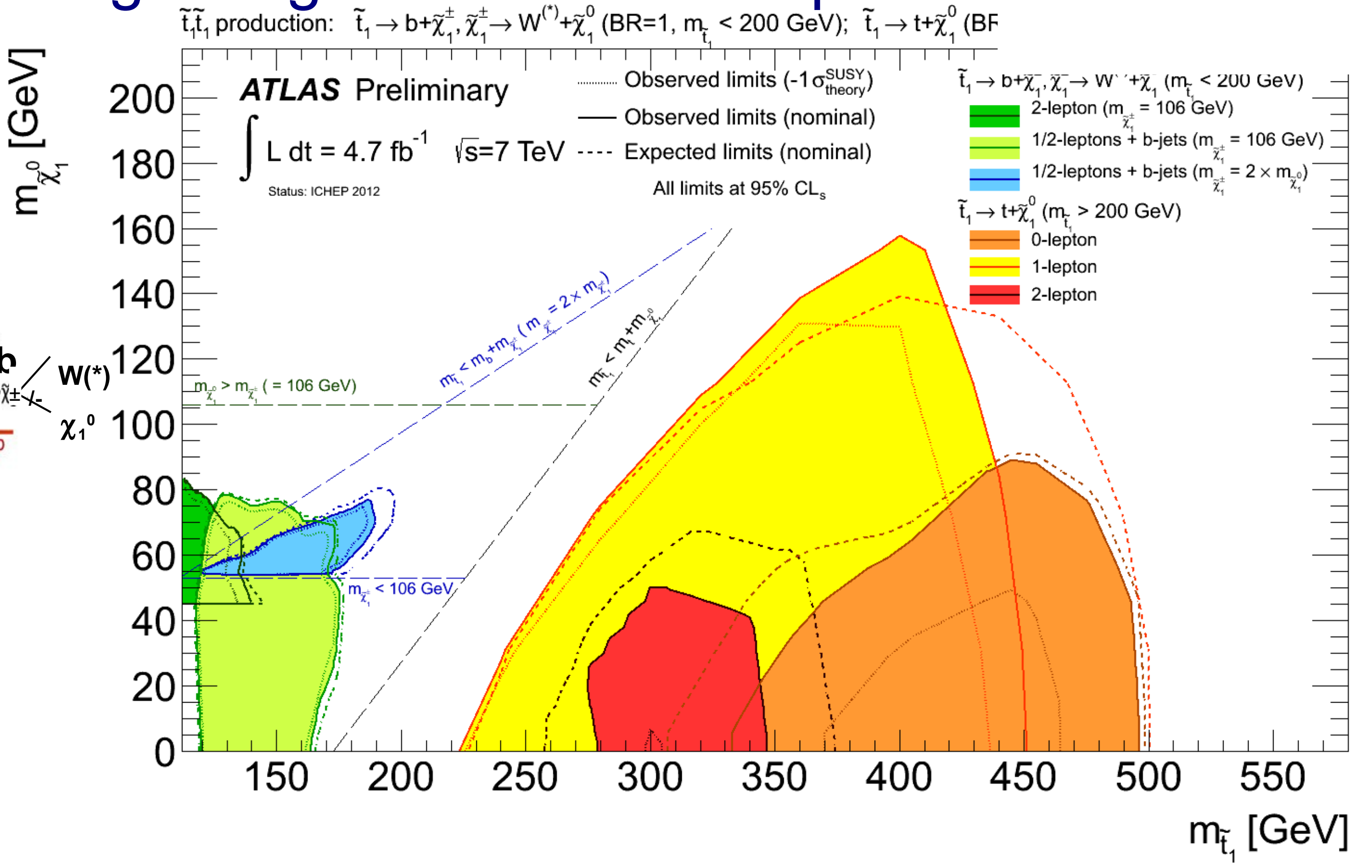


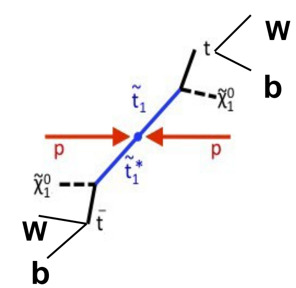
"Natural" SUSY: a lighter 3rd generation? Direct Stop Production

- If m(stop) > m(top) + m(LSP): look for ttbar + MET
- If stop is very light, look for decays involving charginos → b's and leptons



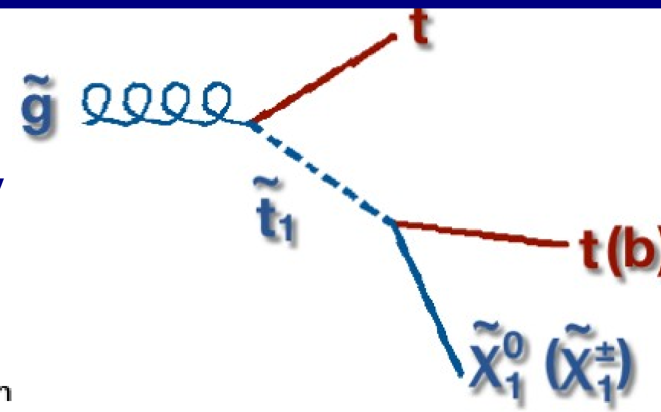


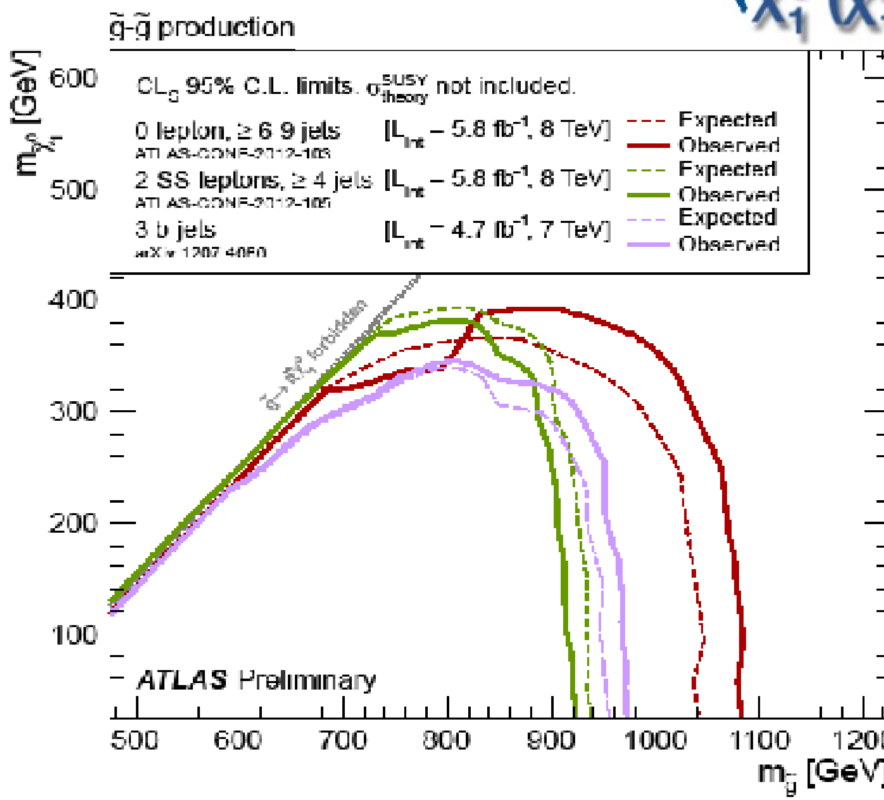


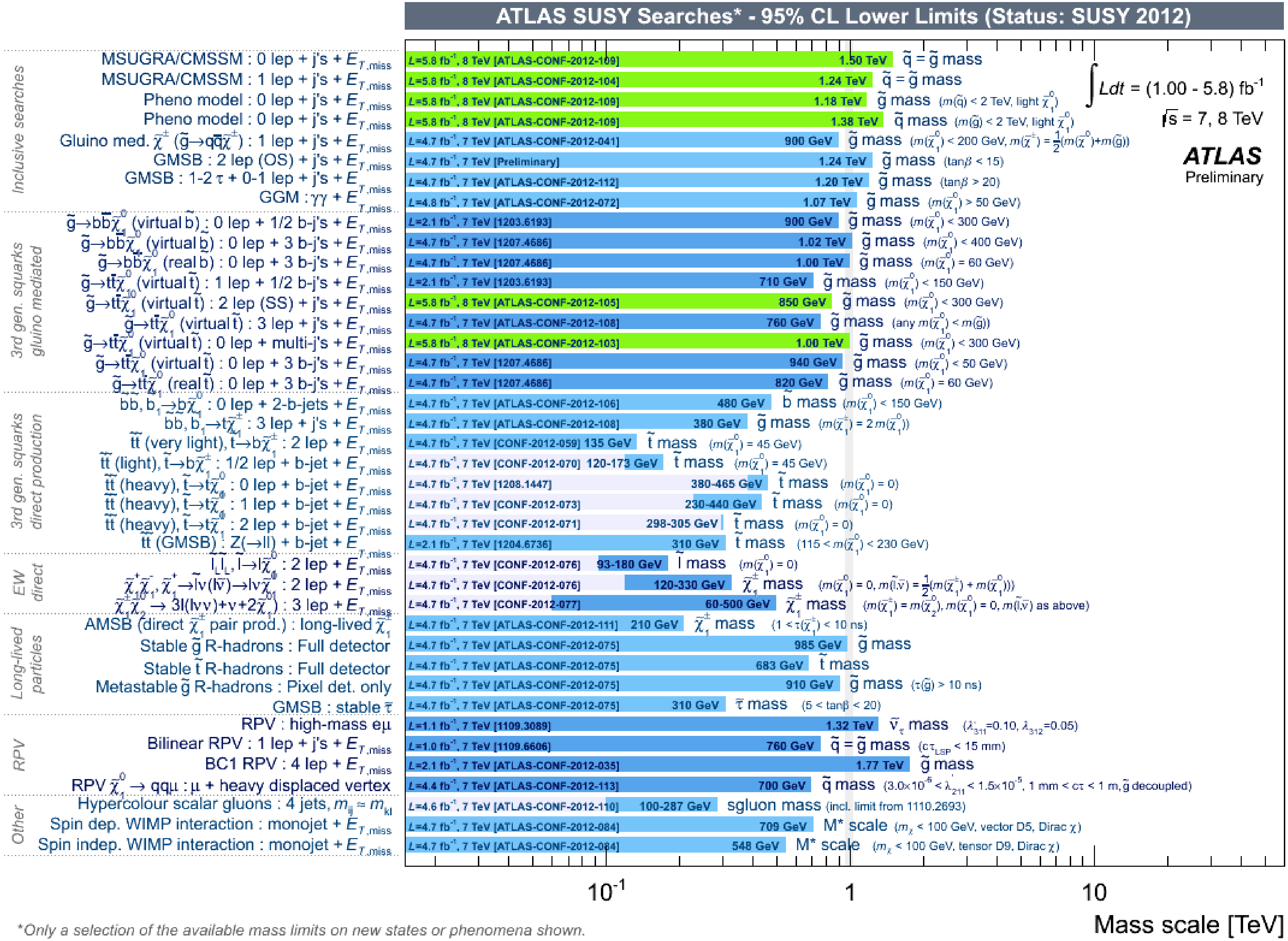


"Natural" SUSY: a lighter 3rd generation? Stop in gluino decays

- Look for 4 top quarks and missing ET
- Main background is ttbar → reject it by requiring either of the following:
  - → 3 b-jets
  - → 2 same-sign leptons
  - → Large jet multiplicity
- Sensitive to m(gluino) <1000 GeV for m(LSP) <380 GeV







*Only a selection of the available mass limits on new states or phenomena shown.
All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

Supersymmetry: Summary

- SUSY MSUGRA/CMSSM is starting to be fine-tuned
  - → Might be its last year to live...
- With more than 5 fb^{-1}, SUSY prod. mechanisms open up → exclusive 3rd generation and gaugino production

  Look for "Natural SUSY"
- Focusing more and more on non-CMSSM scenarii that make SUSY harder to find:

  "Split", "compressed", R-parity violation

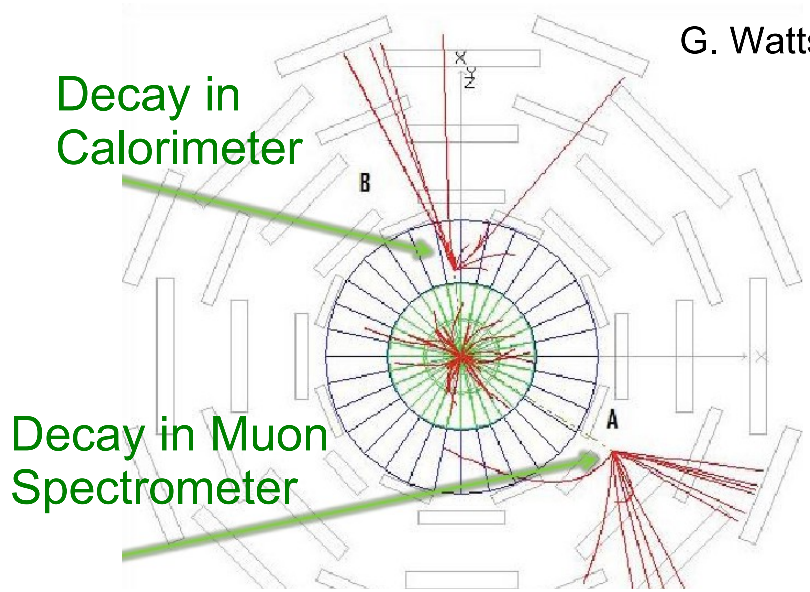
  More exotic signatures:
  - → SUSY with low Missing ET
  - → Multi-jet resonances
  - → Long-Lived Particles (R-hadrons, staus) → see next slides

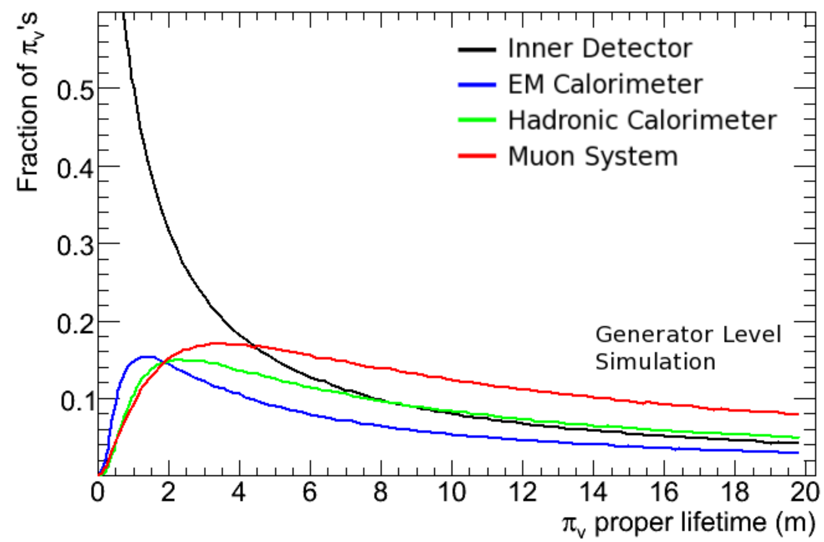
Long-Lived Particles

Long-Lived Particles

- Predicted by:
  - → SUSY (R-parity violating or split/compressed mass spectra): stau, or gluino/stop hadronized into R-hadrons
  - → Hidden Valley
- Experimentally very diverse:
  - → Depends widely on particle's properties: life-time, charge, decay
  - → highly displaced vertices
  - → highly ionizing (dE/dx)
  - → slow (time-of-flight)
  - → kinked tracks
  - → disappearing tracks
  - → out-of-time (wrt collision) decay

G. Watts



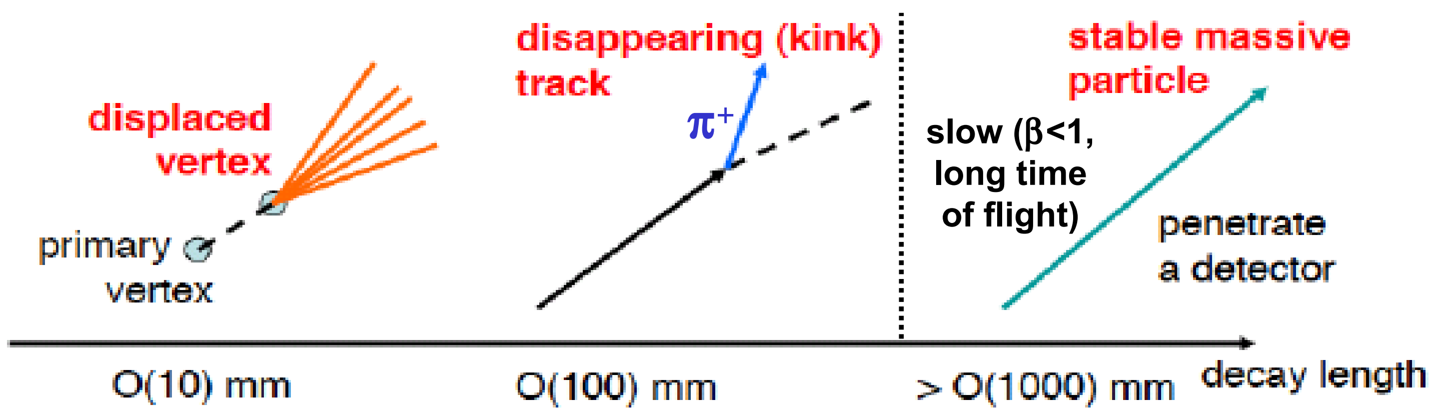


SUSY and Long-Lived Particles

Three main mechanisms

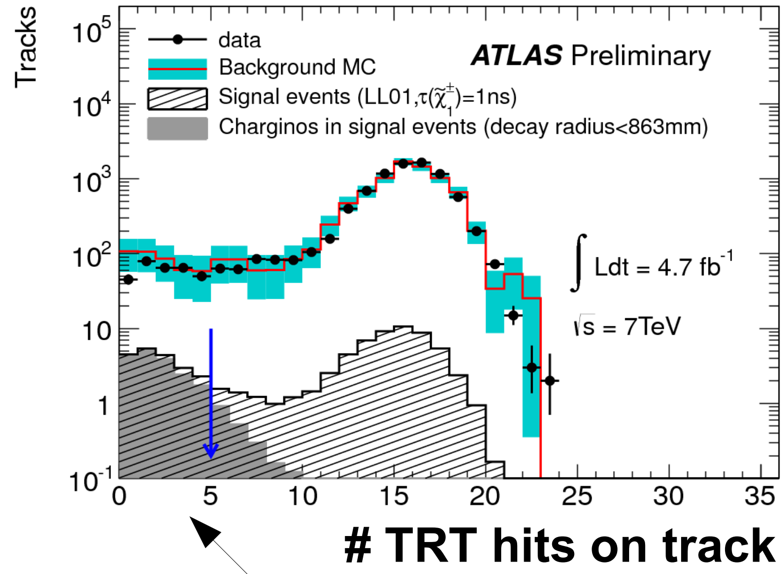
- R-Parity violation: Lifetime proportional to λ^2, λ'^2, λ''^2 → Displaced vertex if $\lambda, \lambda', \lambda'' < 10^{-7}$
- Low $\Delta m(\tilde{\chi}_1^+ - \tilde{\chi}_1^0)$~100 MeV in AMSB → Low π emitted, kinked track
  Low $\Delta m(\tilde{g}/\tilde{q} - \tilde{\chi}_1^0)$ for coloured particles → R-hadron ($\tilde{g}$ or $\tilde{q}$)
- Weak coupling to $\tilde{G}$ in GMSB → Stable sleptons

MetaStable | **Stable**

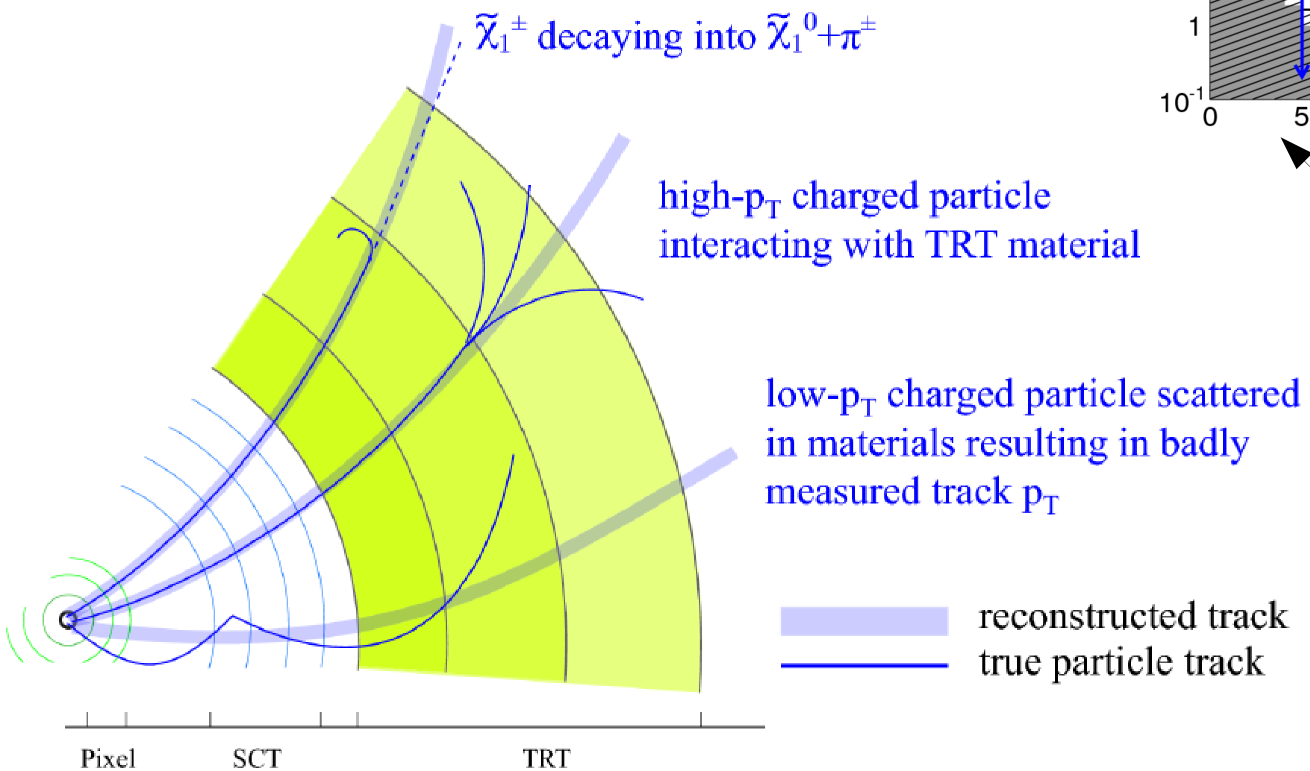


Long-Lived Particles: Disappearing Track

- m(chargino) ~ m(neutralino)
- Chargino long-lived
- Chargino → neutralino + soft pion

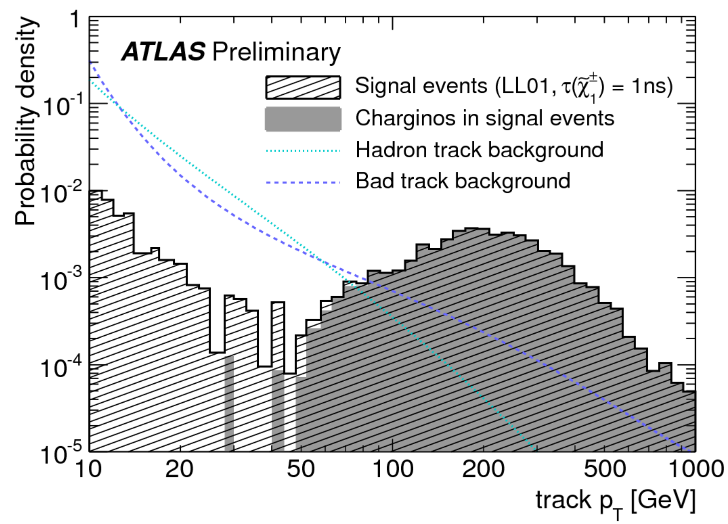


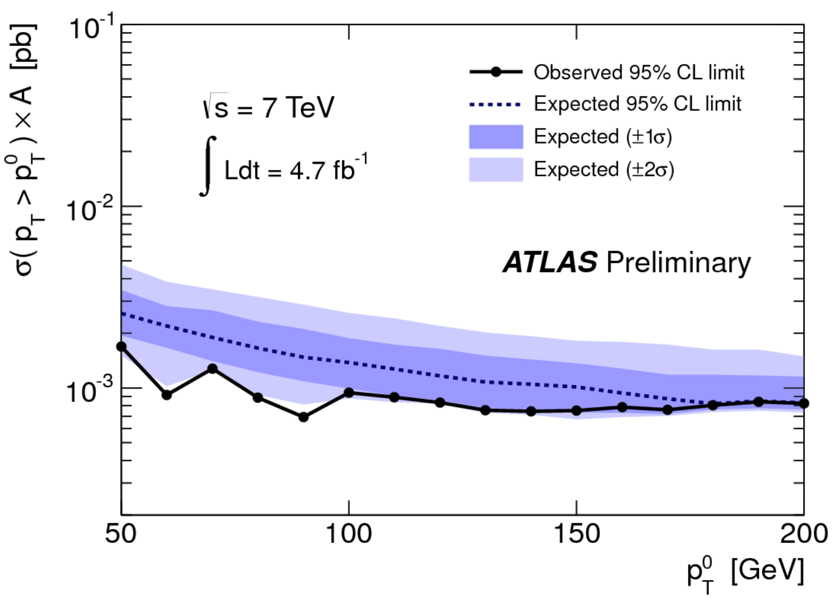
Select tracks With less than 5 TRT hits

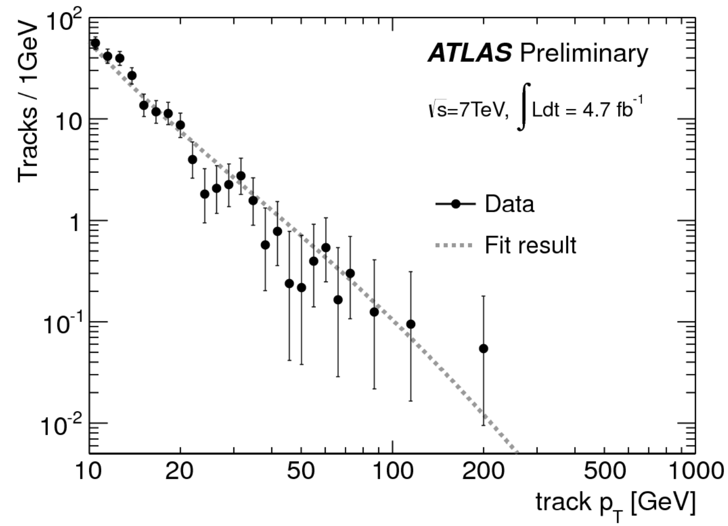


Long-Lived Particles: Disappearing Track

- Look at events with at least 3 jets and large missing ET
- Discr. Variable: pT of tracks with less than 5 TRT hits

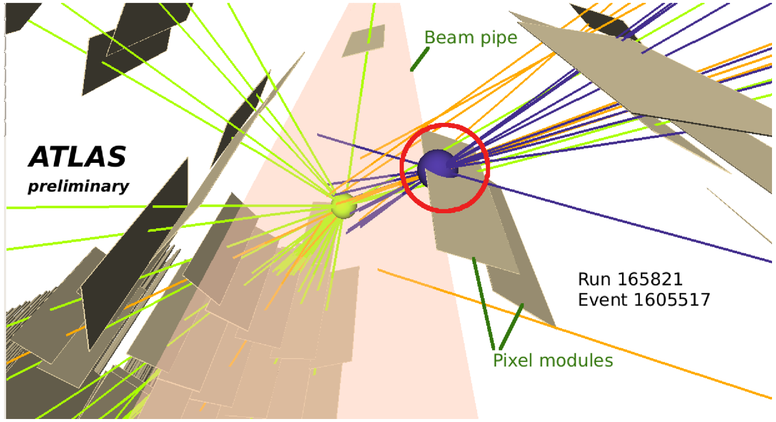


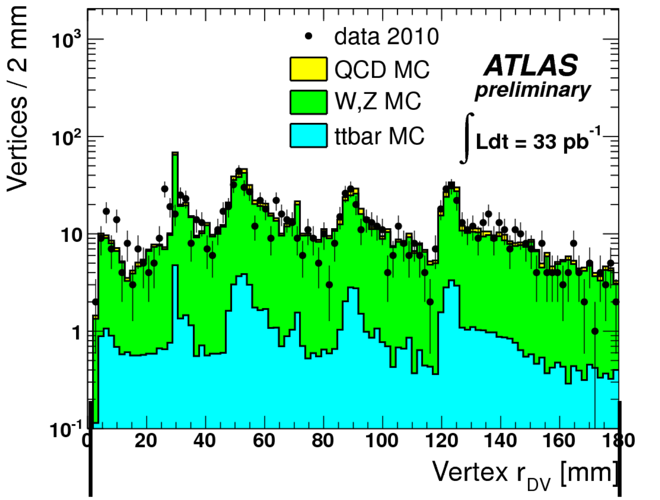




Long-Lived Particles: Decay in the Inner Detector

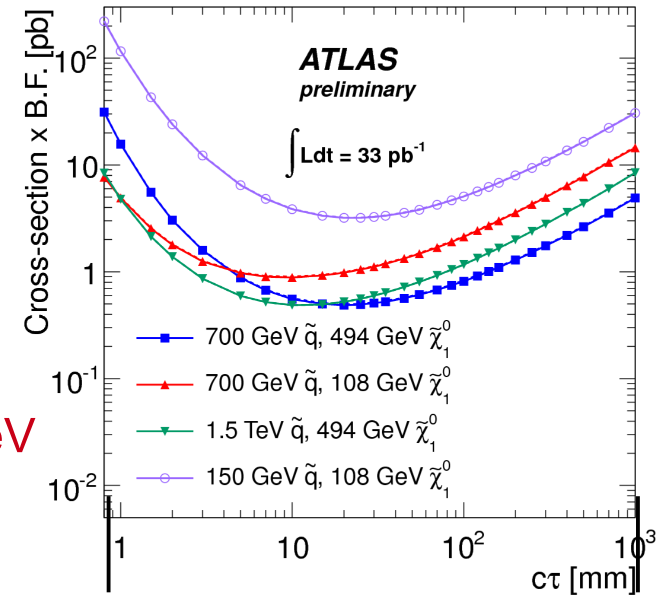
- R- hadrons (hadronized squarks or gluinos)
- Vertex outside the beampipe, in association with a high-pT muon
- Requires good understanding of tracking, detector passive material





0 cm Decay Radius 18 cm

Signal Region:
* Ntracks > 4
* Vertex Mass > 10 GeV



1 mm 1 m

Long-Lived Particle Vertex Triggers

- (b-tagging triggers)
- Trackless jet trigger:
  - → decays late in inner detector
  - → jet E T > 35 GeV
  - → no tracks with p T > 1 GeV near jet
  - → muon spectrometer activity
- Hadronic / EM (decays beyond the EM calorimeter)
  - → jet ET > 35 GeV
  - → no tracks with p T > 1 GeV near jet
  - → E_{had} / E_{EM} > 10
- Muon spectrometer cluster trigger
  - → 3 muon triggers close from each other
  - → no jets, no tracks

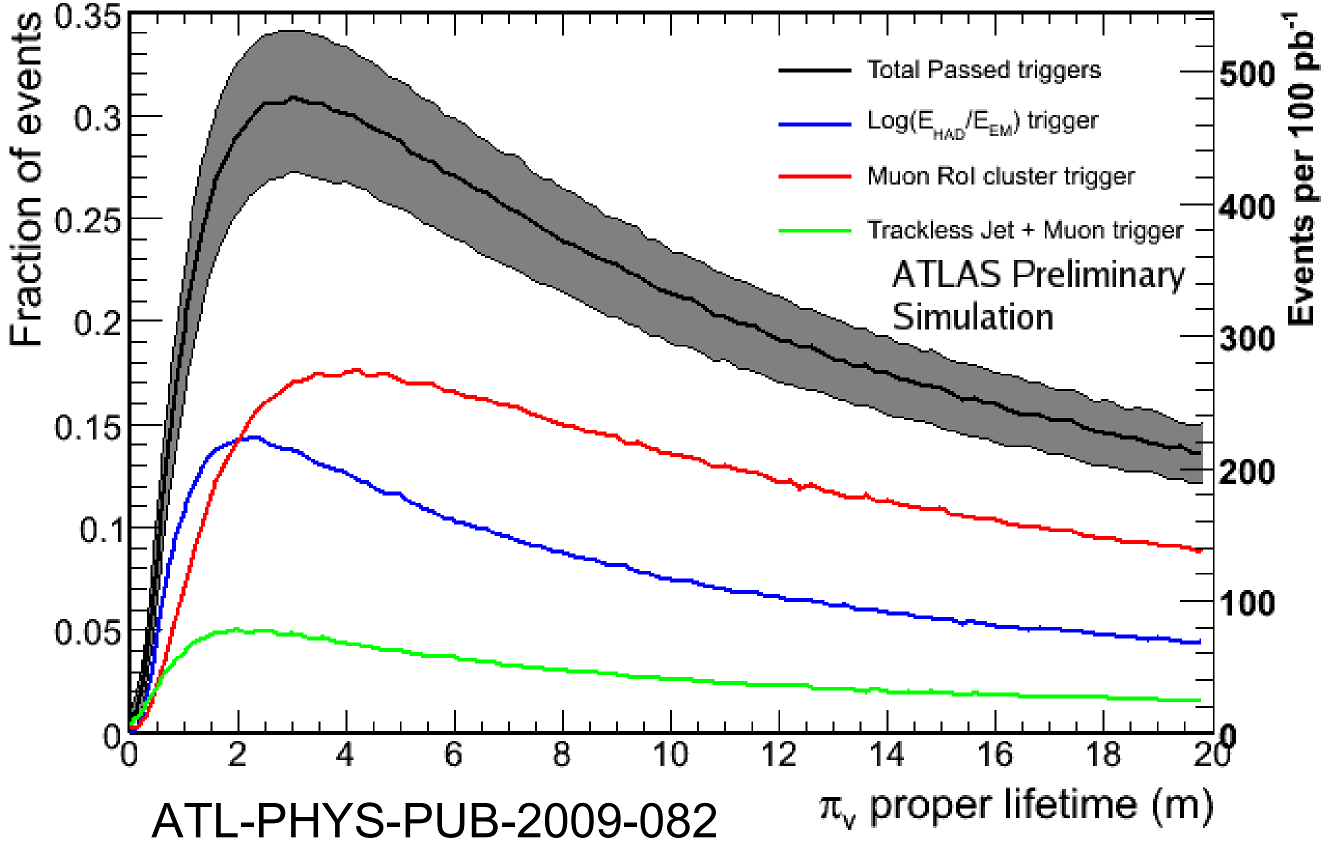
Typical decay length (1 mm - 5 cm)

1 - 3 m

2 - 3 m

4 - 7 m

Long-Lived Particles Vertex Triggers



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Long-Lived Particle Vertex Triggers

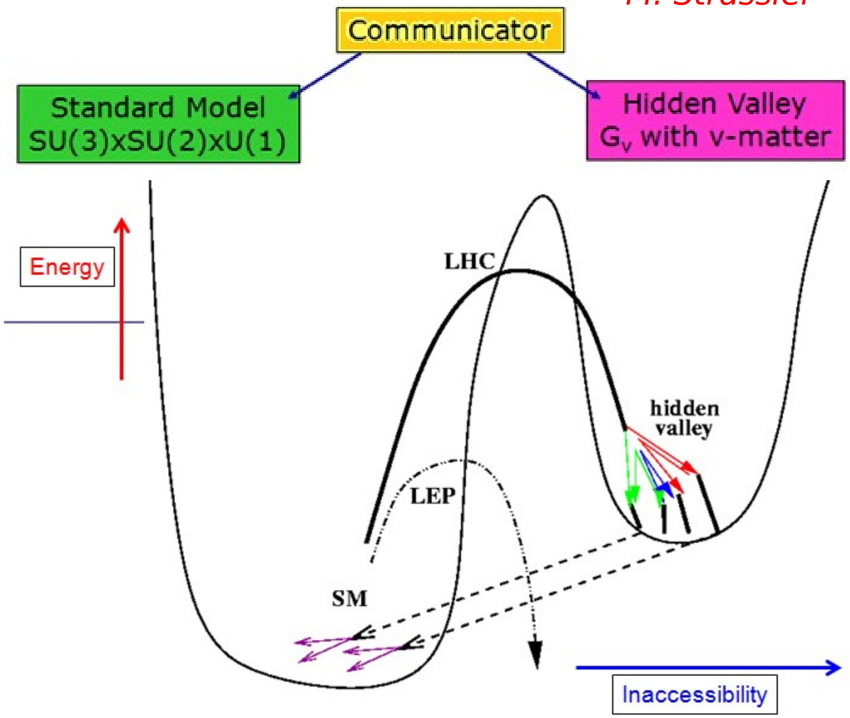
Typical decay length

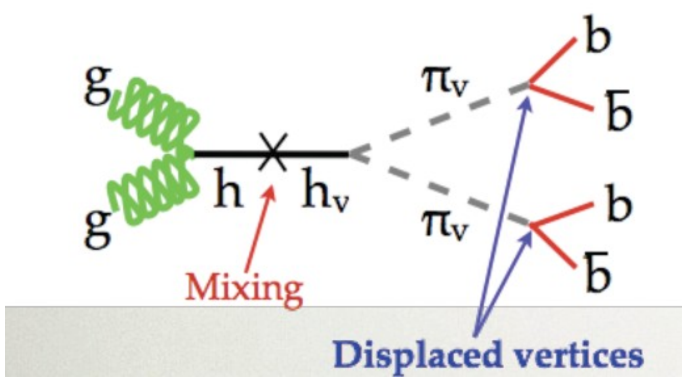
- (b-tagging triggers) — (1 mm - 5 cm)
- Trackless jet trigger: — 1 - 3 m
  - → decays late in inner detector
  - → jet E T > 35 GeV
  - → no tracks with p T > 1 GeV near jet
  - → muon spectrometer activity
- Hadronic / EM (decays beyond the EM calorimeter) — 2 - 3 m
  - → jet ET > 35 GeV
  - → no tracks with p T > 1 GeV near jet
  - → log(Ehad /E EM) > 1.0
- Muon spectrometer cluster trigger — 4 - 7 m
  - → 3 muon triggers close from each other
  - → no jets, no tracks

Long-Lived Particles: Decay in the Muon Spectrometer

- Hidden-Valley theories predict a hidden sector coupled to the SM only through some heavy communicator → weakly coupled → long-lived particles
- Ex: $h \rightarrow h_v \rightarrow \pi_v\ \pi_v \rightarrow$ 4b's
- Life-time of π_v is unknown
- Look for 2 pairs of b-jets appearing outside the calorimeter.
- Sort of b-tagging with the Muon Spectrometer!

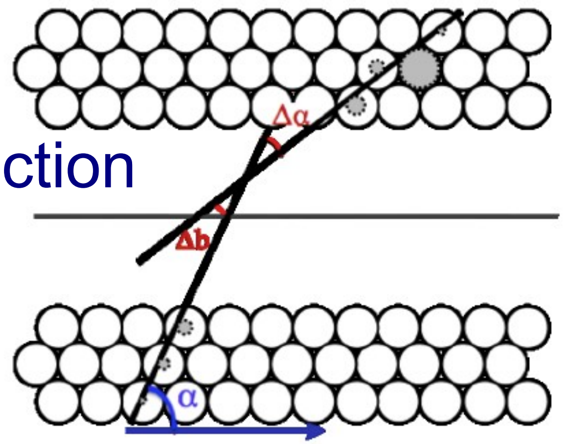
M. Strassler

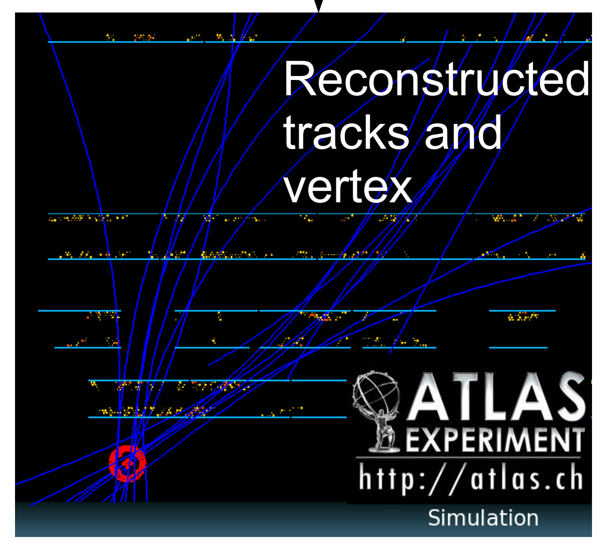


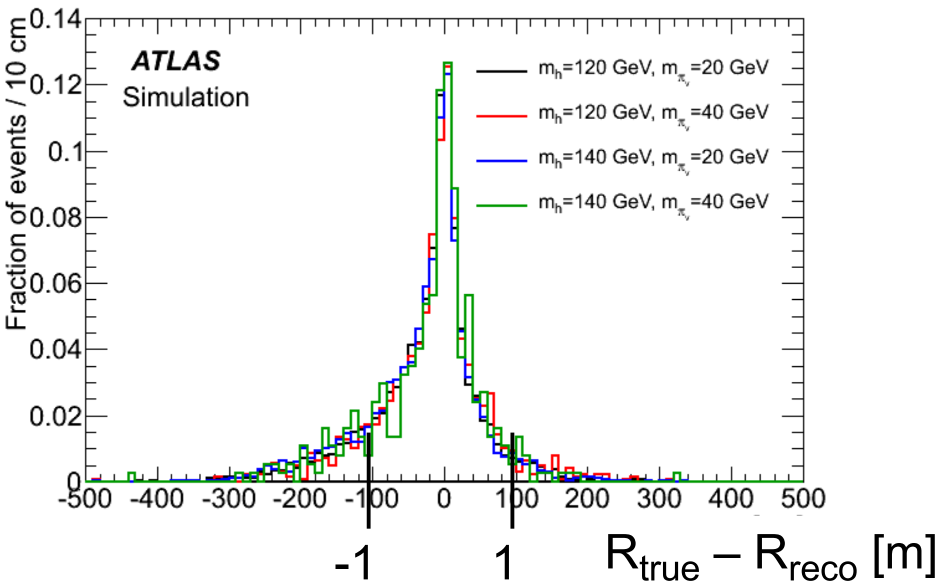


Long-Lived Particles: Vertex Reconstruction in the Muon Spectrometer

- Very high occupancy
- Partial track reconstruction
- Efficiency ~ 50%
- Very coarse spatial resolution:



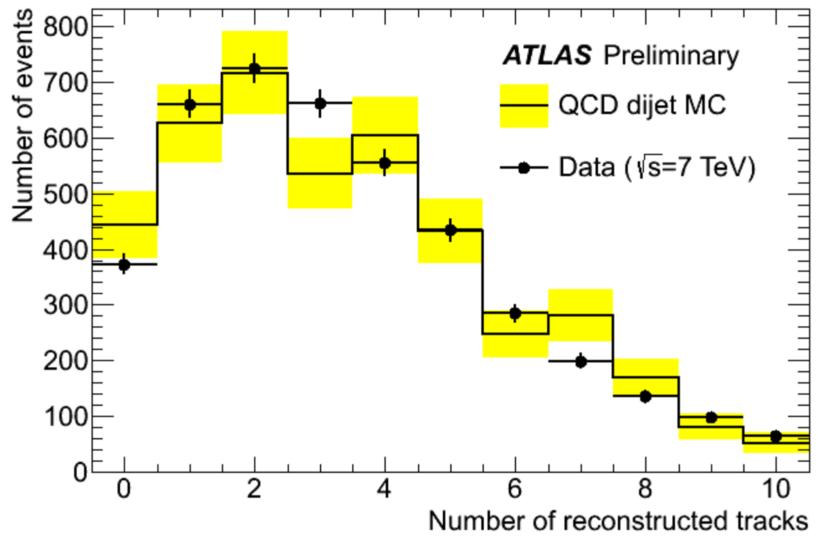


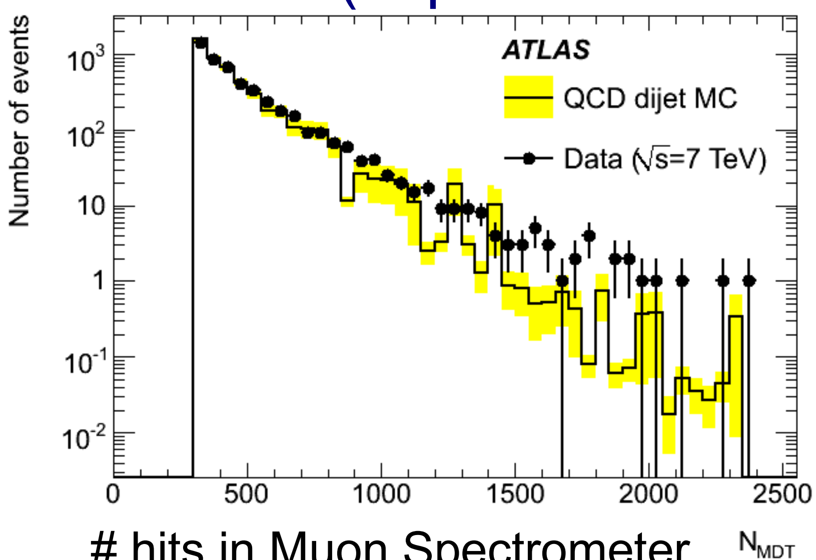


Long-Lived Particles: Decay in the Muon Spectrometer

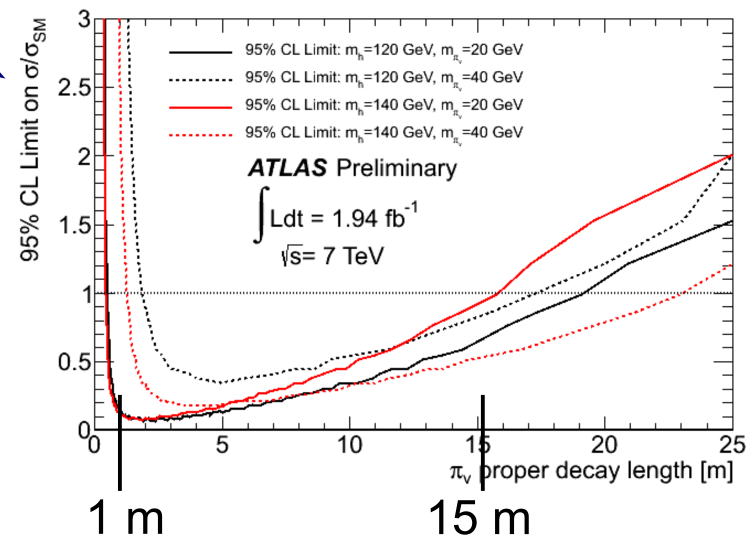
- Validation of simulation with punch-through events
- Note: punch-through's very well described by the simulation!
- After final selection: no event observed (exp: 0.03±0.02 ev.)

Tracks caused by jets in Muon Spectrometer





hits in Muon Spectrometer behind a jet



Backup

Sidenote: How to avoid bias

- “The easiest person to fool is yourself” - R. Feynman

- You have two methods to estimate your background
  - → Method 1 predicts N(background events) = 2.2 ± 0.2 (sys.)
  - → Method 2 predicts N(background events) = 5 ± 3 (sys.)

- Case 1: choice made a priori (before looking at the data)
- Methods are compatible and method 1 gives best sensitivity => choose Method 1
- In the data, you observe N(events) = 7 events

- 3-sigma excess: you will not graduate this year

Sidenote: How to avoid bias

- “The easiest person to fool is yourself” - R. Feynman

- You have two methods to estimate your background
  - → Method 1 predicts N(background events) = 2.2 ± 0.2 (sys.)
  - → Method 2 predicts N(background events) = 5 ± 3 (sys.)

- Case 2: choice made a posteriori
- You observe 7 events (and you must graduate before the end of the year)
- You decide to choose the most conservative method, just to be more conservative
- No excess: you just missed the Nobel price.