LHC (ATLAS) Dark Matter Searches: Uncertainties

Alan Barr

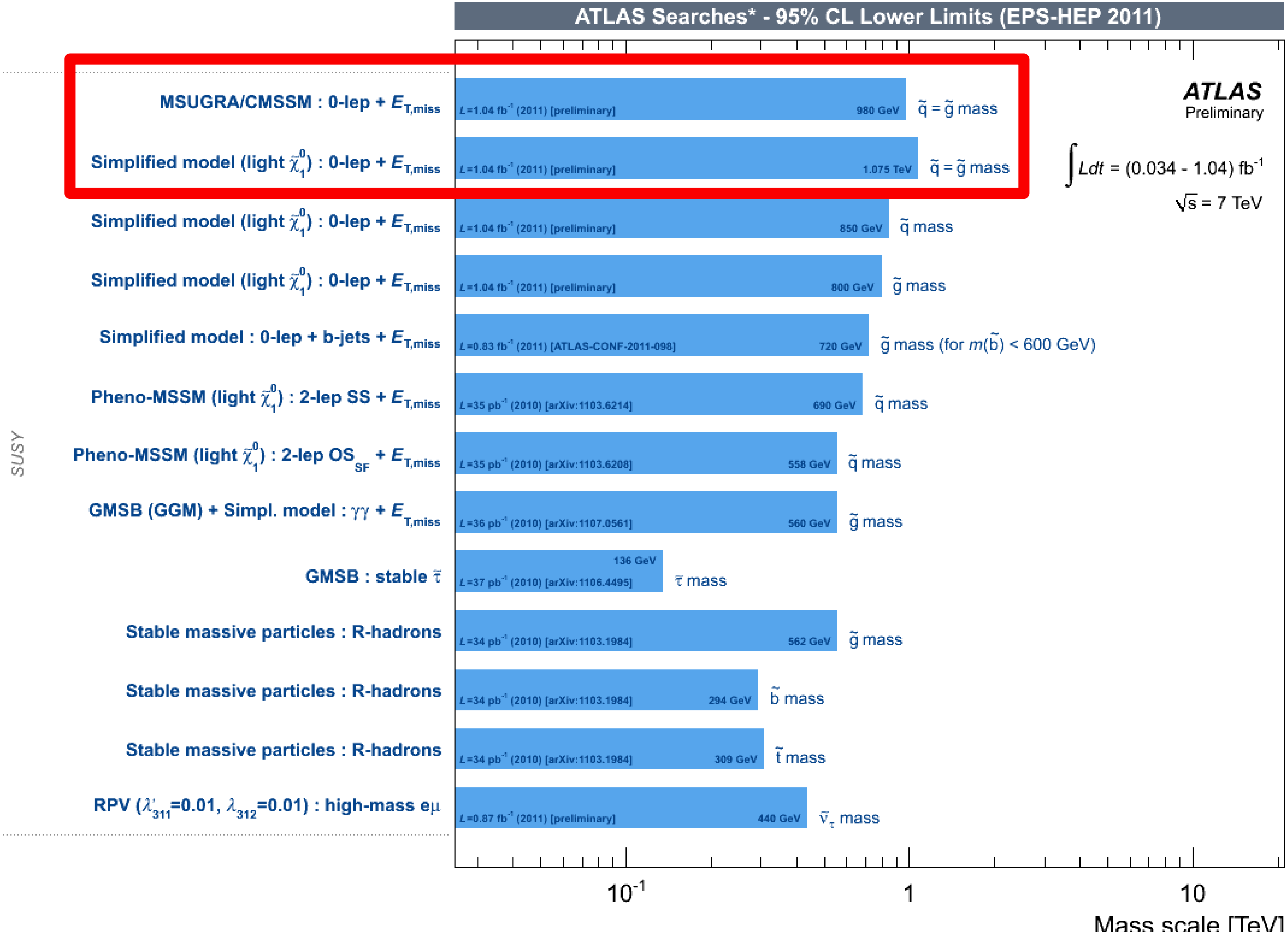
University of Oxford

DMUH, July 2011

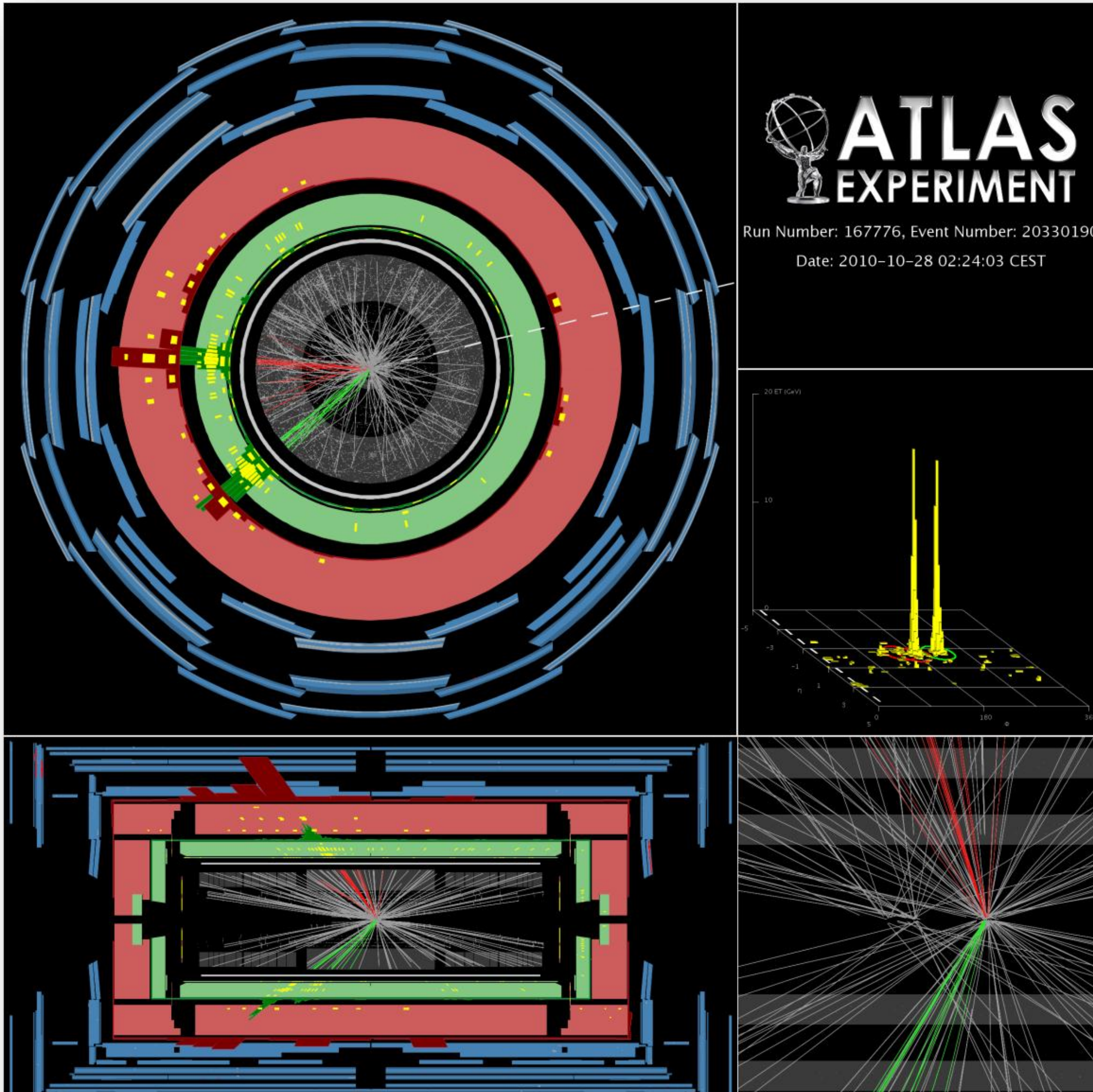
WARNING

?

- Theme is **certainties** and **uncertainties**
- **Not** a standard “ATLAS Searches” talk
- **Some** topical analysis highlights
- Concentrate on **how** uncertainties determined



*Only a selection of the available results shown


ATLAS
EXPERIMENT
Run Number: 167776, Event Number: 20330190
Date: 2010-10-28 02:24:03 CEST

Example conference note

ATLAS NOTE

ATLAS-CONF-2011-086

June 3, 2011

Search for squarks and gluinos using final states with jets and missing transverse momentum with the ATLAS detector in $\sqrt{s}$ = 7 TeV proton-proton collisions

ATLAS-CONF-2011-086

Example conference note

- 7 Page note
  - 1 Page introduction
  - 1 Page definitions
  - **2.5 pages on uncertainties**
  - 1.5 page results/interpretation

- 10 public plots of control measurements
- Dozens of others made internally

>200 page internal document describes cross-checks
and uncertainty determination for this one analysis (not public)

165 pb^{-1}

Signal Region	≥ 2 jets	≥ 3 jets	≥ 4 jets
E_T^{miss} [GeV]	> 130	> 130	> 130
Leading jet p_T [GeV]	> 130	> 130	> 130
Second jet p_T [GeV]	> 40	> 40	> 40
Third jet p_T [GeV]	–	> 40	> 40
Fourth jet p_T [GeV]	–	–	> 40
$\Delta\phi(\text{jet}_i, E_T^{miss})_{min}$ $(i = 1, 2, 3)$	> 0.4	> 0.4	> 0.4
E_T^{miss}/m_{eff}	> 0.3	> 0.25	> 0.25
m_{eff} [GeV]	> 1000	> 1000	> 1000

Fiducial cuts

ATLAS-CONF-2011-086

165 pb^{-1}

Process	Signal Region		
	$\geq$ 2 jets	$\geq$ 3 jets	$\geq$ 4 jets
$Z \rightarrow (\nu\nu)$+jets	5.6 ± 2.1	4.4 ± 1.6	3.0 ± 1.3
$W \rightarrow (\ell\nu)$+jets	6.2 ± 1.8	4.5 ± 1.6	2.7 ± 1.3
$t\bar{t}$+ single top	0.2 ± 0.3	1.0 ± 0.9	1.4 ± 0.9
QCD jets	0.05 ± 0.04	0.21 ± 0.07	0.16 ± 0.11
Total	12.1 ± 2.8	10.1 ± 2.3	7.3 ± 1.7
Observed	10	8	7

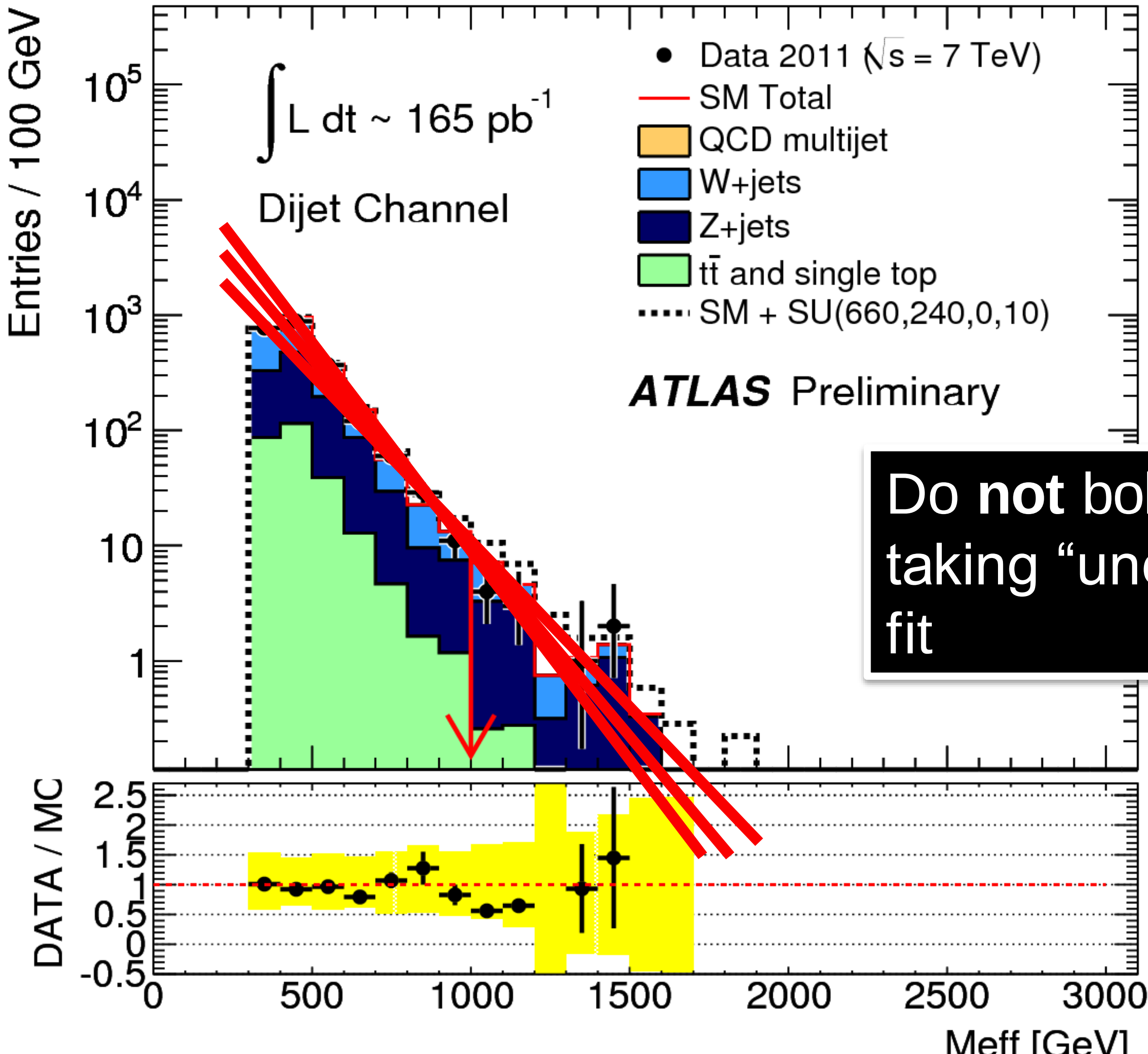
Counts, expectations and **uncertainties**

ATLAS-CONF-2011-086

Expected

Observed

What we do **NOT** do…



Do **not** boldly extrapolate taking "uncertainty" from fit

Uncertainties?

Standard Model backgrounds

Instrumental backgrounds

Expected Signal?

Momentum imbalance…

- Mismeasurement?
- Cosmics?
- Noise?
- Beam halo?

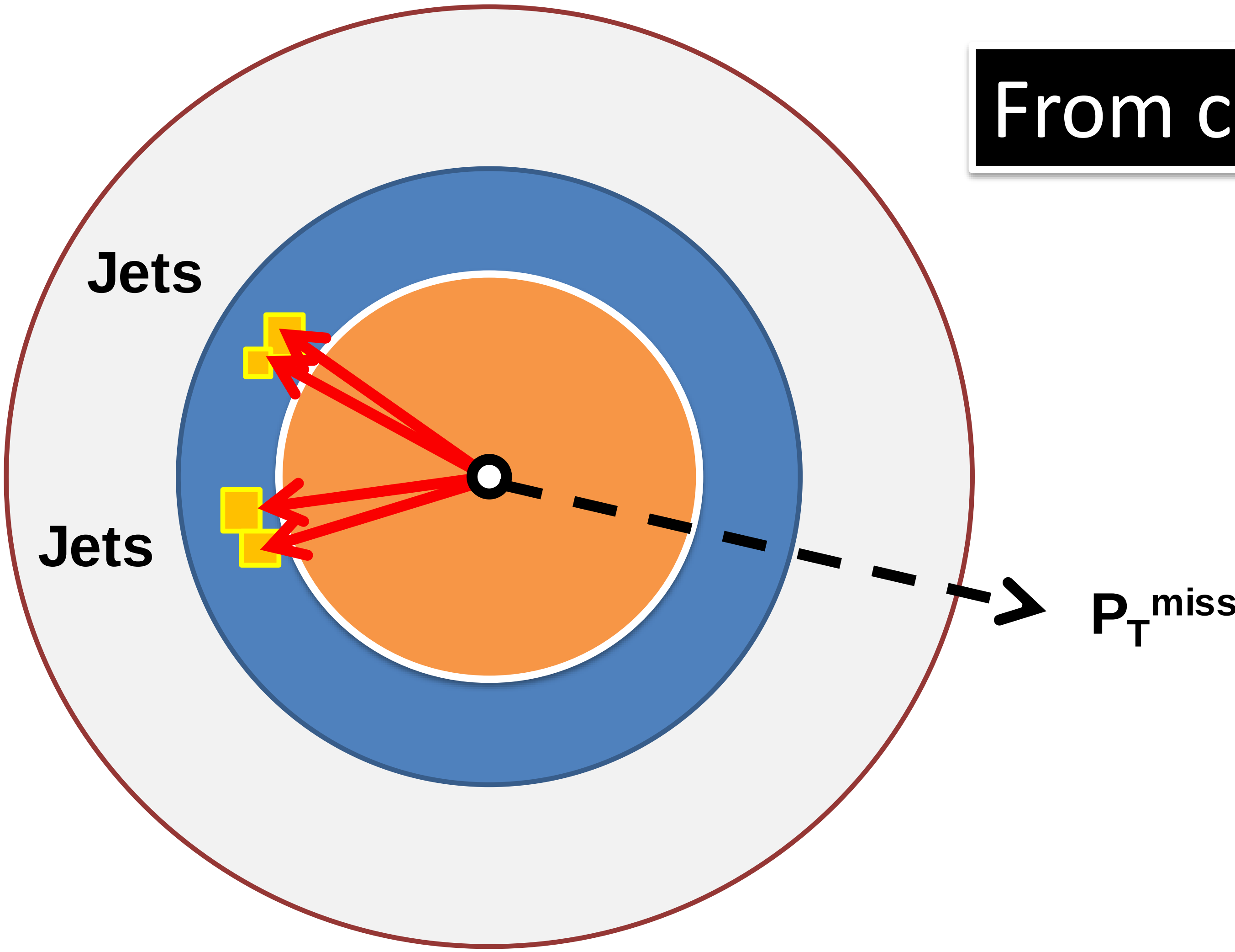
PATHOLOGIES

- Neutrinos?
- WIMPs?

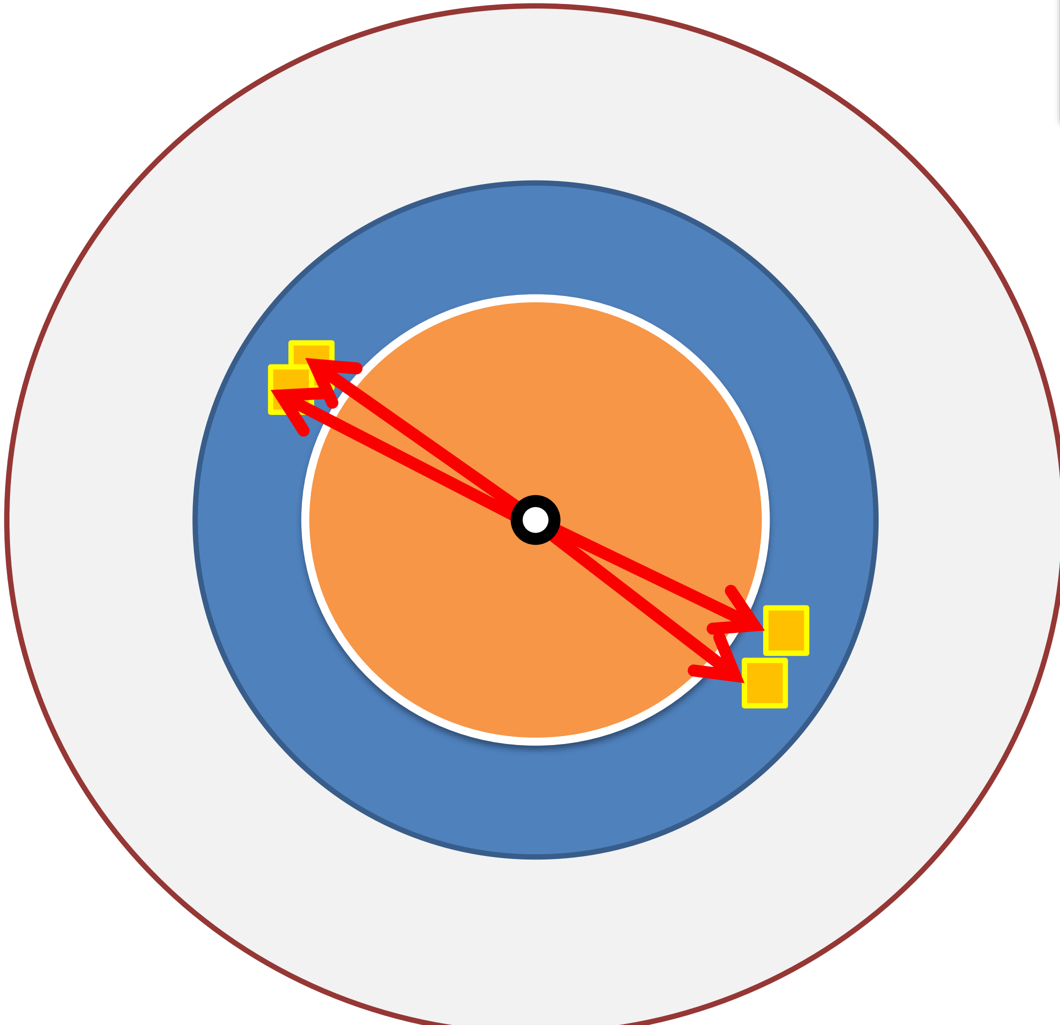
PHYSICS

JETS + MISSING MOMENTUM

From collisions



JETS

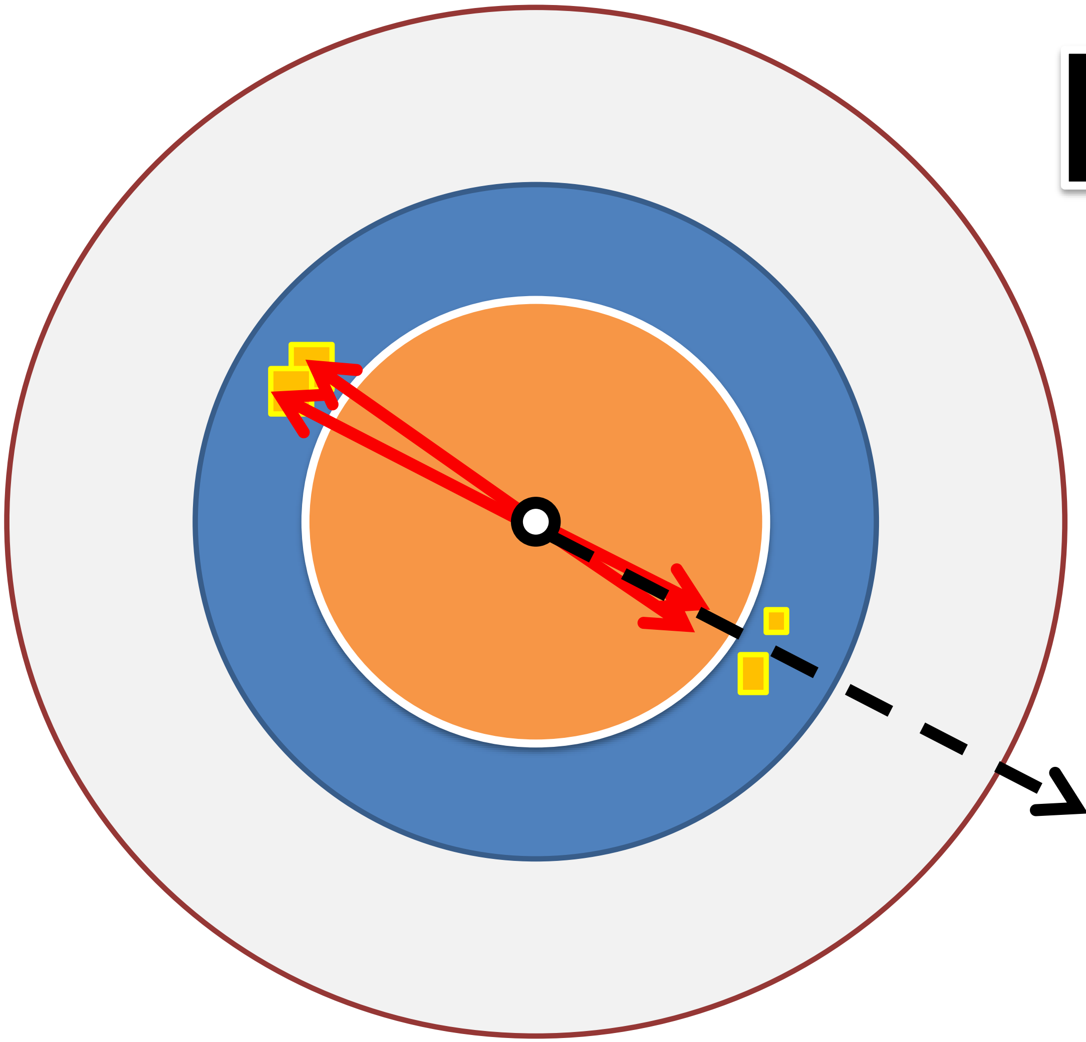


From collisions

Jets:
Had. Calorimeter
E.M. Calorimeter
Tracks from vertex
In-time

b,c quark jets
➔ can decay
to neutrinos

JETS + MISSING MOMENTUM



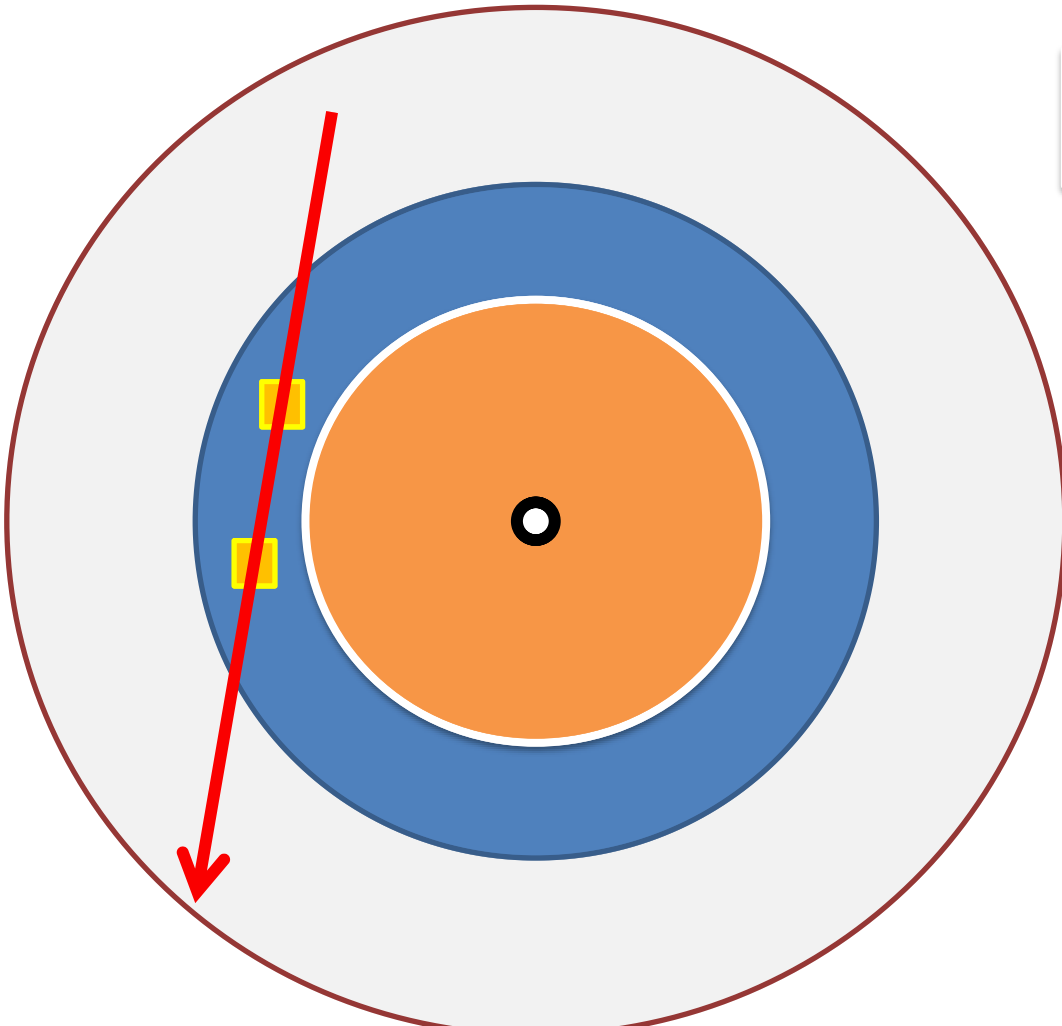
Measurements

Jets:
$\Delta\phi$ cut

Reduce:
Had. Calorimeter
E.M. Calorimeter
Tracks from vertex

Measure remainder
at small $\Delta\phi$

JETS + MISSING MOMENTUM

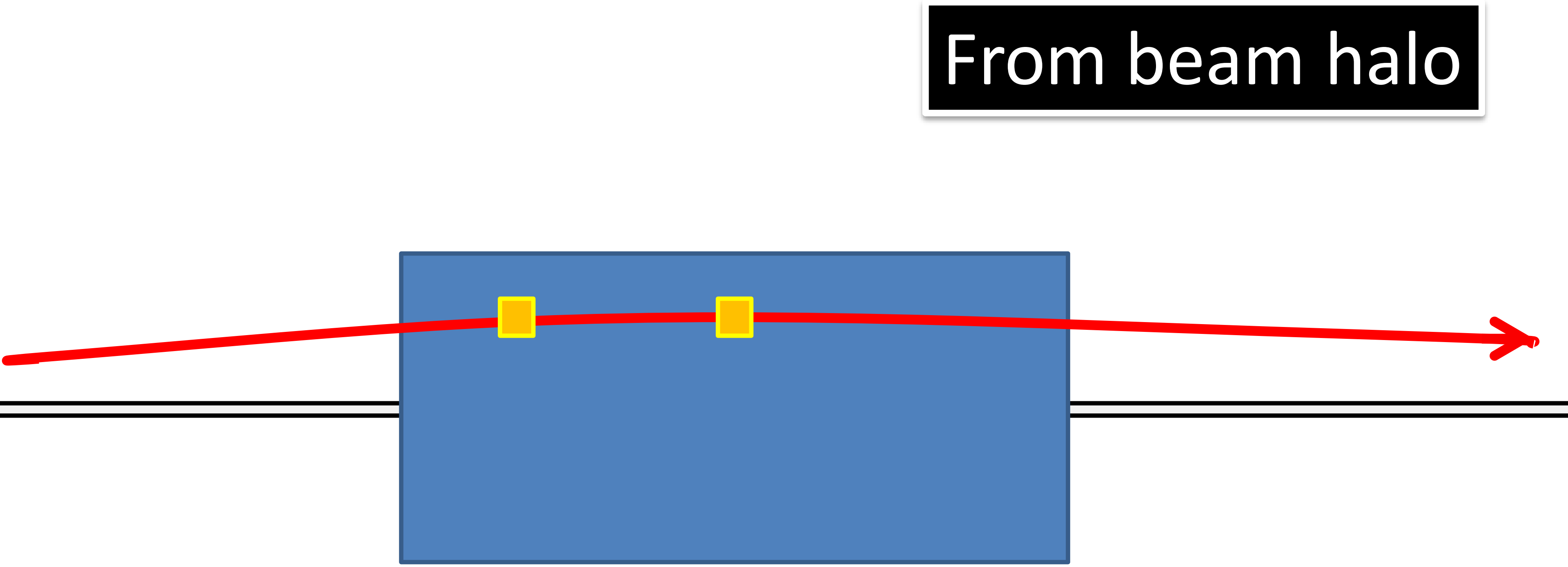


From cosmics

Reduce by:
(a) requiring tracks with jets
(b) look for muon hits

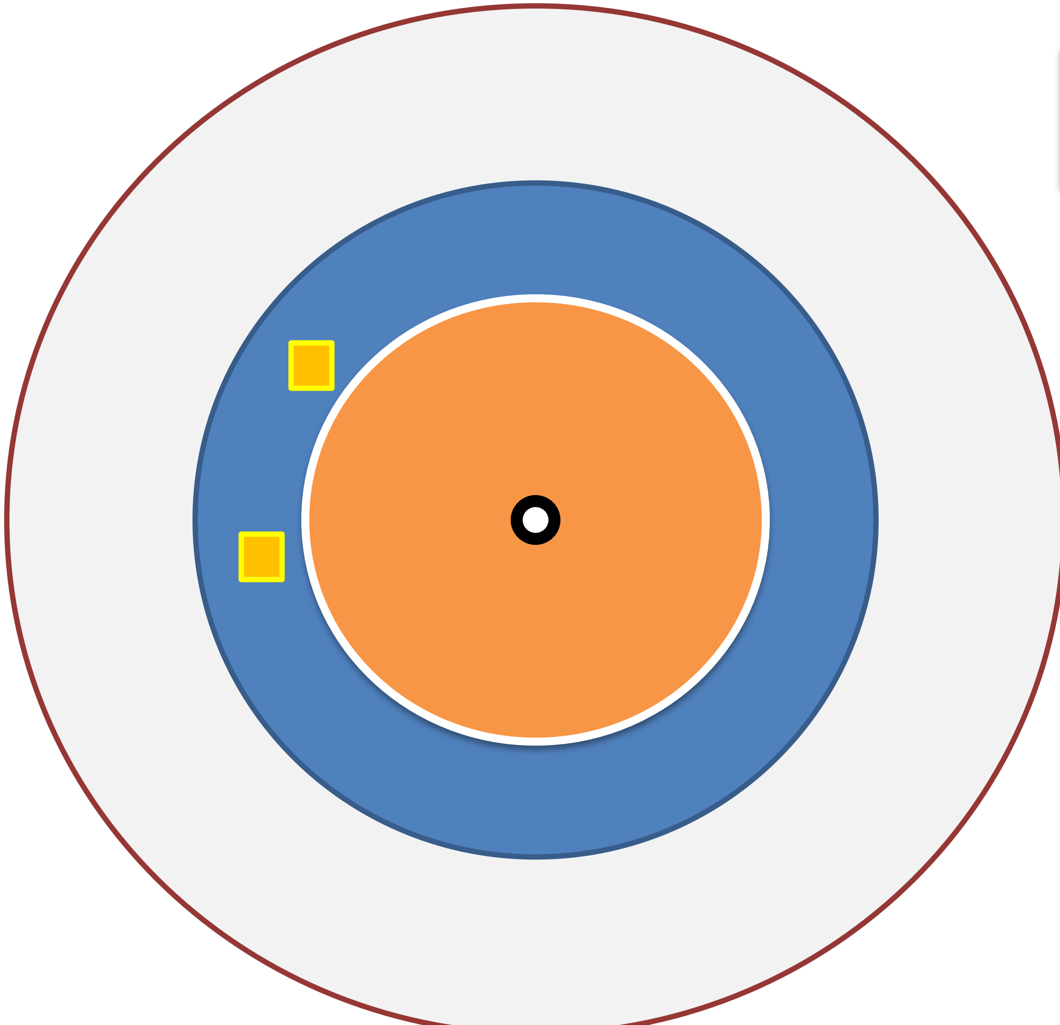
Measure remainder:
(a) no beam
(b) timing

JETS + MISSING MOMENTUM



Reduce by requiring tracks with jets
Measure remainder with single beam / timing

JETS + MISSING MOMENTUM



Calorimeter noise

Reduce by requiring tracks with jets

Measure remainder
(a) no beam
(b) timing

Neutrinos

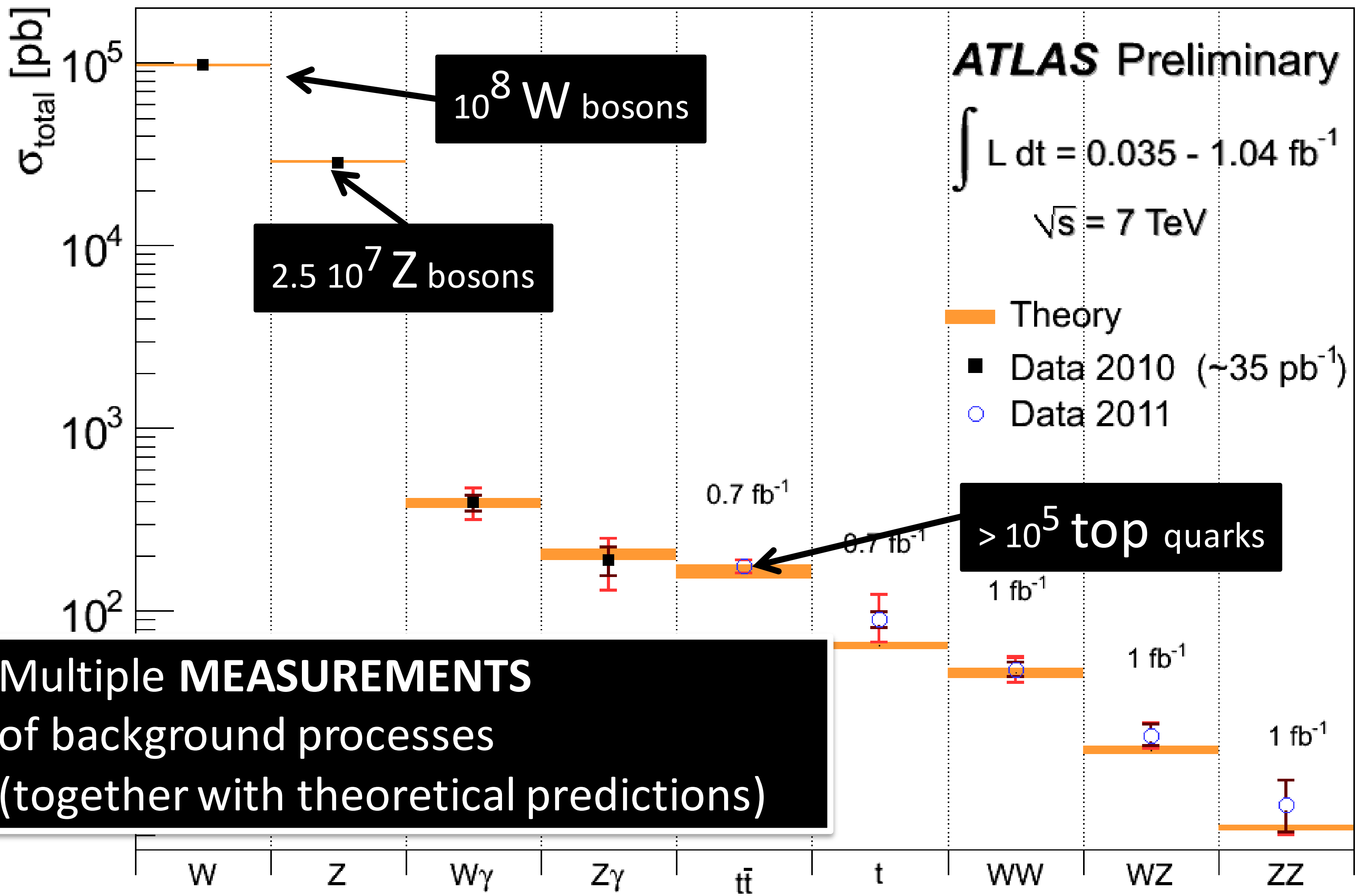
$Z\ (\rightarrow \upsilon\upsilon) + \text{jets}$

$t\bar{t}\ (+\ \text{jets})$

$W\ (\rightarrow \ell\upsilon) + \text{jets}$

$\mathcal{B}$ jets

Calibration, confirmations, cross-checks



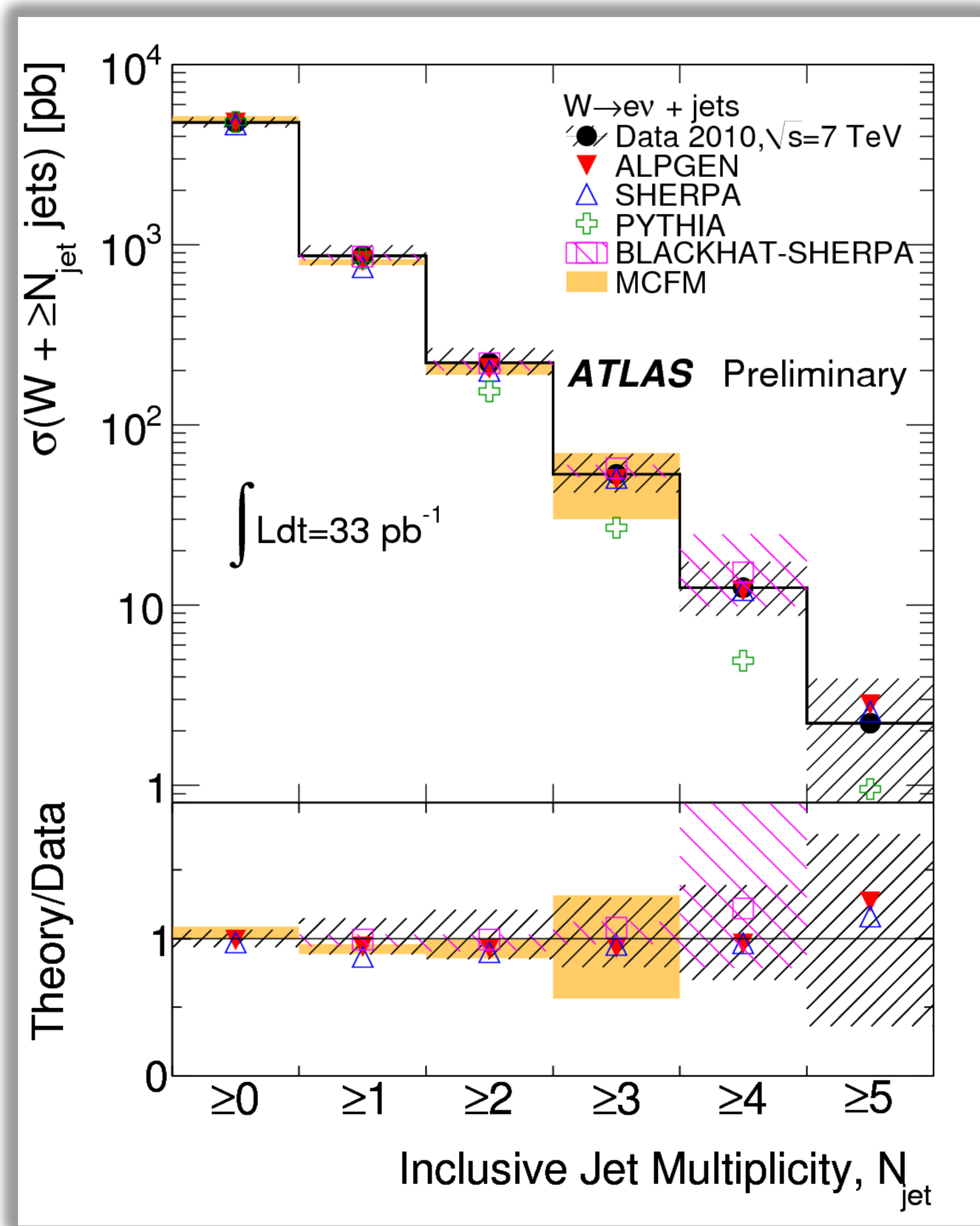
Multiple **MEASUREMENTS**
of background processes
(together with theoretical predictions)

W + Jets

MEASUREMENTS
test MC simulations

Huge numbers of *W*s

Differential in many parameters



Monte Carlo uncertainties

- State of the art generators
  - LO → NLO → NNLO
  - **Decreasing** uncertainties from higher order corrections
  - Very **non-Gaussian** uncertainties
  - Somewhat arbitrary "uncertainty" → untrusted
- Full GEANT detector simulations
  - Remarkably good description of detector response
- Multiple **cross checks**

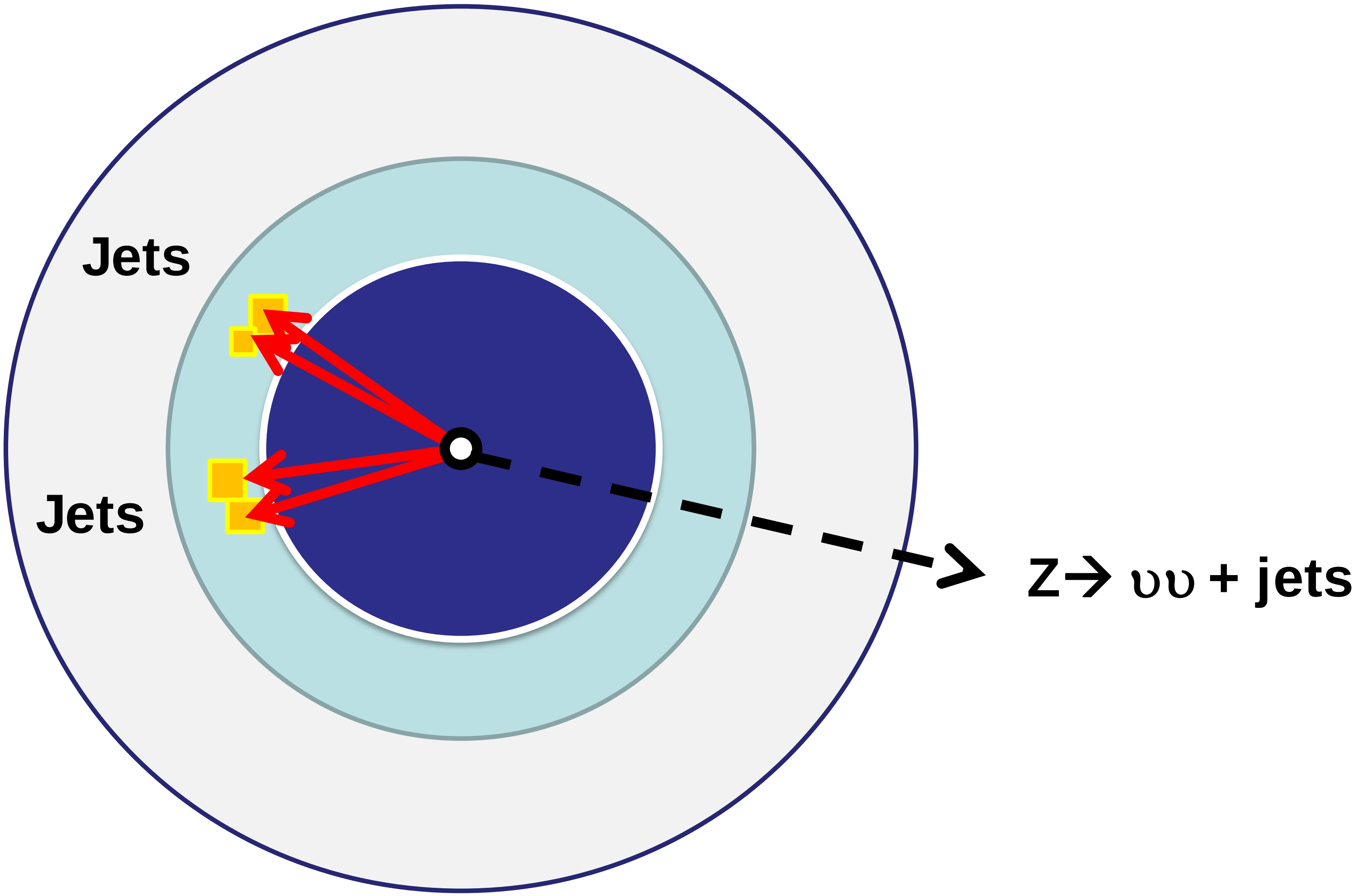
Do we trust the Monte Carlo?

MC simulation samples are used to develop the analysis, determine the transfer factors used to estimate W+jets, Z+jets and top quark production backgrounds, and to assess sensitivity to specific SUSY signal models. Samples of simulated multi-jet events from quantum-chromodynamic (QCD) processes are generated with PYTHIA [21], using the MRST2007LO* modified leading-order parton density functions (PDFs) [22], which are used for all leading-order (LO) MC. Production of top quark pairs is simulated

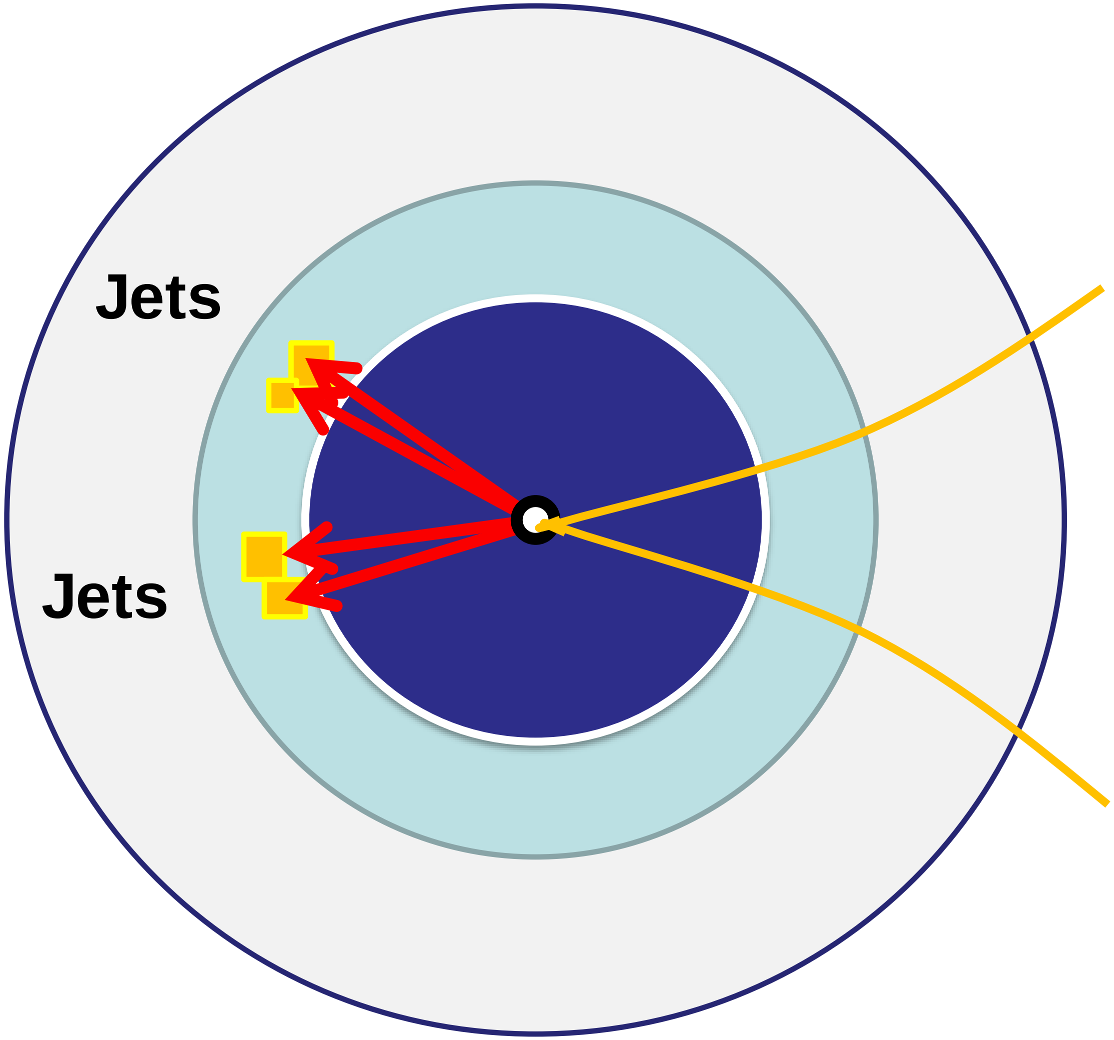
Reduce use of Monte Carlo wherever possible

Background determined from **MEASUREMENTS** where possible
→ uncertainties under experimental control

Final results depend largely on **measurements** from control regions

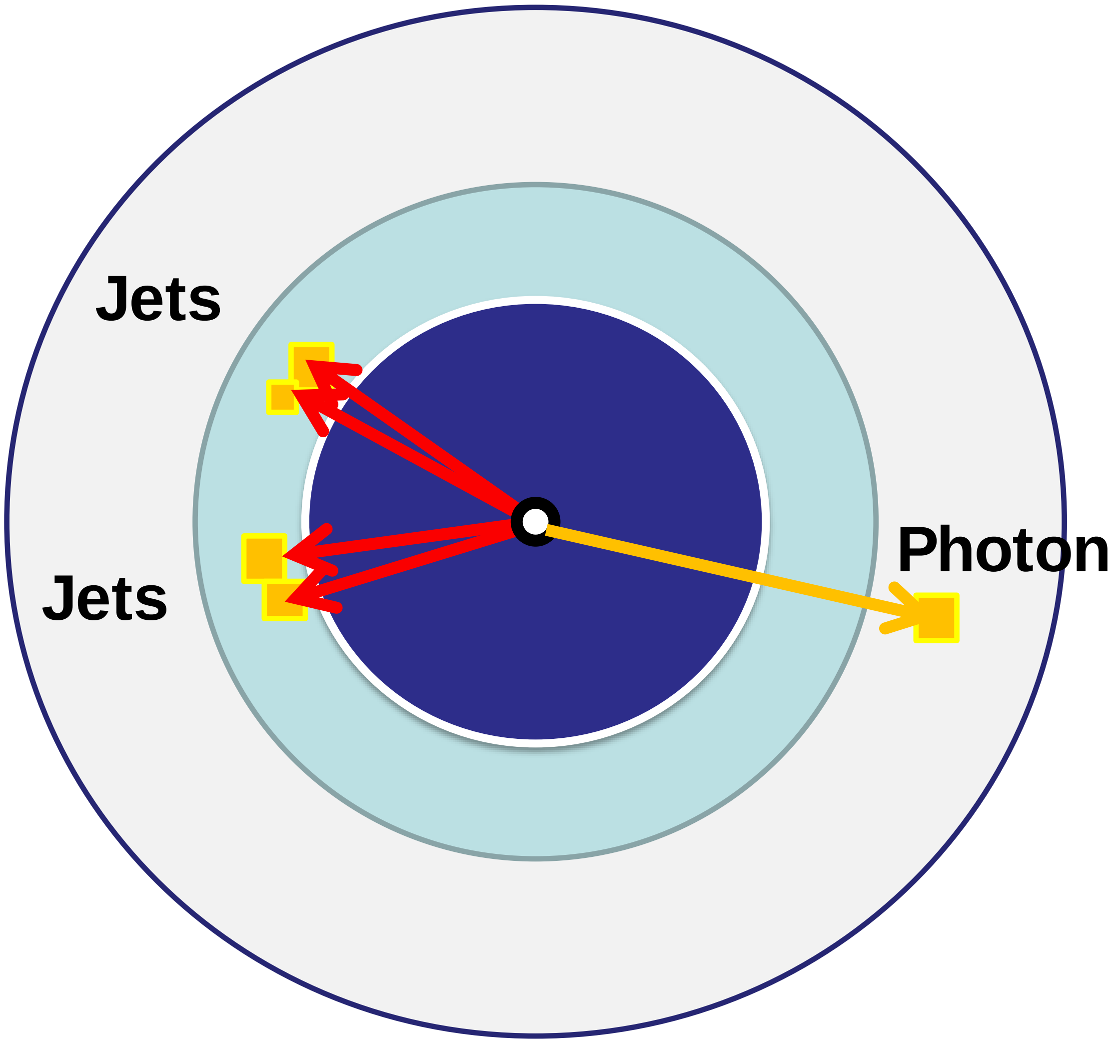


Final results depend largely on **measurements** from control regions



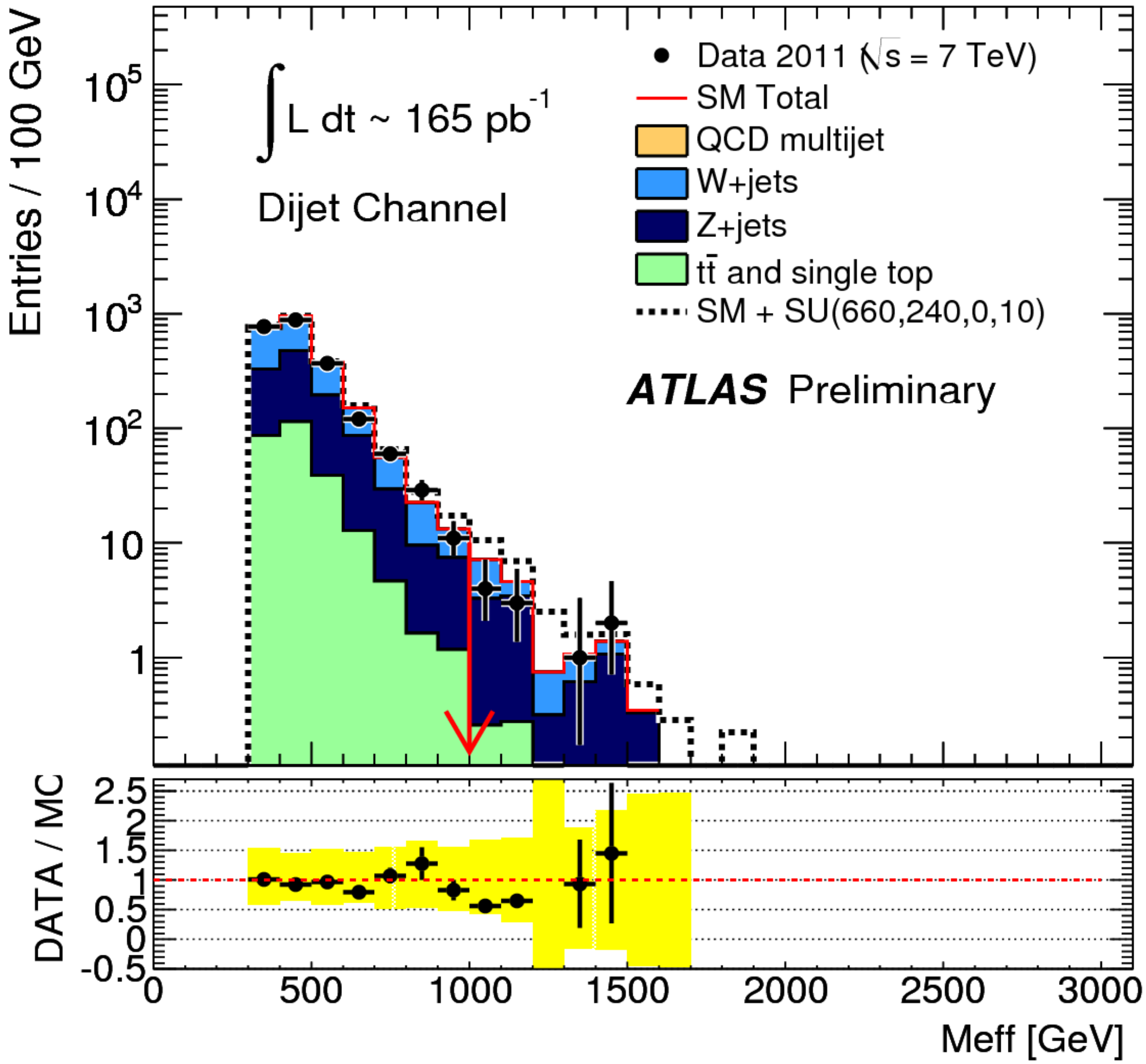
Z→μμ + jets

Final results depend largely on **measurements** from control regions



γ + jets

A distribution we care about:



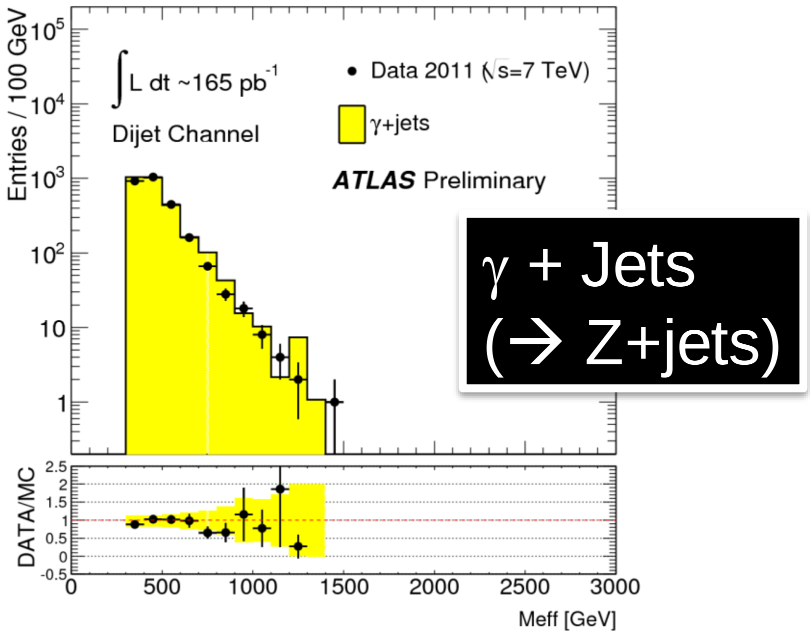
Full Simulation
Monte Carlo

(Alpgen)

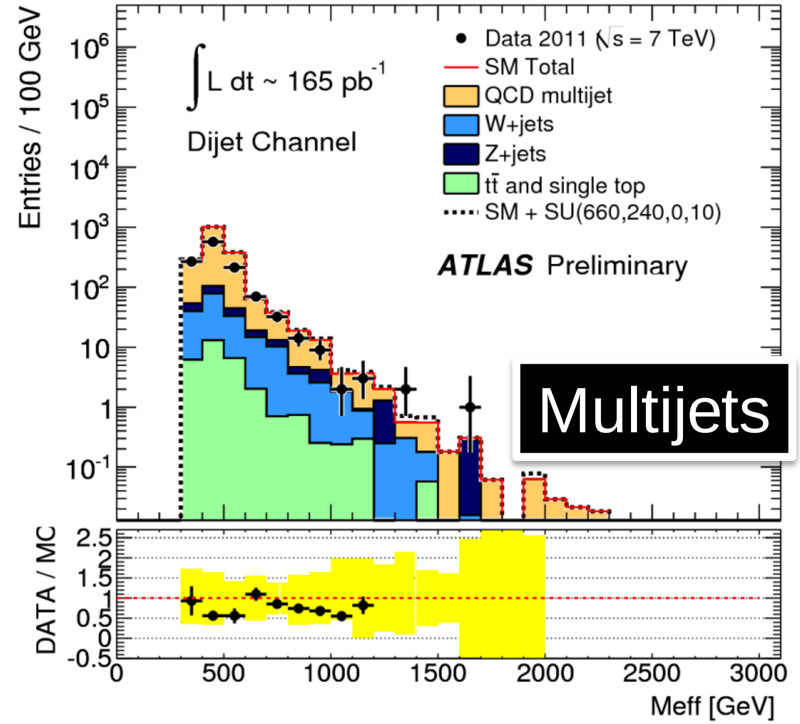
Leading Order

Multi-leg

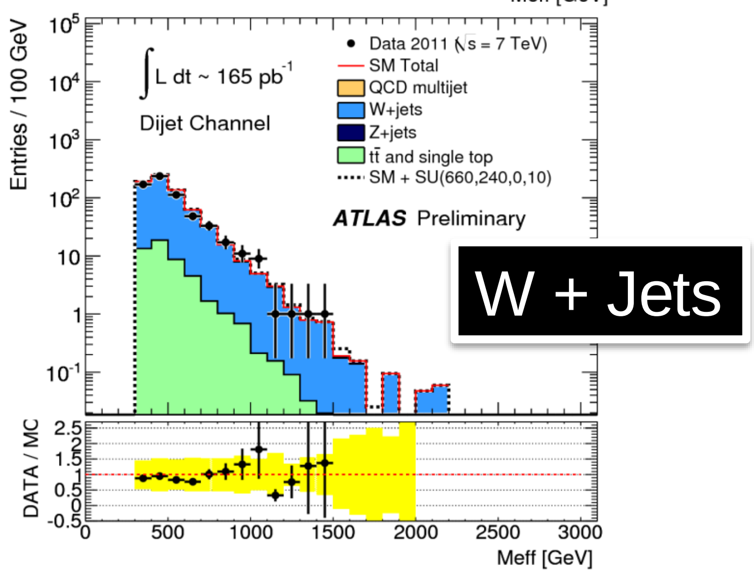
What we **DO** do



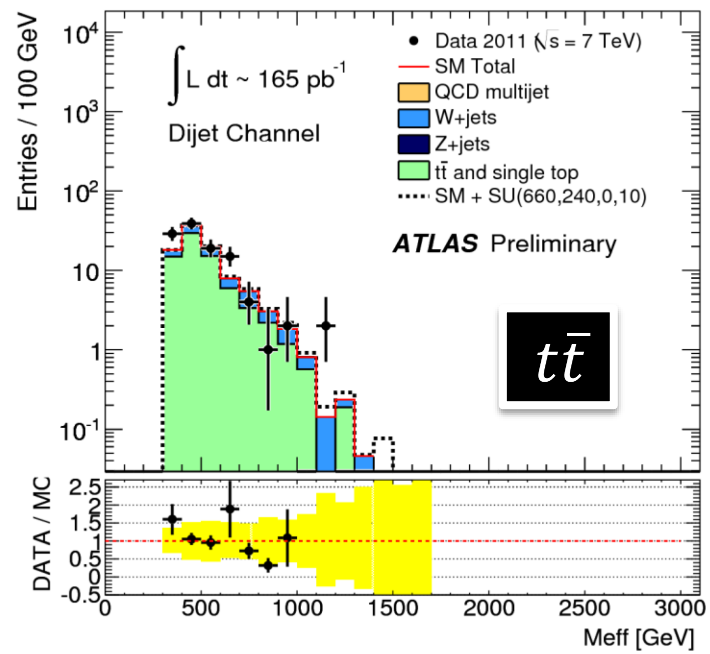
∫L dt ~165 pb⁻¹
Dijet Channel
Data 2011 (√s=7 TeV)
γ+jets
ATLAS Preliminary
Entries / 100 GeV
DATA/MC
Meff [GeV]
γ + Jets
(→ Z+jets)



∫L dt ~ 165 pb⁻¹
Dijet Channel
Data 2011 (√s = 7 TeV)
SM Total
QCD multijet
W+jets
Z+jets
tt̄ and single top
SM + SU(660,240,0,10)
ATLAS Preliminary
Entries / 100 GeV
DATA / MC
Meff [GeV]
Multijets



∫L dt ~ 165 pb⁻¹
Dijet Channel
Data 2011 (√s = 7 TeV)
SM Total
QCD multijet
W+jets
Z+jets
tt̄ and single top
SM + SU(660,240,0,10)
ATLAS Preliminary
Entries / 100 GeV
DATA / MC
Meff [GeV]
W + Jets



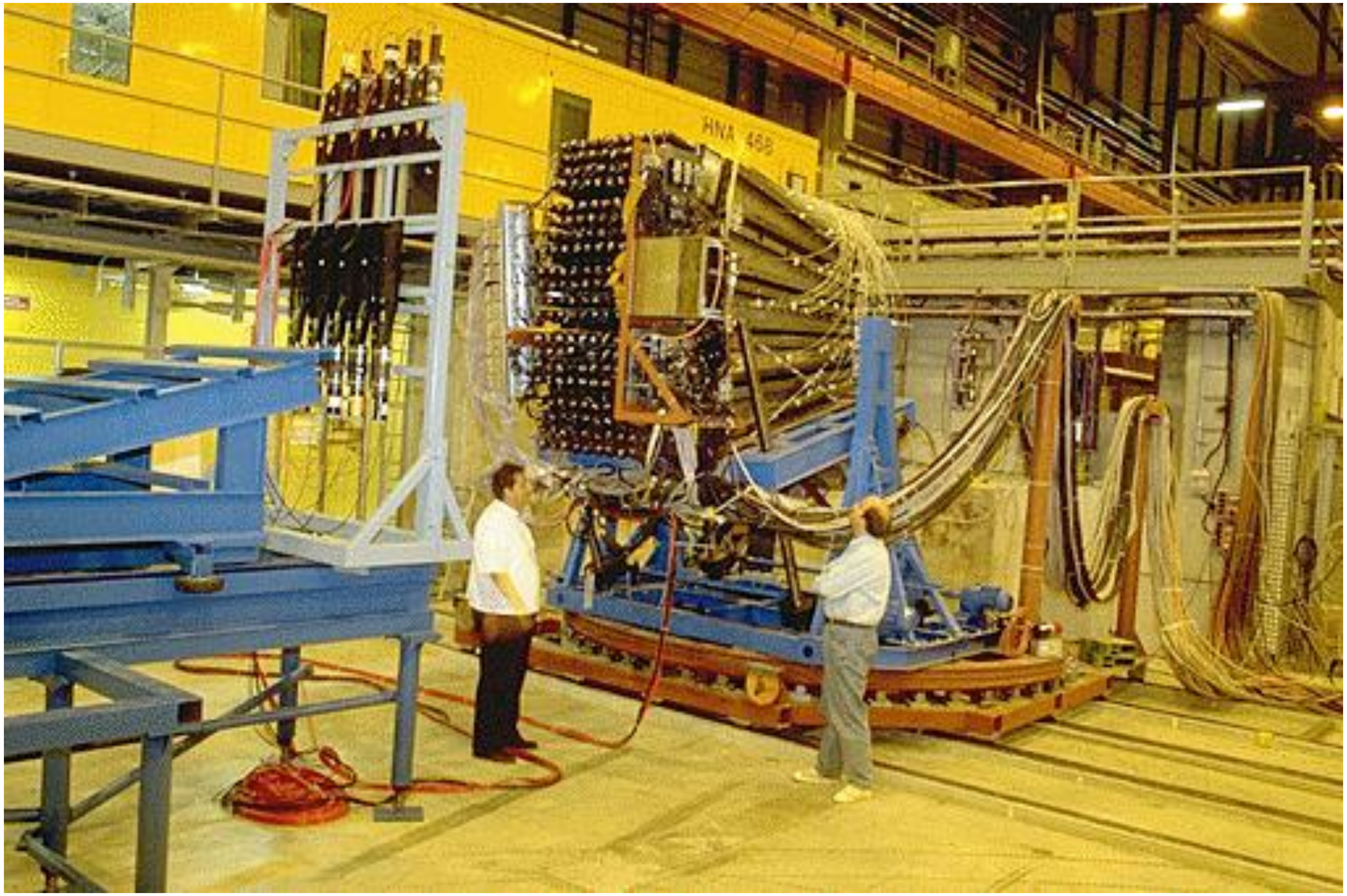
∫L dt ~ 165 pb⁻¹
Dijet Channel
Data 2011 (√s = 7 TeV)
SM Total
QCD multijet
W+jets
Z+jets
tt̄ and single top
SM + SU(660,240,0,10)
ATLAS Preliminary
Entries / 100 GeV
DATA / MC
Meff [GeV]
tt̄

Other uncertainties include

- Luminosity:
  - **MEASURED** in Van-der-Meer scans, …
- Proton Structure:
  - **MEASURED** at HERA ep collider
  - Cross-checked/refined with LHC data
- JET Energy Scale (detector response)
  - **MEASURED** in beam tests
  - Cross-checked/refined with LHC data

Dependence on these effects (and on MC) greatly reduced by **measuring** background rates in LHC data

JET ENERGY SCALE?



H8 calorimeter beam test 1999

Putting it together: Likelihood

$$L(\boldsymbol{n}|\mu, \boldsymbol{b}, \boldsymbol{\theta}) = P_{\text{SR}} \times P_{\text{WR}} \times P_{\text{TR}} \times P_{\text{ZRa}} \times P_{\text{ZRb}} \times P_{\text{QR}} \times C_{\text{Syst}}$$

Poisson for signal region

Poisson for control regions (fns of nuisance parameters signal strength, …)

Nuisance parameters largely uncorrelated

$$C_{Syst}(\boldsymbol{\theta}^0, \boldsymbol{\theta}) = \prod_{j \in \text{SU}} G(\theta_j^0, \theta_j)$$

$$C_{\text{process j, region j}\to\text{i}} = C^{\text{nominal}}_{\text{process j, region j}\to\text{i}} \times \left(1 + \sum_k \Delta_{j,i;k}\, \theta_k\right)$$

Shifts due to nuisance parameter

Sources of systematics considered

- Jet energy scale
- Jet energy resolution
- Lepton efficiency
- Lepton energy scale
- B-tag efficiency
- Pile-up/multiple pp interactions
- Out-of-jet energy
- Monte Carlo stats
- MC higher order corrections
- Loss of electronics
- PDFs
- Signal cross section higher order corrections

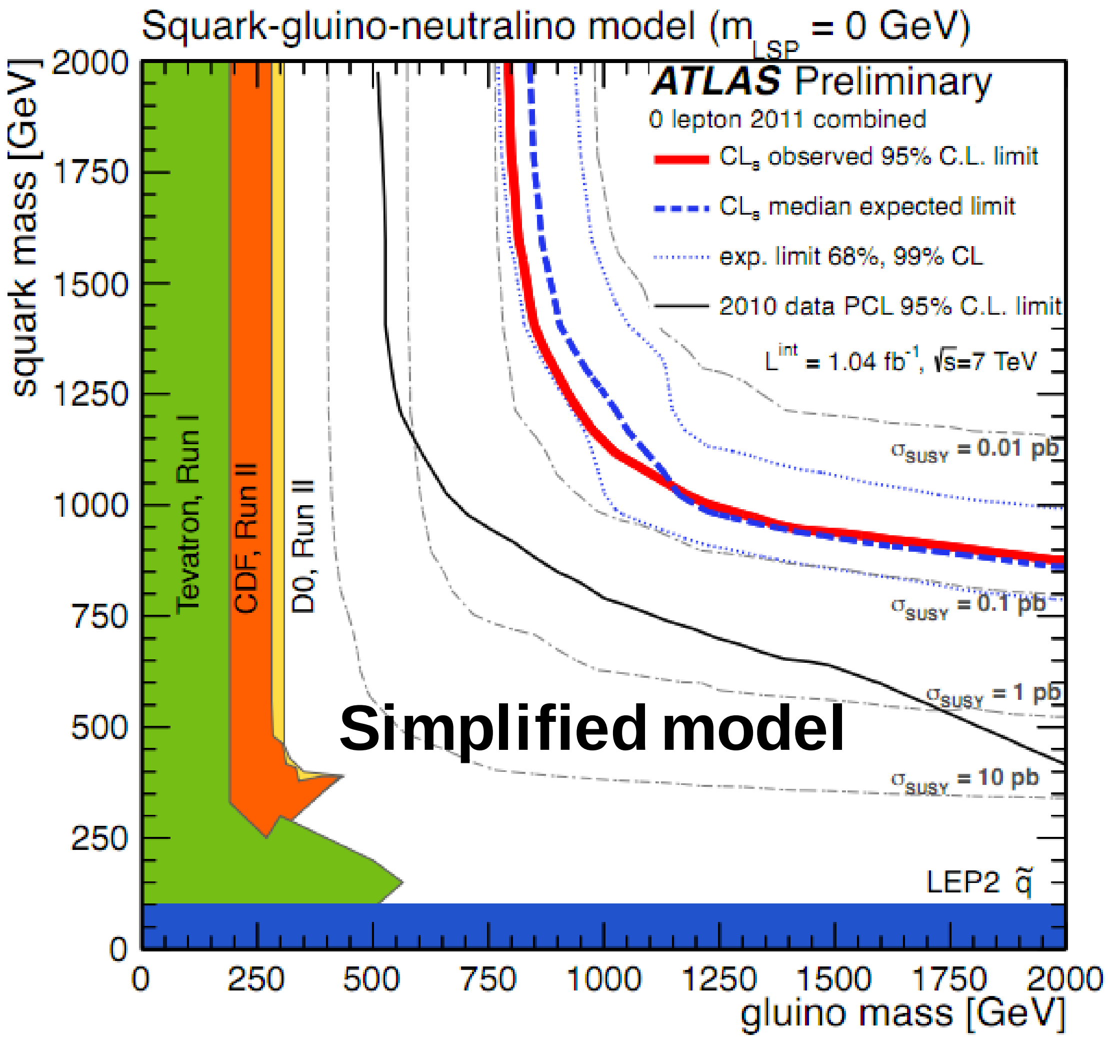
CAVEAT

- I have emphasised that multiple **measurements** give good confidence in size of uncertainties
- **RMS** of measurements/discrepancies often used to define **1-sigma [~fine]**
- Anyone who believes in **Gaussian** uncertainties in such contexts is naive
- One should be correspondingly wary about ***literal*** interpretations of multi-sigma effects

Add additional uncertainties in predicted signal (PDF, higher orders)

Results from
EPS-2011
on Saturday

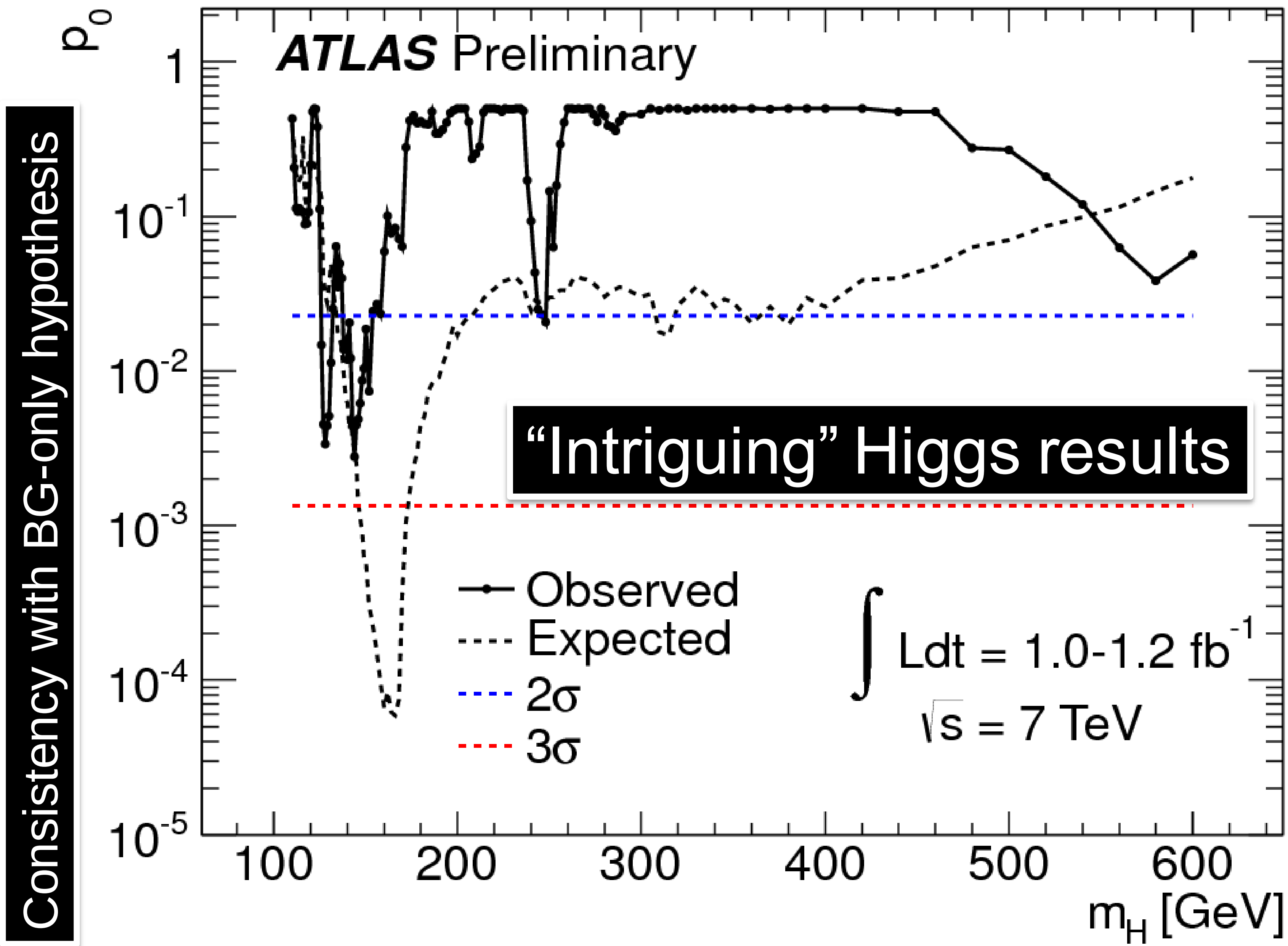
Full talk



ATLAS SUSY Searches

ATLAS SUSY analyses		Publications	
E_T^{miss} + Jets + 0 lepton	New	arXiv:1102:5290 (35 pb^{-1}) [published in PLB]; ATL-CONF-2011-086 (163 pb^{-1}); arXiv:XXXX:XXXX To be submitted (1.04 fb^{-1})	Combination (35 pb^{-1}) ATL-CONF-2011-064
E_T^{miss} + Jets + 1 lepton	New	arXiv:1102:2357 (35pb^{-1}) [published in PRL]; ATL-CONF-2011-090 (163 pb^{-1});	
E_T^{miss} + b Jets + 0/1 lepton	New	arXiv:1103:4344 (35 pb^{-1}) [published in PLB]; ATL-CONF-2011-098 (833 pb^{-1})	
E_T^{miss} + Jets + 2 leptons (OS, SS, SF subtraction)		arXiv:1103:6214 (35 pb^{-1}) [published in EPJC]; ATL-CONF-2011-091 (simplified model interpretation to SS) arXiv:1103:6208 (35 pb^{-1}) [published in EPJC];	
E_T^{miss} + Jets + >= 3 leptons		ATL-CONF-2011-039 (34 pb^{-1})	
E_T^{miss} +γγ		arXiv:1107:0561 (36 pb^{-1}) [submitted to EPJCL];	
eμ resonance (RPV)	New	arXiv:1103:5559 (35 pb^{-1}) [published in PRL]; ATL-CONF-2011-109 (870 pb^{-1})	
Stable hadronising squarks & gluinos		arXiv:1103:1984 (34 pb^{-1}) [published in PLB];	
Heavy Long-lived charged particles		arXiv:1106:4495 (37 pb^{-1}) [submitted to PLB];	

I CAN’T RESIST SHOWING…



Consistency with BG-only hypothesis
p_0
ATLAS Preliminary
"Intriguing" Higgs results
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
100
200
300
400
500
600
m_H [GeV]
Observed
Expected
2σ
3σ
$\int Ldt = 1.0\text{-}1.2\ fb^{-1}$
$\sqrt{s} = 7$ TeV

Getting the results?

- **ATLAS** public results
  - **EPS 2011**, 21-27 July; link
  - Supersymmetry searches summary

TWiki > AtlasPublic Web > WebHome (23-Jul-2011, RichardHawkings) Edit Attach PDF

ATLAS EXPERIMENT - Public Results

Quick links: Papers - CONF notes - Physics Groups - Combined Performance & Detector - Data Collected - Event Displays

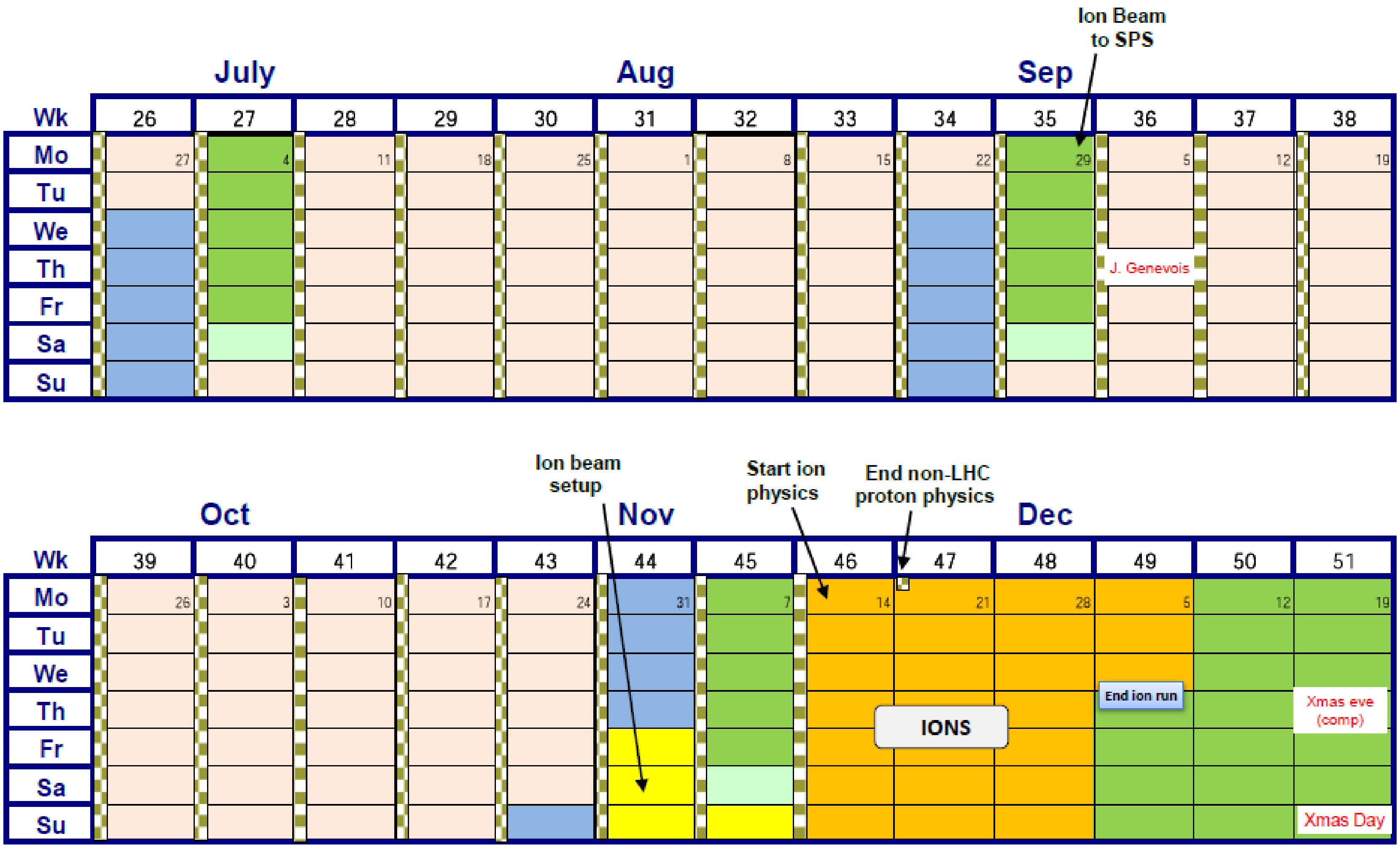
This is the central ATLAS results page. It is intended for physicists who are looking for documentation on ATLAS physics, detector and combined performance results. ATLAS results from LHC collision data are made available via three routes: publications, listed under the first sub-heading; performance plots; and conference (CONF) notes, which describe preliminary results. Approved event displays are also available. Links to results pages with performance plots and CONF notes are given in the tables below. In addition, public PUB notes may be available, these typically describe either technical work not related to collision data performance, or studies of the physics capabilities of ATLAS using simulation. PUB notes are usually linked from the results pages referenced in the tables below.

Most recent results being presented

LHC PHYSICS

EXTRA SLIDES

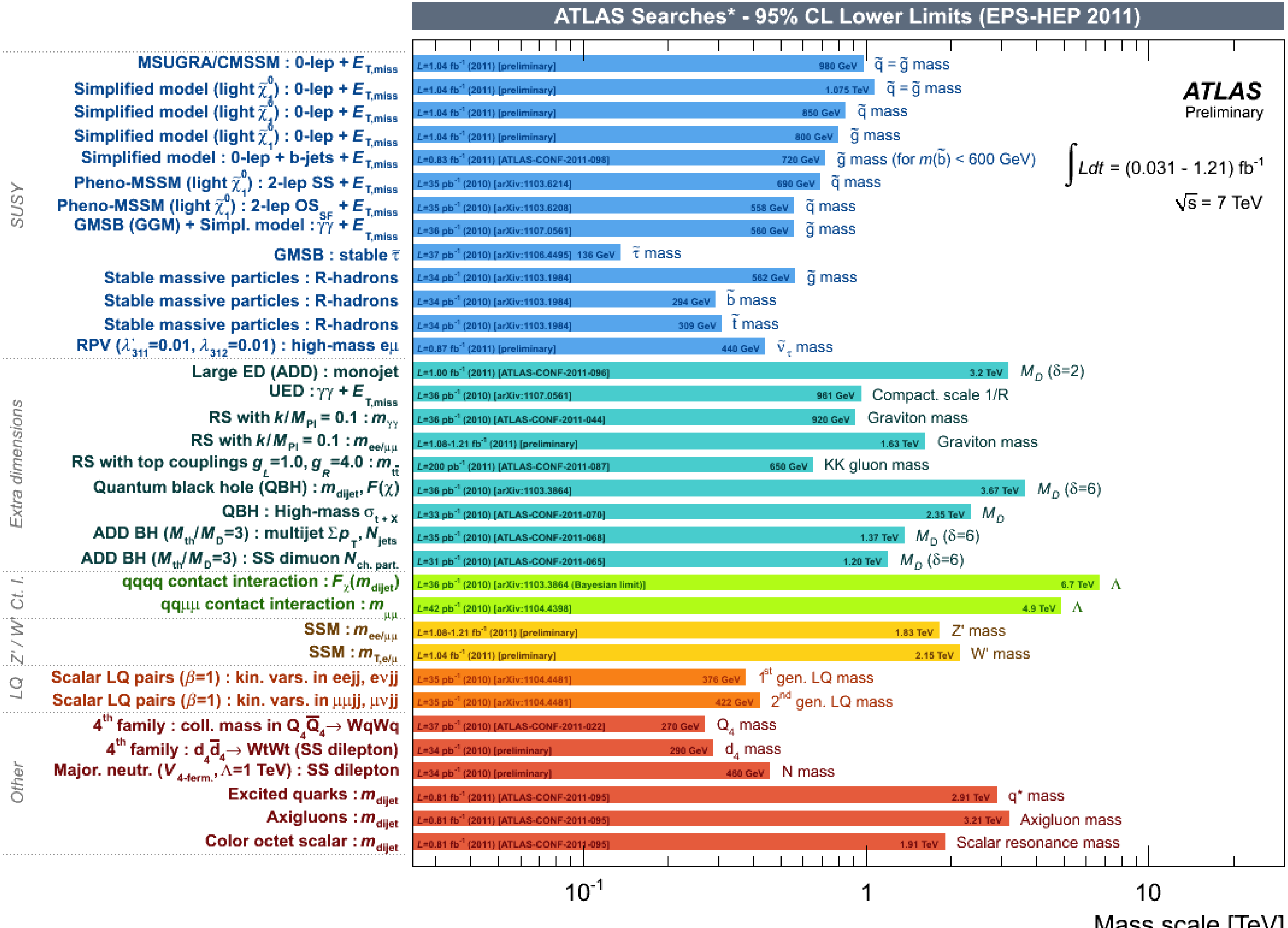
2011 Plans…


Ion Beam to SPS
July
Aug
Sep
Wk
26 27 28 29 30 31 32 33 34 35 36 37 38
Mo
Tu
We
Th
Fr
Sa
Su
27 4 11 18 25 1 8 15 22 29 5 12 19
J. Genevois
Ion beam setup
Start ion physics
End non-LHC proton physics
Oct
Nov
Dec
Wk
39 40 41 42 43 44 45 46 47 48 49 50 51
Mo
Tu
We
Th
Fr
Sa
Su
26 3 10 17 24 31 7 14 21 28 5 12 19
End ion run
IONS
Xmas eve (comp)
Xmas Day


Software
Operations
Hardware
Grid
Computing
Detector & Upgrade

Further search papers

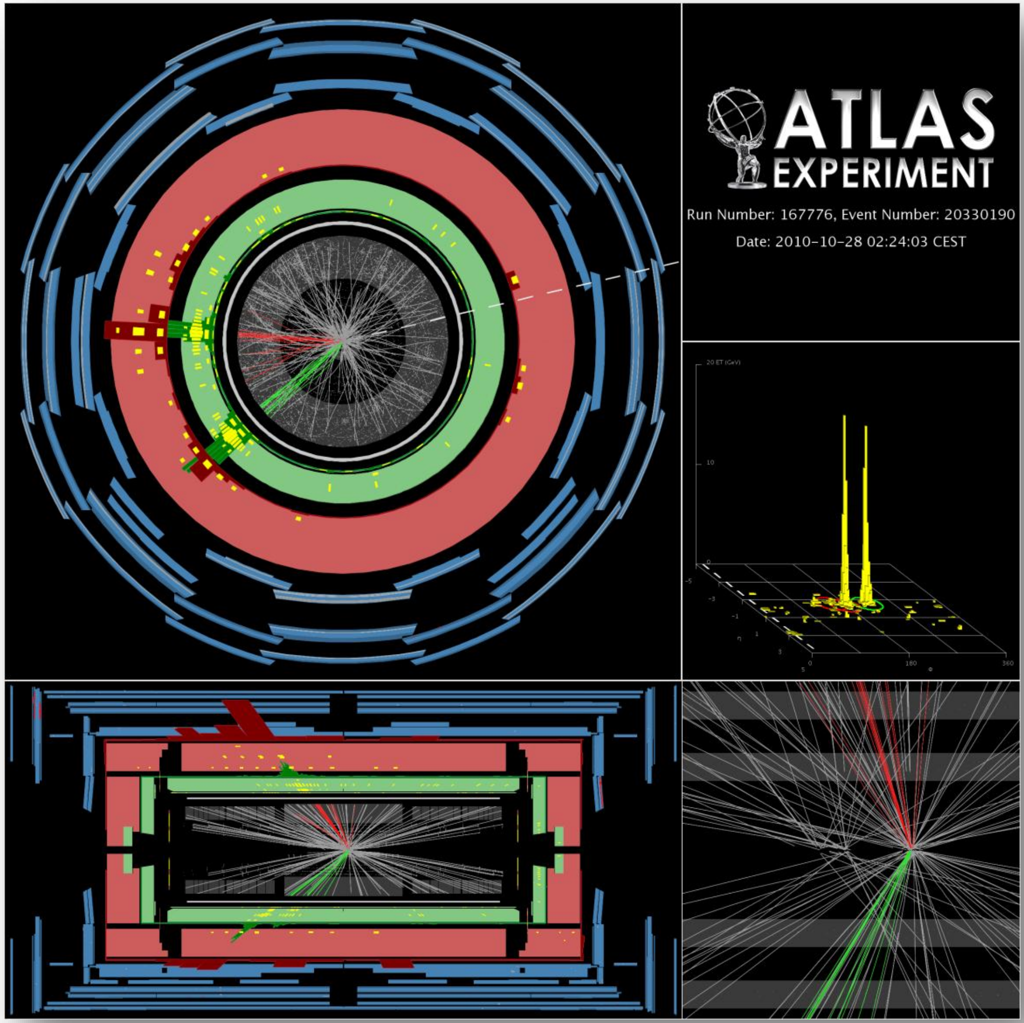
- **Supersymmetry:**
  - **Squarks or gluinos**
  - **Lepton + jet + invis**
  - **Dilepton + invis**
  - **Same sign leptons + invis**
  - **Z + invis**
  - **b-jet(s) + invis**
  - **R-hadrons**
- **Others**
  - **Monojets**
  - **e-mu resonances**
  - **Dilepton resonances**
  - **Leptoquarks**
  - **CHAMPS**
  - **Dimuons (contact)**
  - **W' → $\ell\,\upsilon$**
  - **Z' → $\ell\,\ell$**



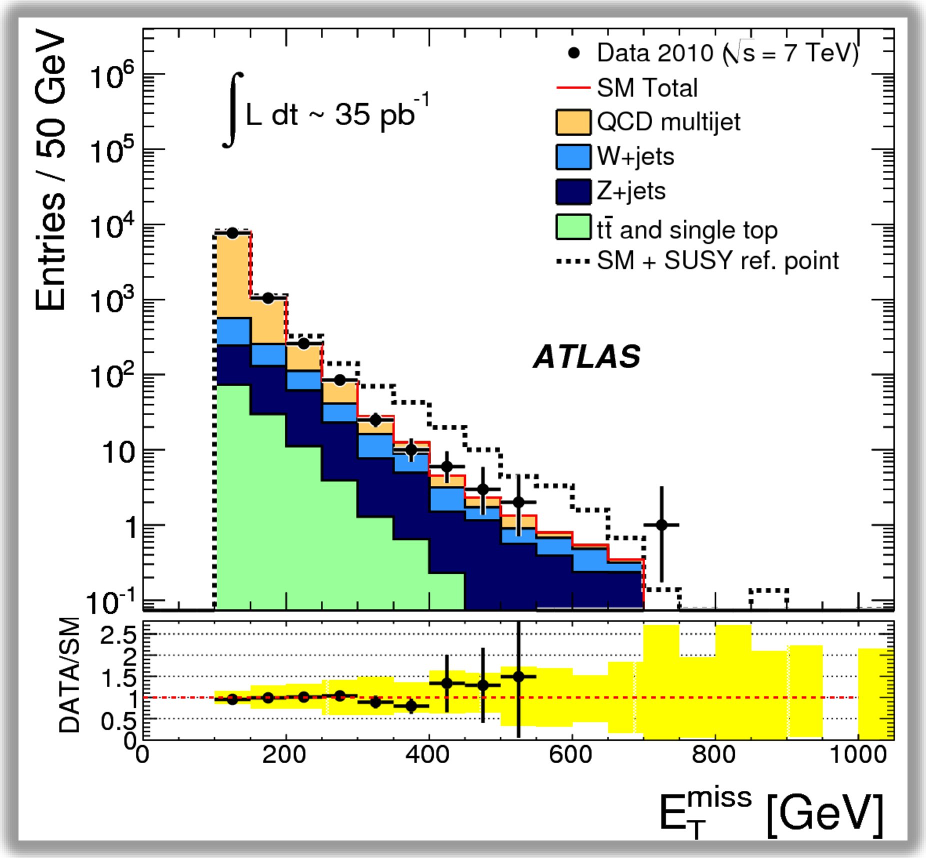
*Only a selection of the available results shown

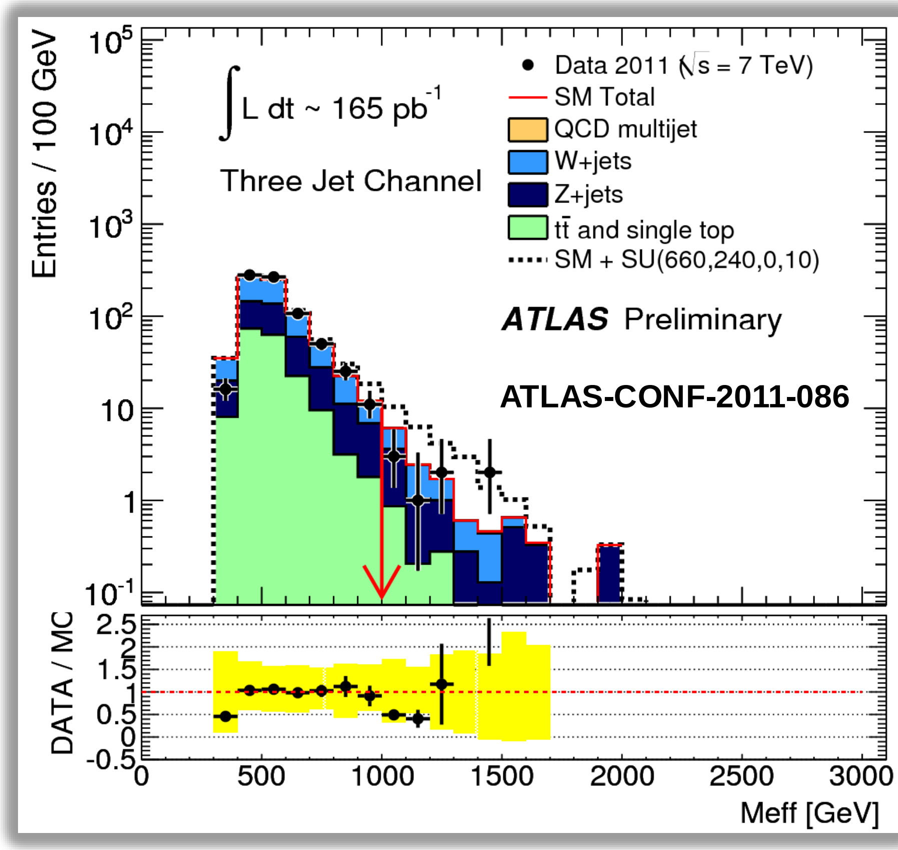
Supersymmetry

- Partner particles
- Spin differ by ½
- Stabilise m_H
- Dark Matter candidates
- "Missing" momentum
- Big reach at LHC



Supersymmetry searches

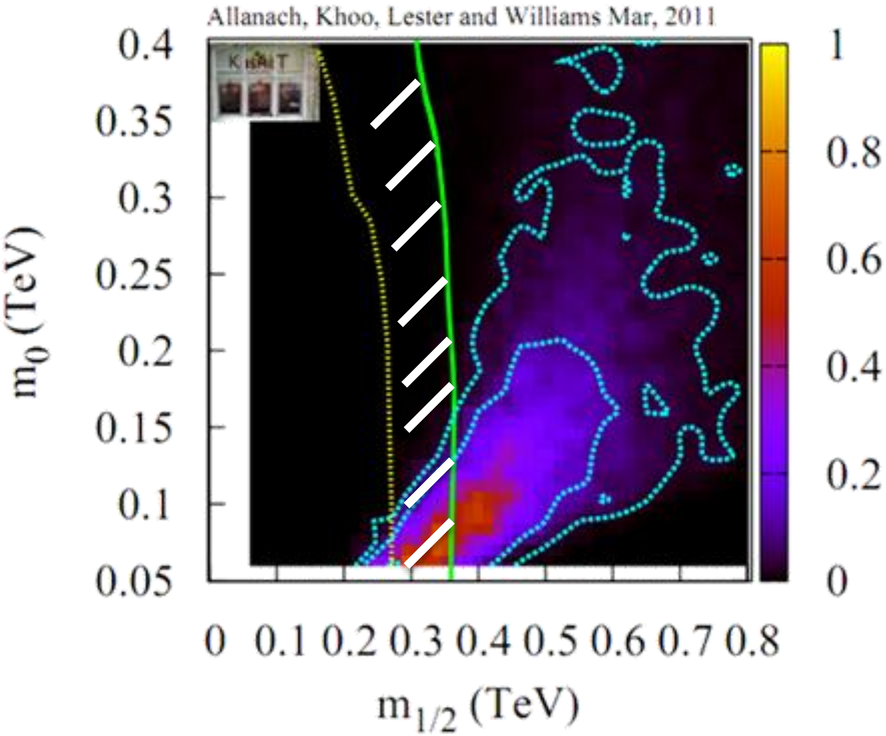




"Missing" momentum

Scalar sum of momentum

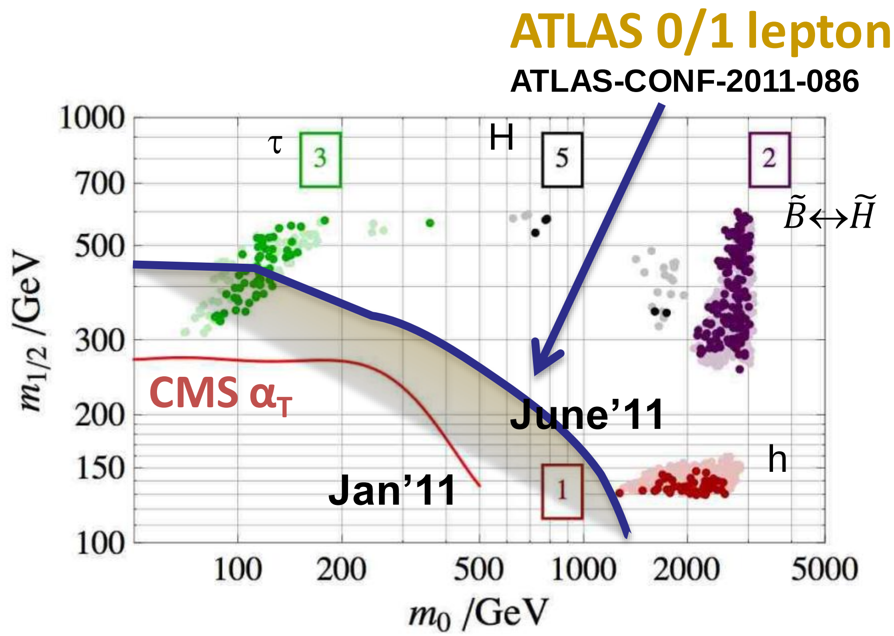
Wider interpretation...



Allanach, Khoo, Lester, Williams

http://arxiv.org/abs/1103.0969

Points sampled from fits to global data Global CMSSM fits

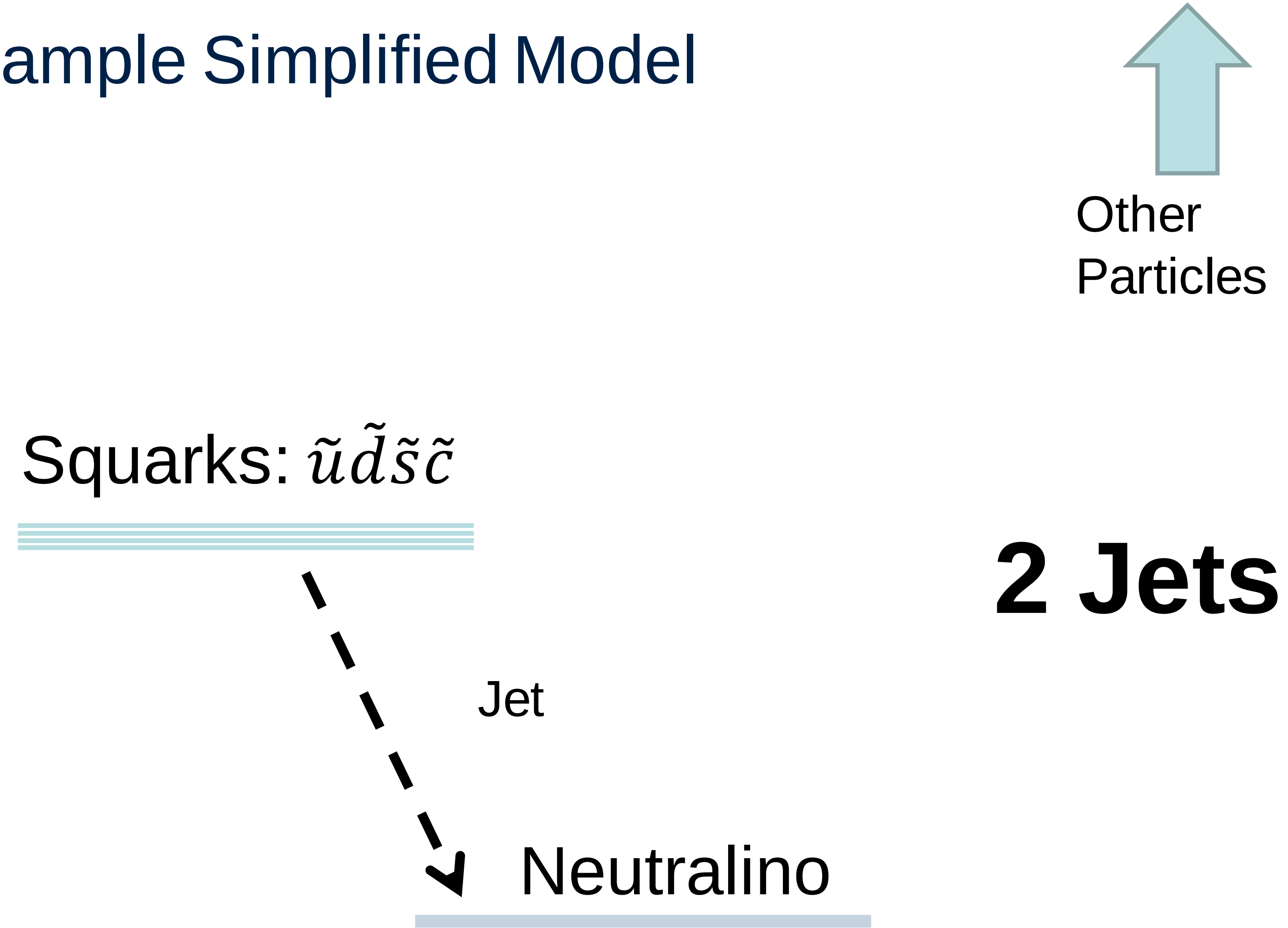


Cassel, Ghilencea, Kraml, Lessa, Ross

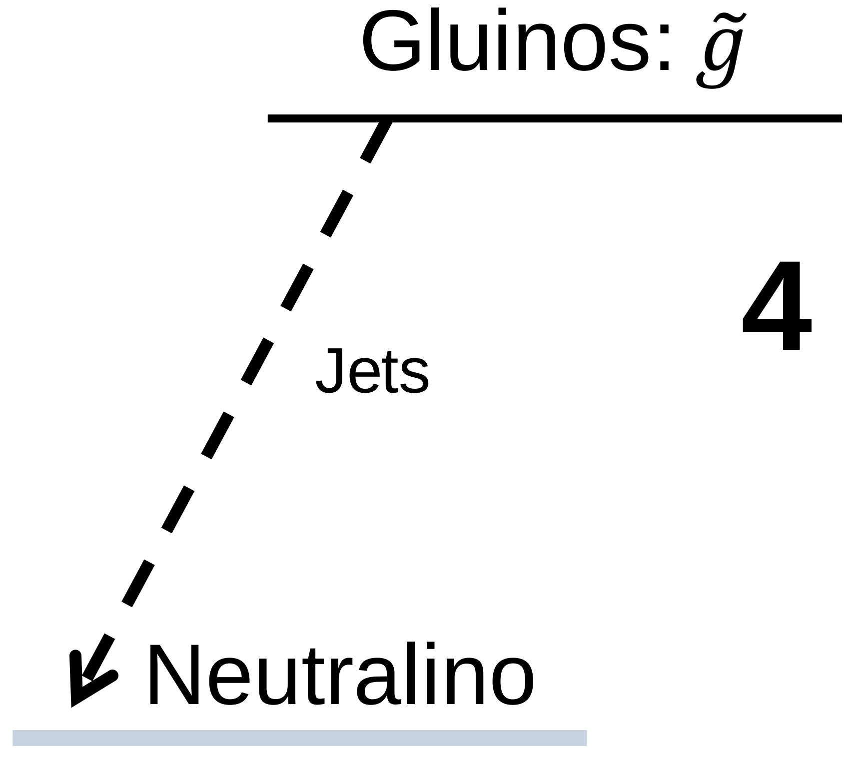
http://arxiv.org/abs/1101.4664

Regions with low fine tuning

Example Simplified Model

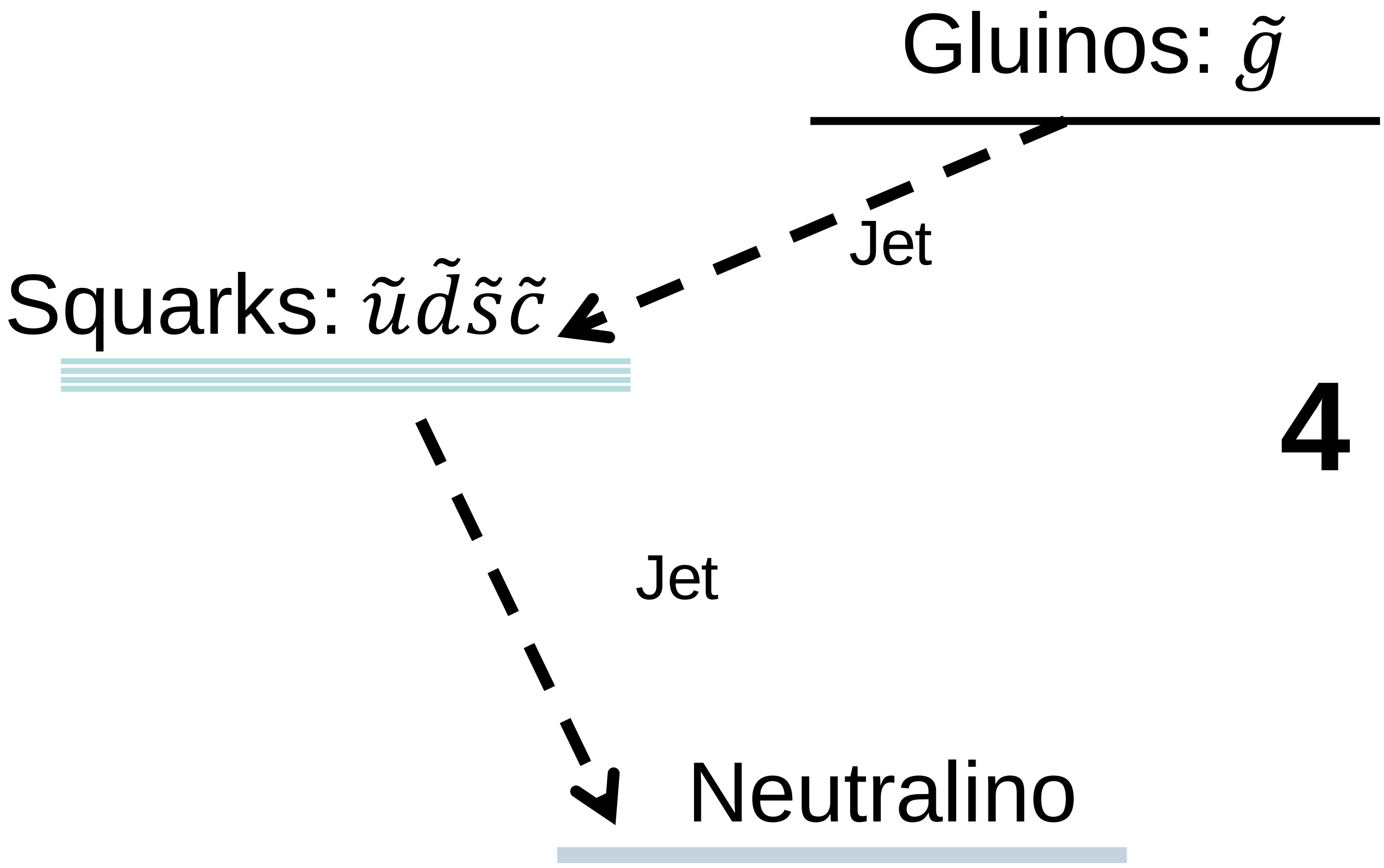


Example Simplified Model



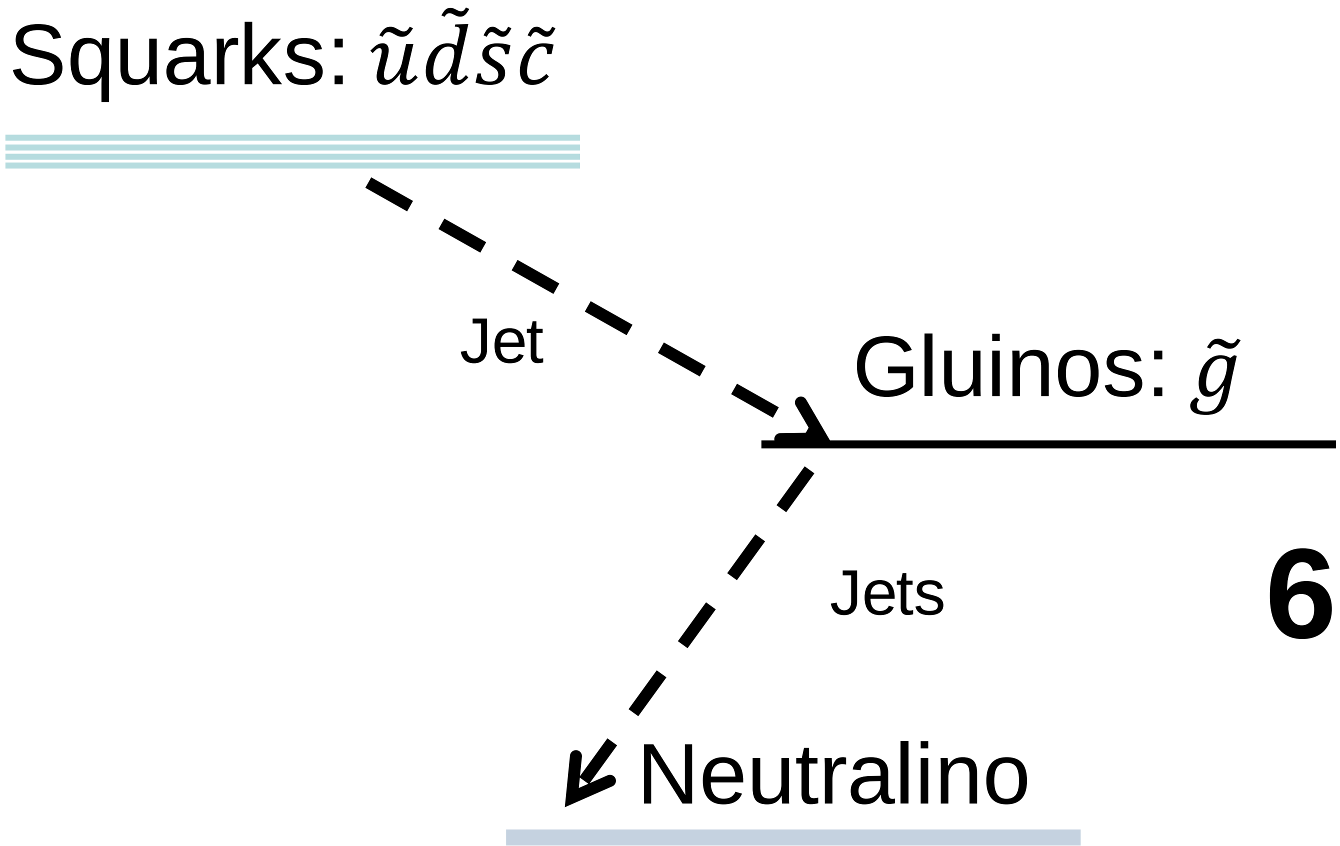
4 Jets

Example Simplified Model

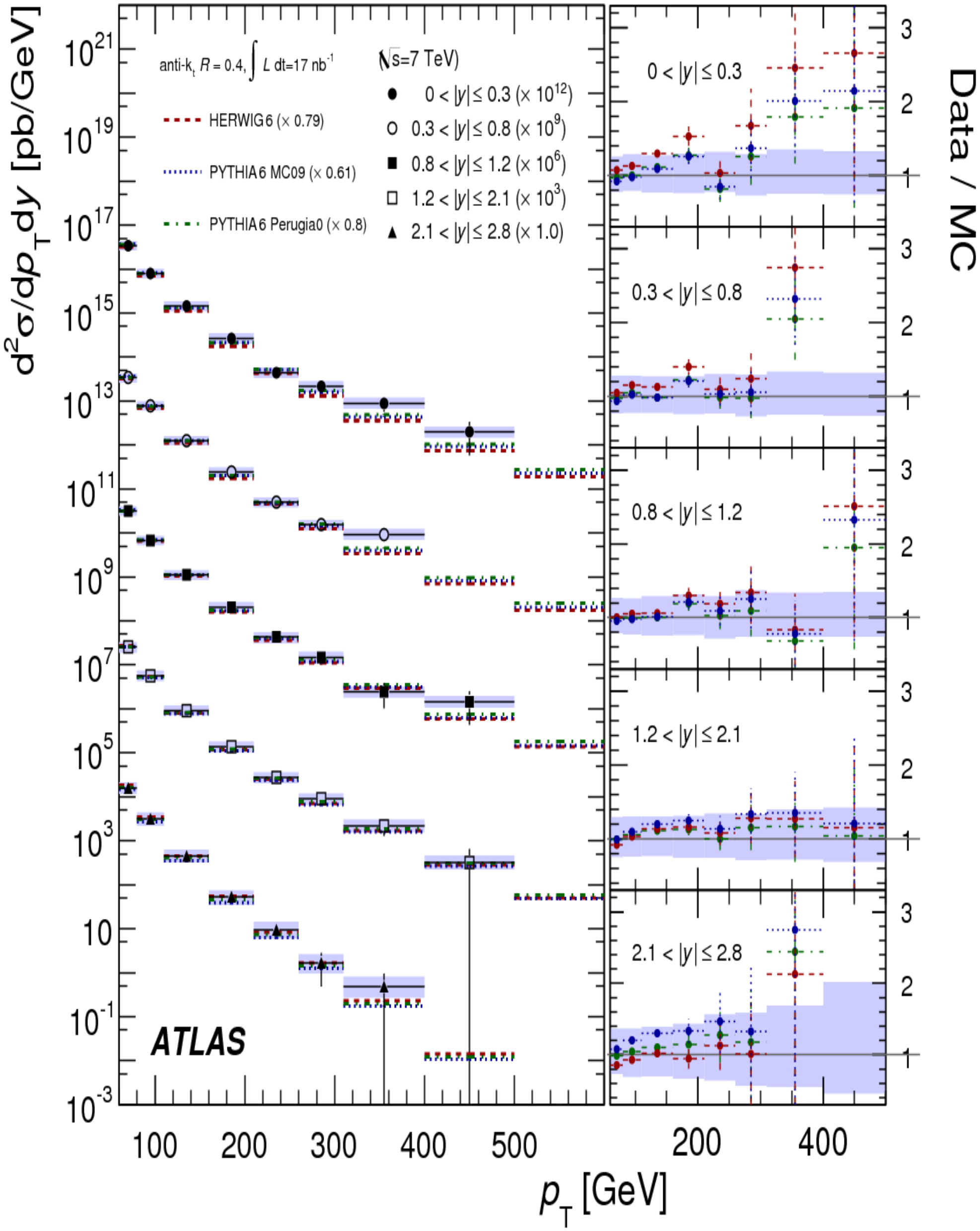


4 Jets

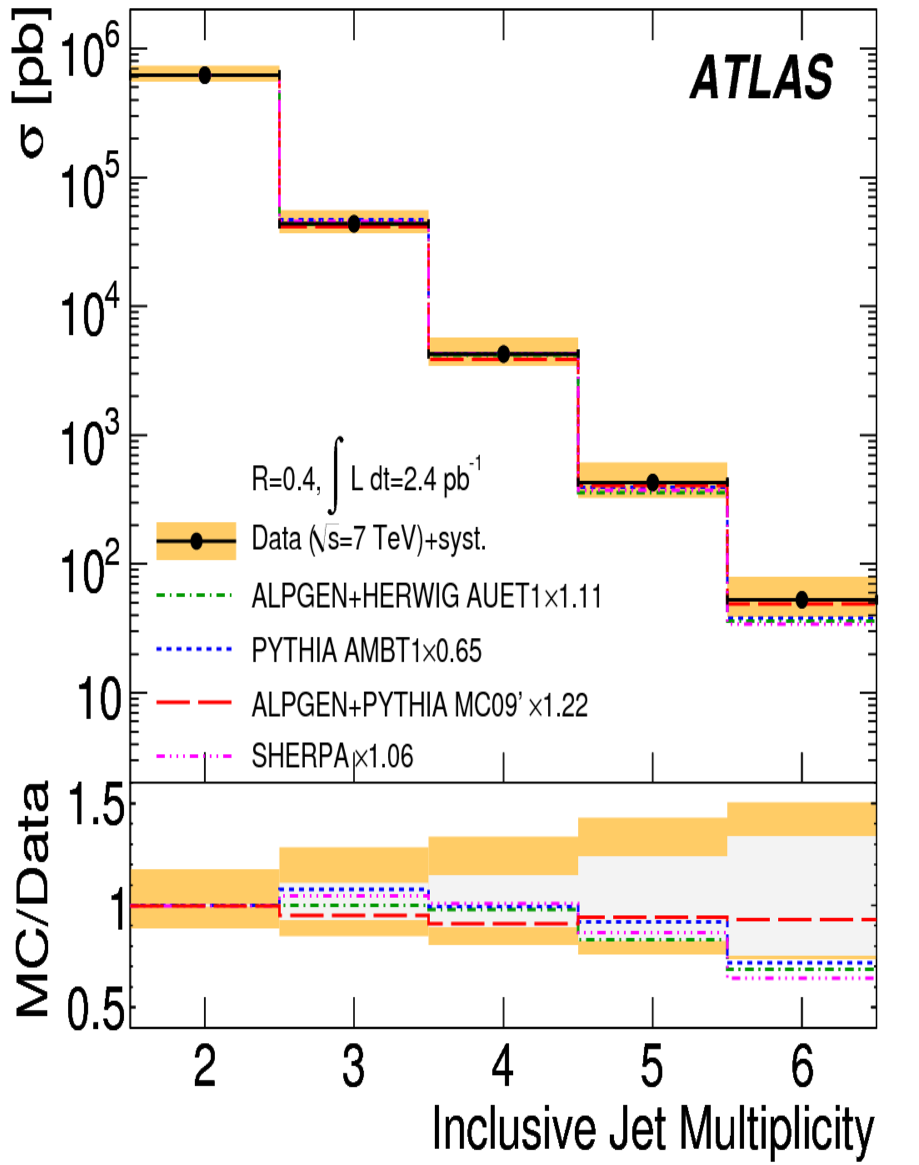
Example Simplified Model



6 Jets



New J. Phys. 13 (2011) 053044

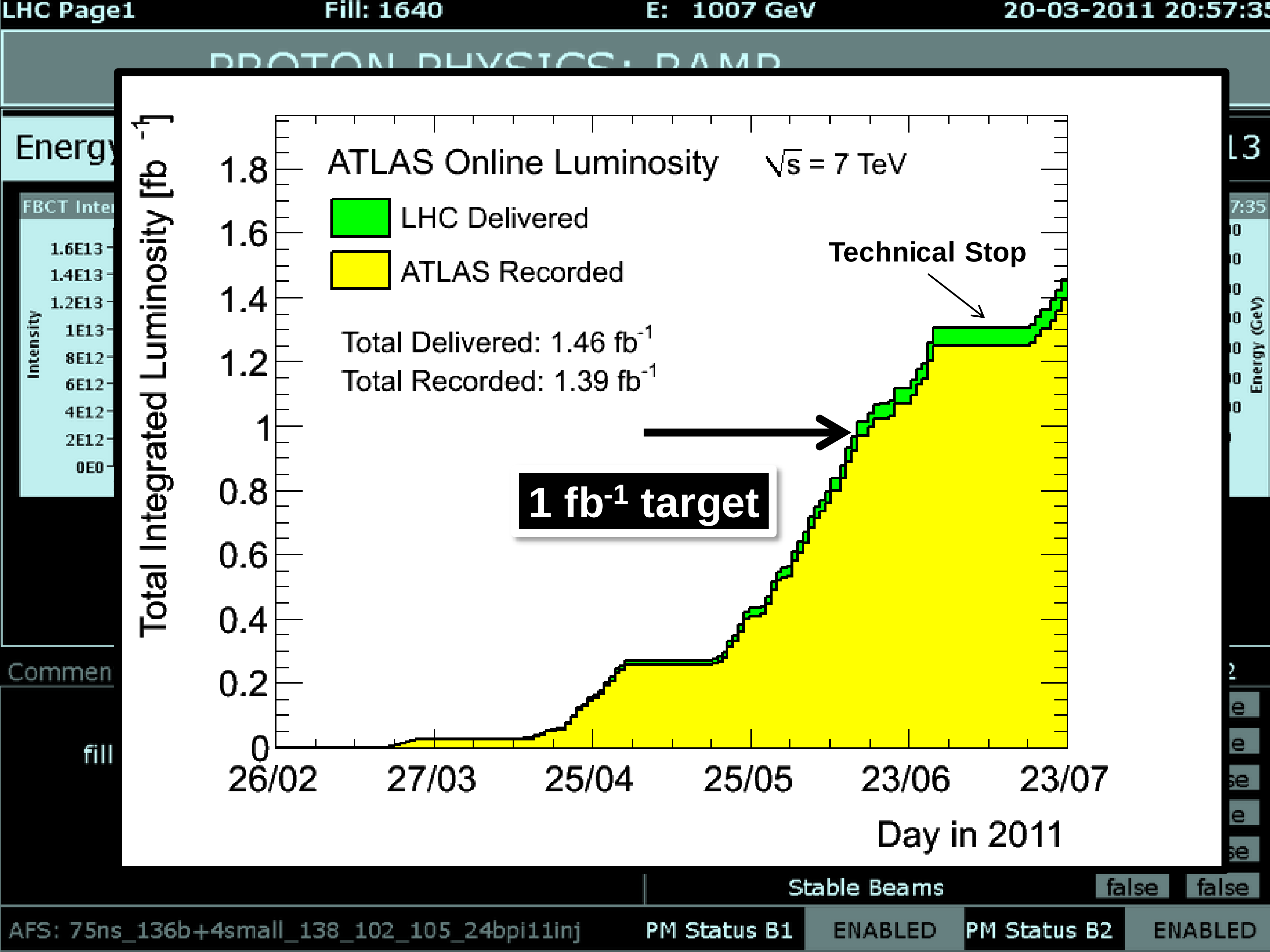


arXiv:1107.2092

A year is a long time at the LHC

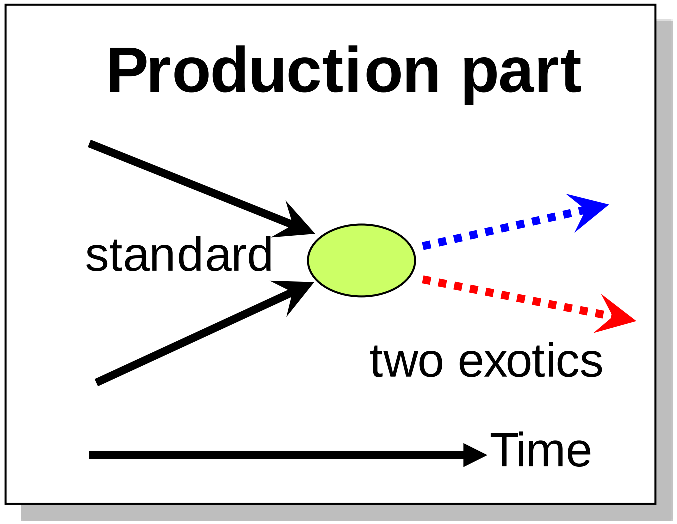
	July 2010	July 2011	x
Bunches / beam	25	1380	55
Protons / bunch	2×10^{10}	1.2×10^{11}	6
Lumi / day	60 nb^{-1}	50 pb^{-1}	800
Integrated	200 nb^{-1}	1.4 fb^{-1}	**7000**

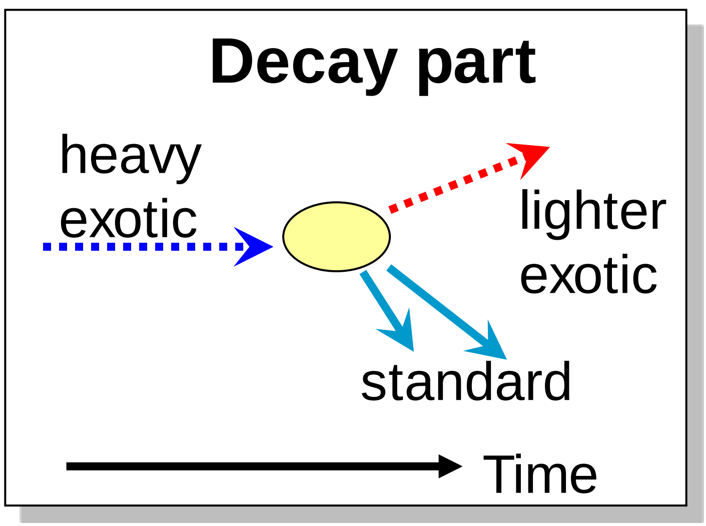
Commissioned bunch trains
50 ns bunch-crossing operation

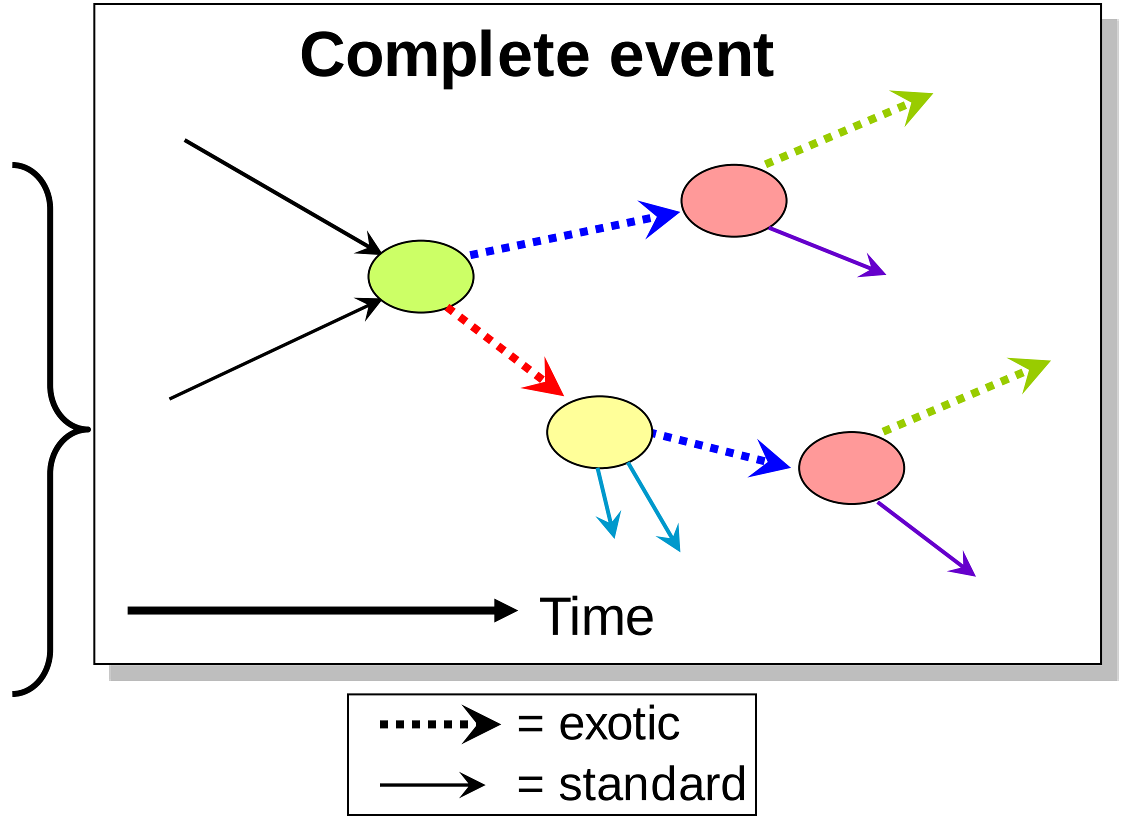


LHC Page1
Fill: 1640
E: 1007 GeV
20-03-2011 20:57:35
Energy
FBCT Inten
Intensity
1.6E13
1.4E13
1.2E13
1E13
8E12
6E12
4E12
2E12
0E0
Energy (GeV)
Commen
fill
ATLAS Online Luminosity
√s = 7 TeV
LHC Delivered
ATLAS Recorded
Total Delivered: 1.46 fb-1
Total Recorded: 1.39 fb-1
Technical Stop
1 fb-1 target
Total Integrated Luminosity [fb-1]
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
26/02
27/03
25/04
25/05
23/06
23/07
Day in 2011
Stable Beams
false
false
AFS: 75ns_136b+4small_138_102_105_24bpi11inj
PM Status B1
ENABLED
PM Status B2
ENABLED

“Seeing” WIMPs at the LHC



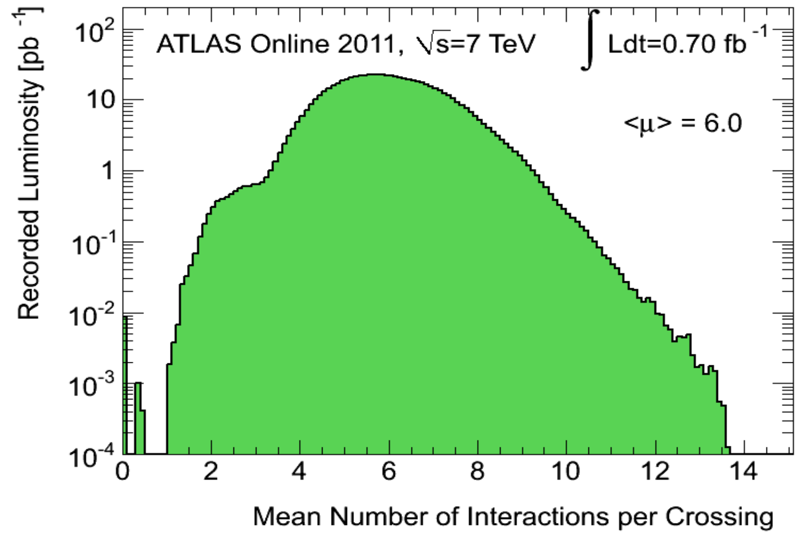


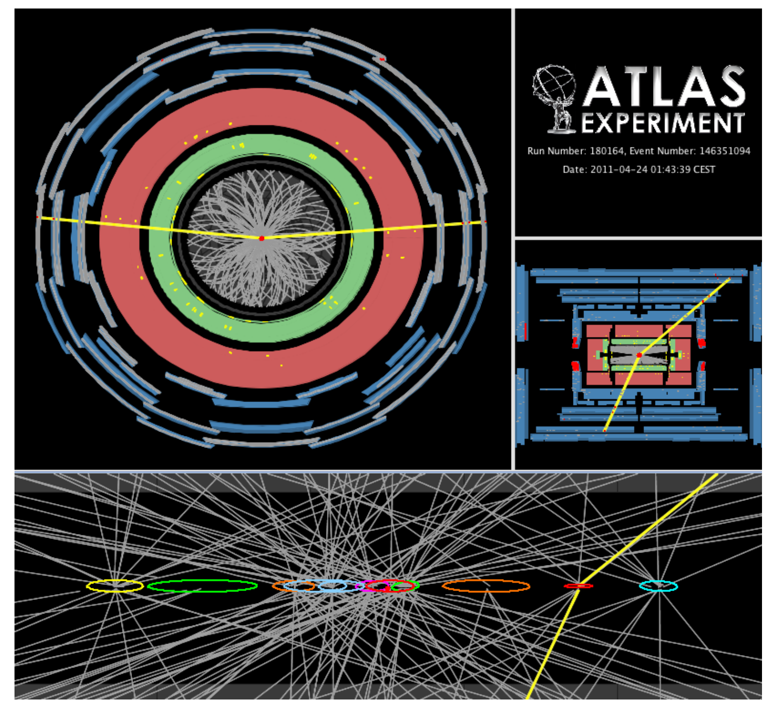


Jets [±b-tag(s)]
Invisibles
Perhaps leptons or photons

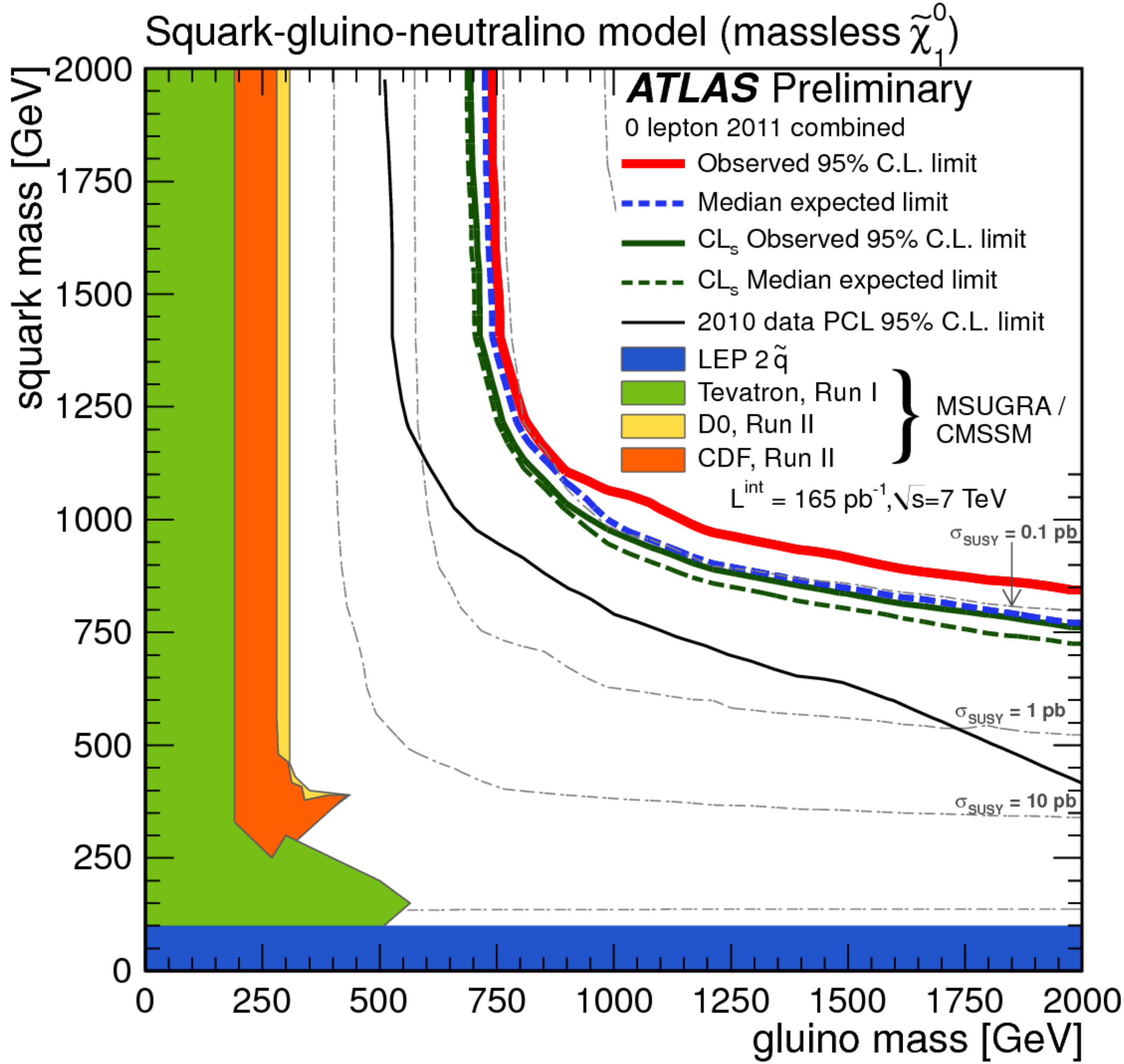
Pileup

- **The pileup in 2011 is on average <μ>=6 interactions per crossing**
  - Significantly higher than 2010
    - And than originally anticipated in early LHC running
  - Tails up to 14 interactions per crossing
    - Due to some bunches with much higher currents
- **Causes challenge for physics analyses and software**
  - Detailed simulation models both the <μ> and the bunch train structure
    - Reweighted according to data <μ> distribution
  - Software performance significantly improved to accommodate Tier0 resources (reco time 11-13s/event)
  - Physics performance reasonably unaffected
    - Jet energy scale uncertainty temporarily increased for low p_T jets

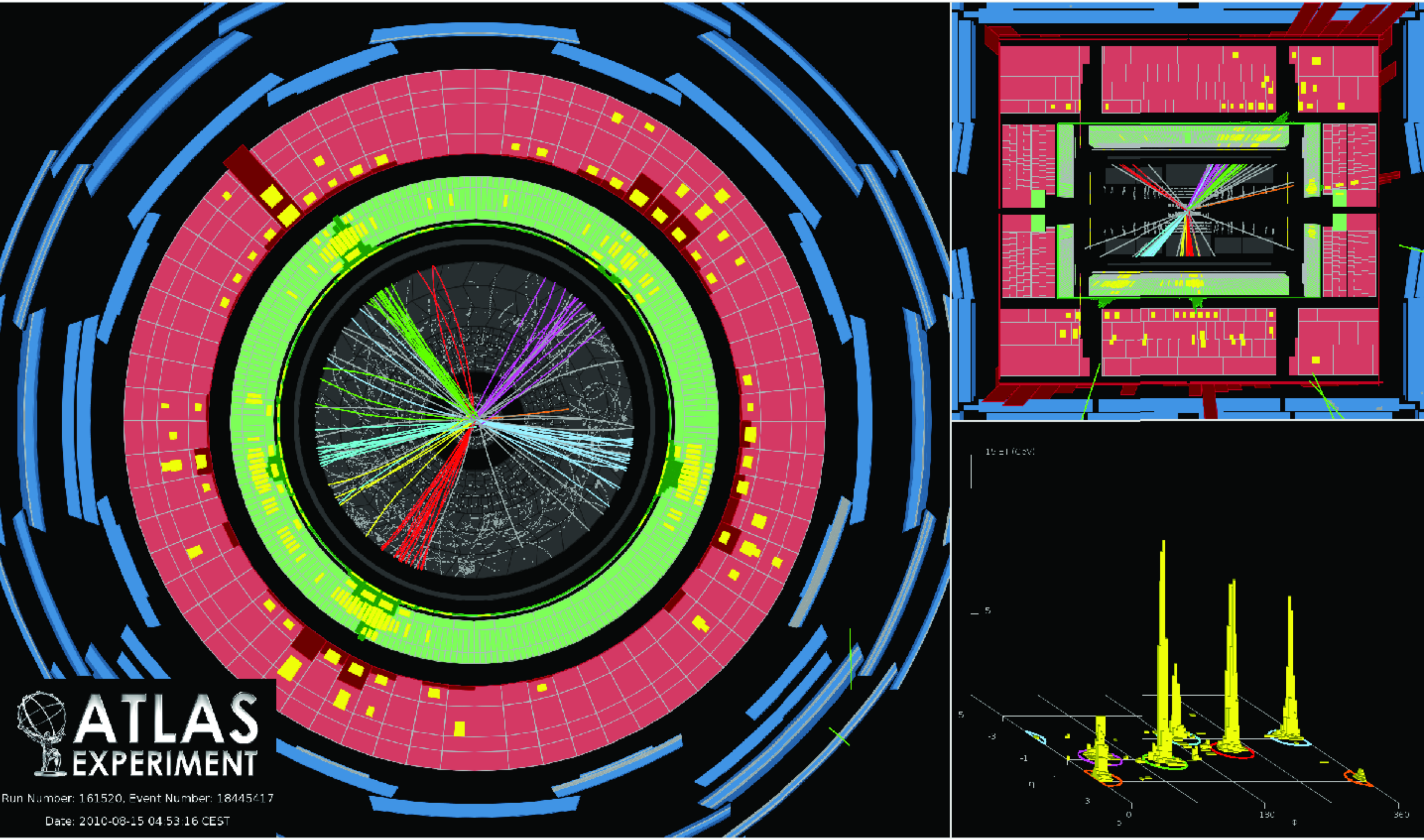




- Particle physics has an accepted definition for a "discovery": a five-sigma level of certainty
- The number of sigmas (or standard deviations) is a measure of how unlikely it is that an experimental result is simply down to chance rather than a real effect
- Similarly, tossing a coin and getting a number of heads in a row may just be chance, rather than a sign of a "loaded" coin
- The "three sigma" level represents about the same likelihood of tossing more than eight heads in a row
- Five sigma, on the other hand, would correspond to tossing more than 20 in a row
- A five-sigma result is highly unlikely to happen by chance, and thus an experimental result becomes an accepted discovery



Squark-gluino-neutralino model (massless $\tilde{\chi}_1^0$)
ATLAS Preliminary
0 lepton 2011 combined
Observed 95% C.L. limit
Median expected limit
CL_s Observed 95% C.L. limit
CL_s Median expected limit
2010 data PCL 95% C.L. limit
LEP 2 $\tilde{q}$
Tevatron, Run I
D0, Run II
CDF, Run II
MSUGRA / CMSSM
L^{int} = 165 pb^{-1}, $\sqrt{s}$=7 TeV
σ_{SUSY} = 0.1 pb
σ_{SUSY} = 1 pb
σ_{SUSY} = 10 pb
squark mass [GeV]
gluino mass [GeV]
0
250
500
750
1000
1250
1500
1750
2000



arXiv:1107.2092