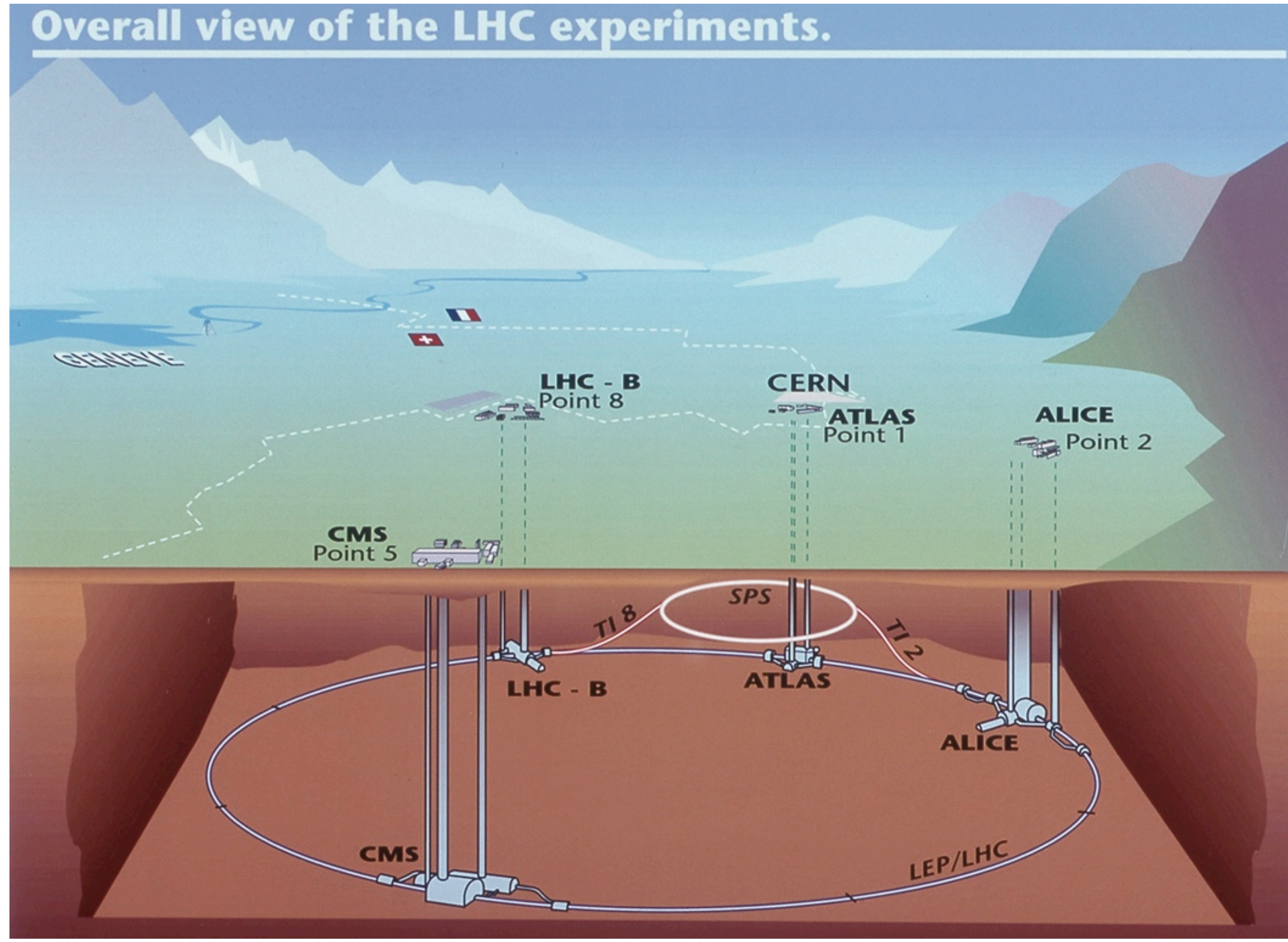
Probing Dark Matter at the LHC

Alex Tapper

Outline

- The LHC and ATLAS and CMS detectors
- Detector performance and Standard Model physics
- Status of Dark Matter searches at the LHC
  - MET based searches
  - Long-lived particle searches
- Future prospects and connection to cosmology
- Summary and outlook

The Large Hadron Collider



 International Workshop on Linear Colliders, 18-22 October 2010, Geneva, Switzerland.

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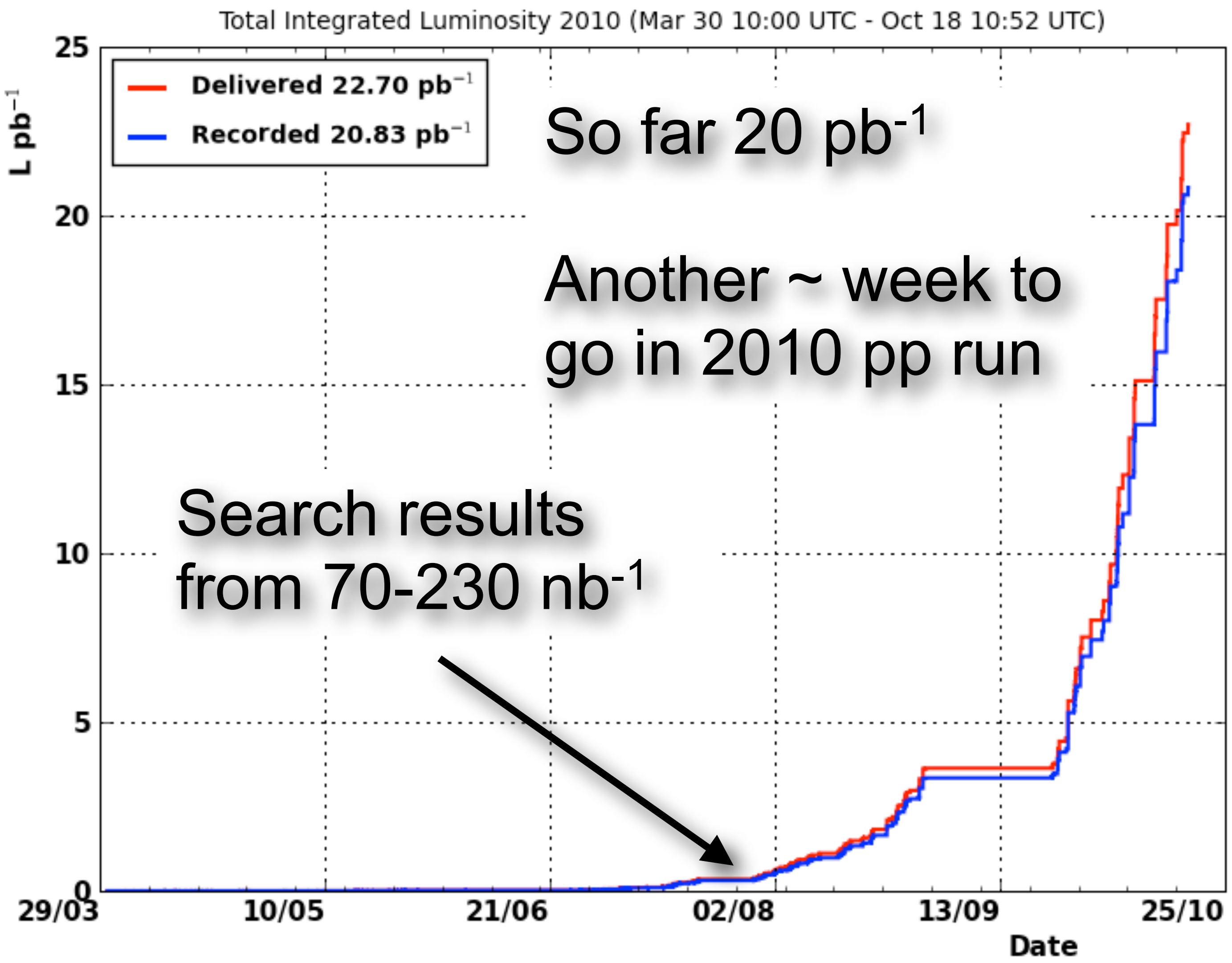
The Large Hadron Collider



So far 20 pb^{-1}

Another ~ week to go in 2010 pp run

Search results from 70-230 nb^{-1}

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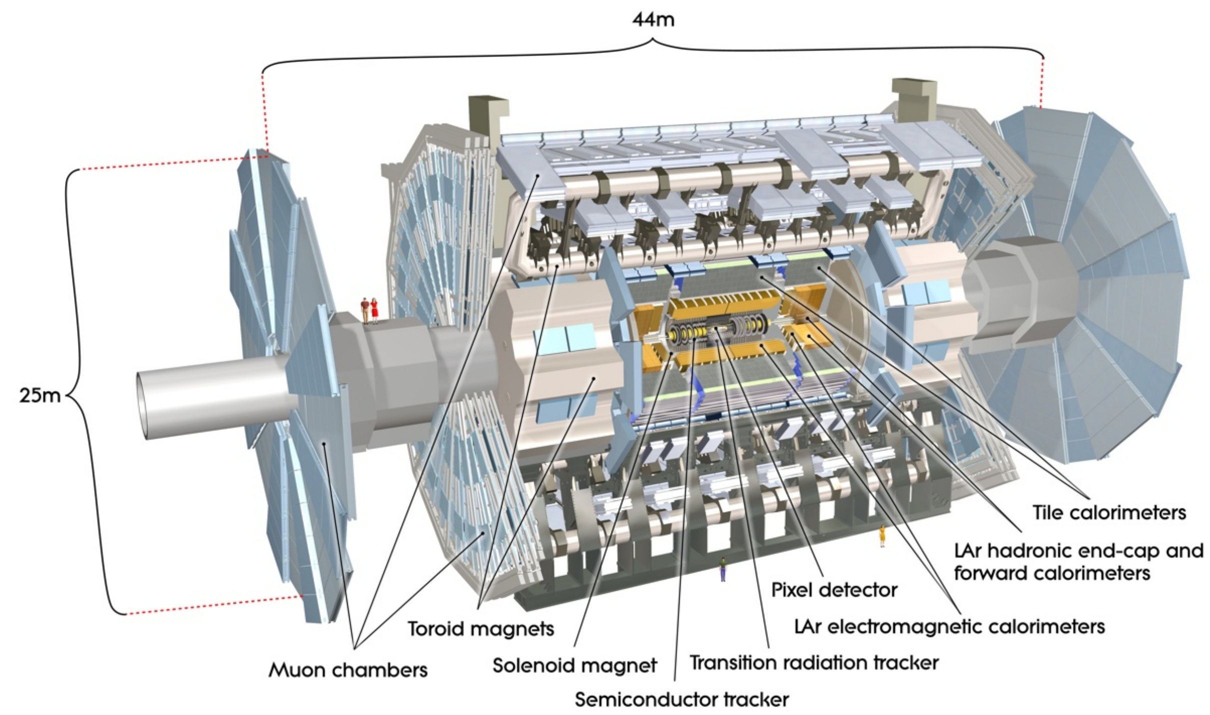
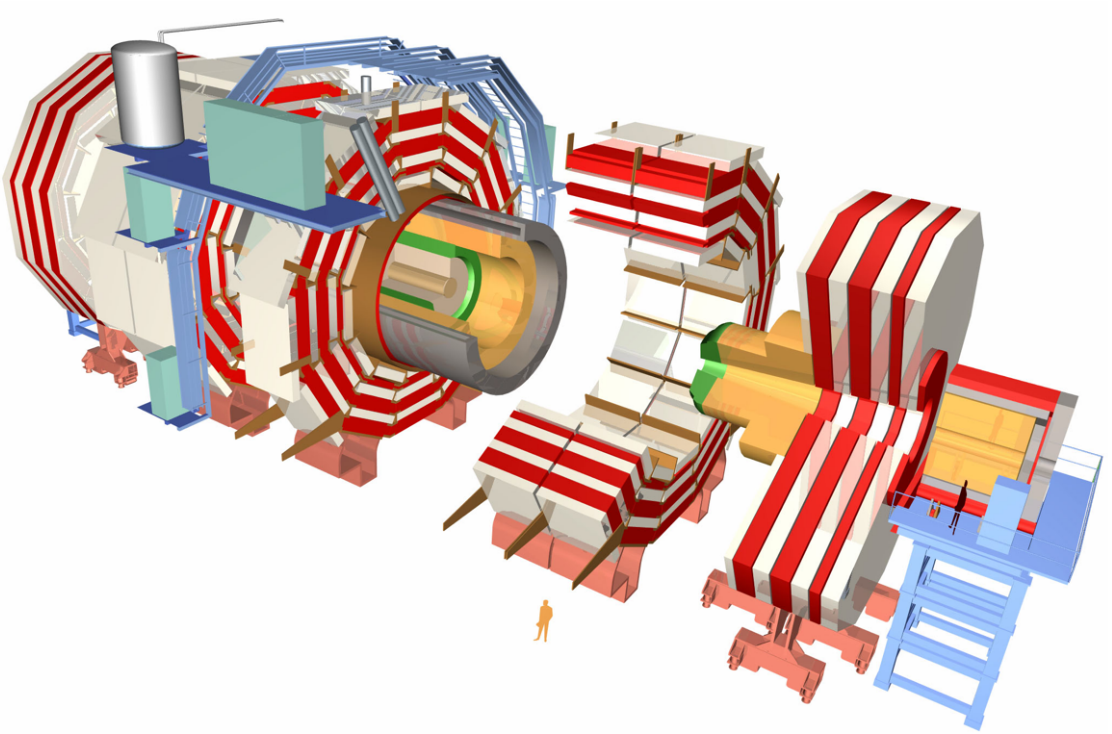
ATLAS and CMS detectors



JINST3:S08003 (2008)

- 2T solenoid & toroid magnets
- Silicon detector (pixel, strips) & TRT
- LAr ECAL $\sigma(E)/E=10\%/\sqrt{E}+0.007$
- **Tile/sci. HCAL $\sigma(E)/E=50\%/\sqrt{E}+0.03$**
- Muon chambers $\sigma(p)/p<10\%$ at 1TeV

- 4T solenoid magnet
- Silicon detector (pixel, strips)
- **Crystal ECAL $\sigma(E)/E=3\%/\sqrt{E}+0.003$,**
- Brass/sci. HCAL $\sigma(E)/E=100\%/\sqrt{E}+0.05$
- Muon chambers $\sigma(p)/p<10\%$ at 1TeV



JINST3:S08004 (2008)

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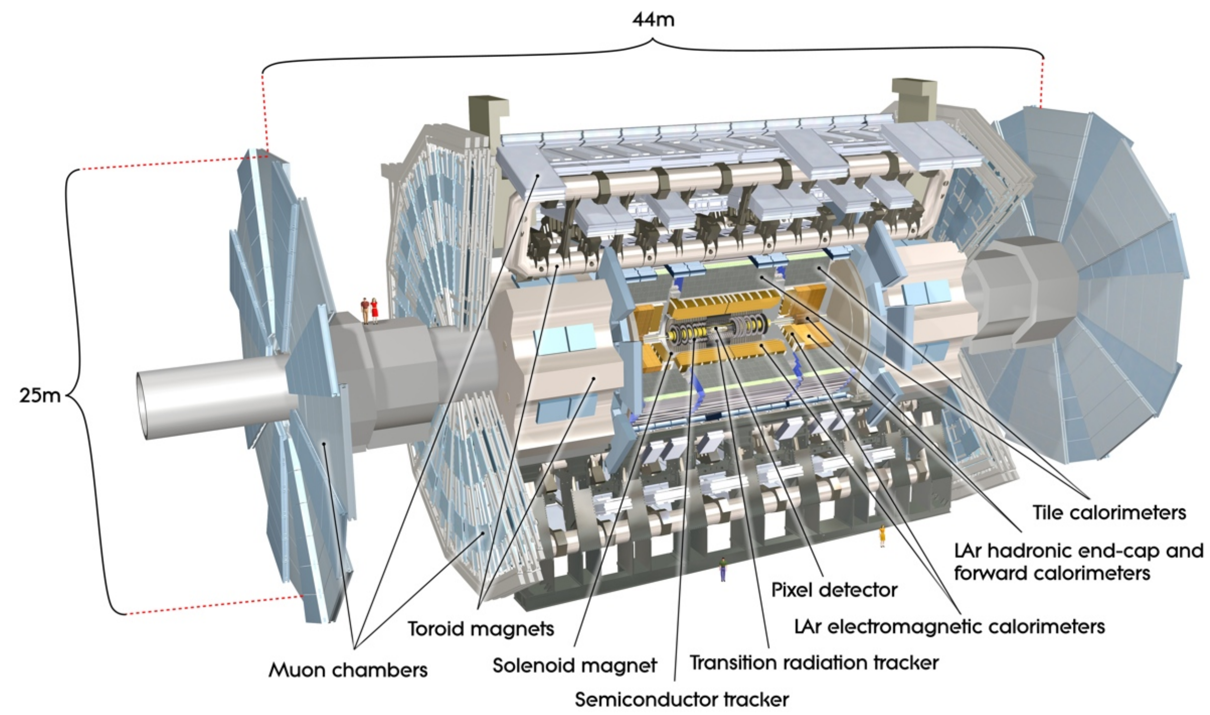
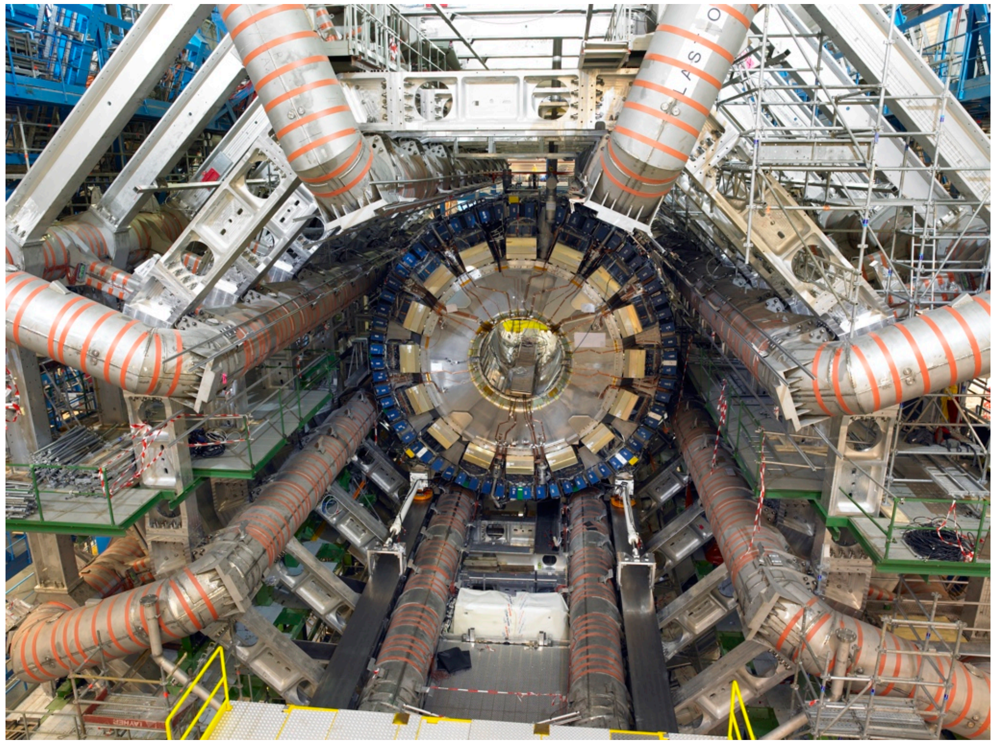
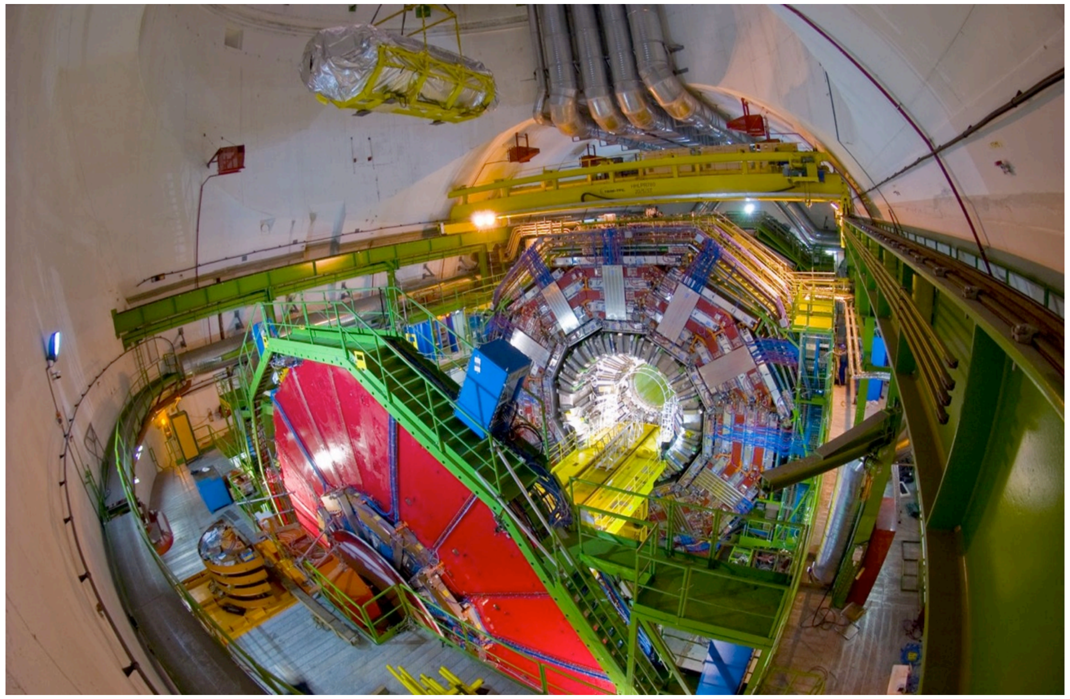
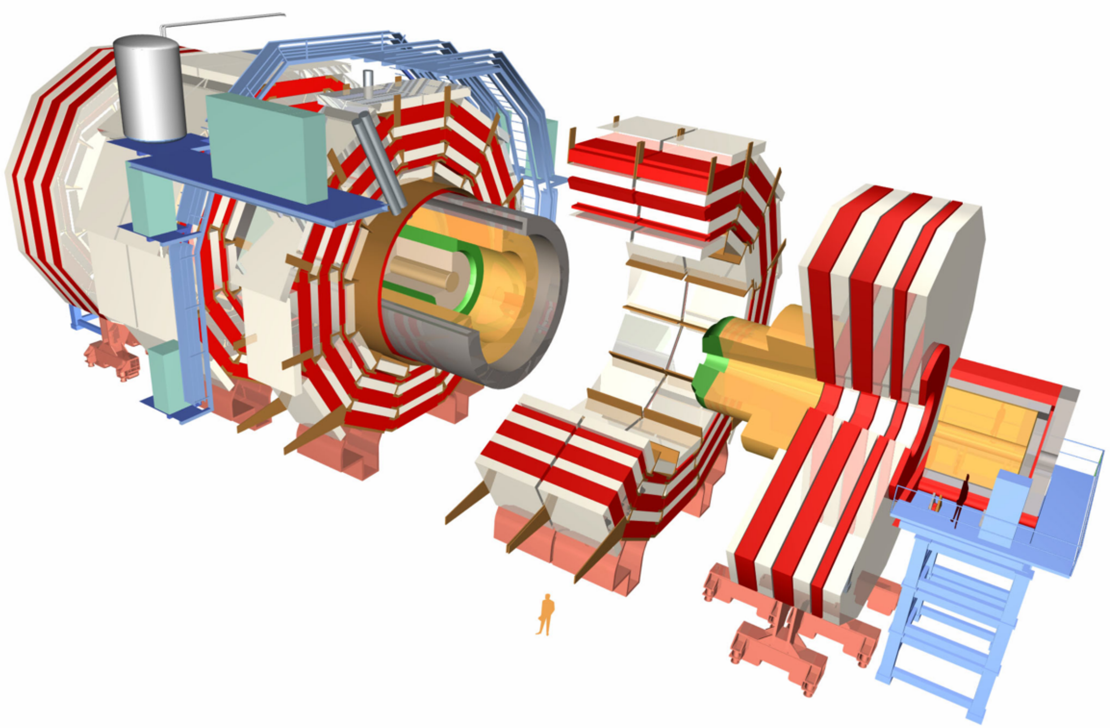
ATLAS and CMS detectors





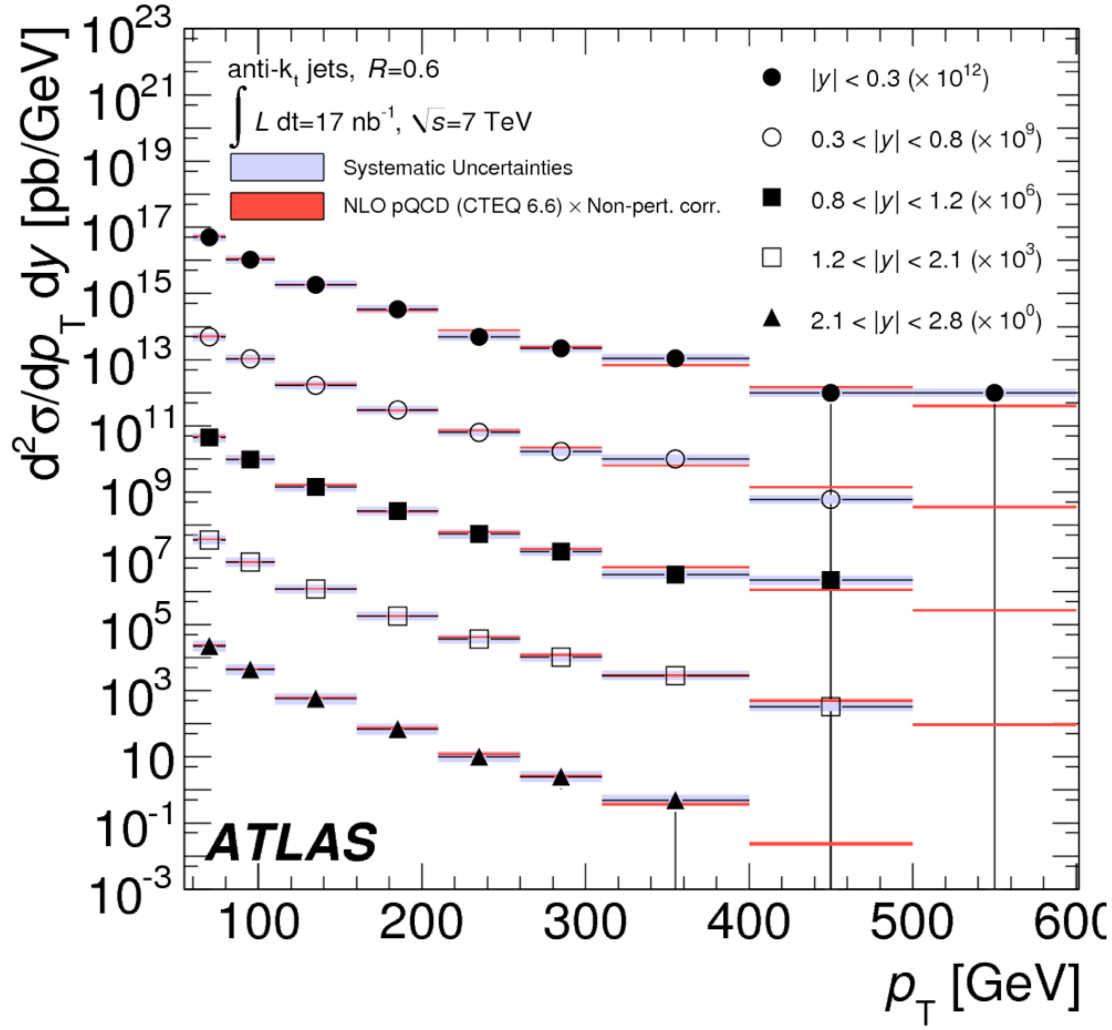


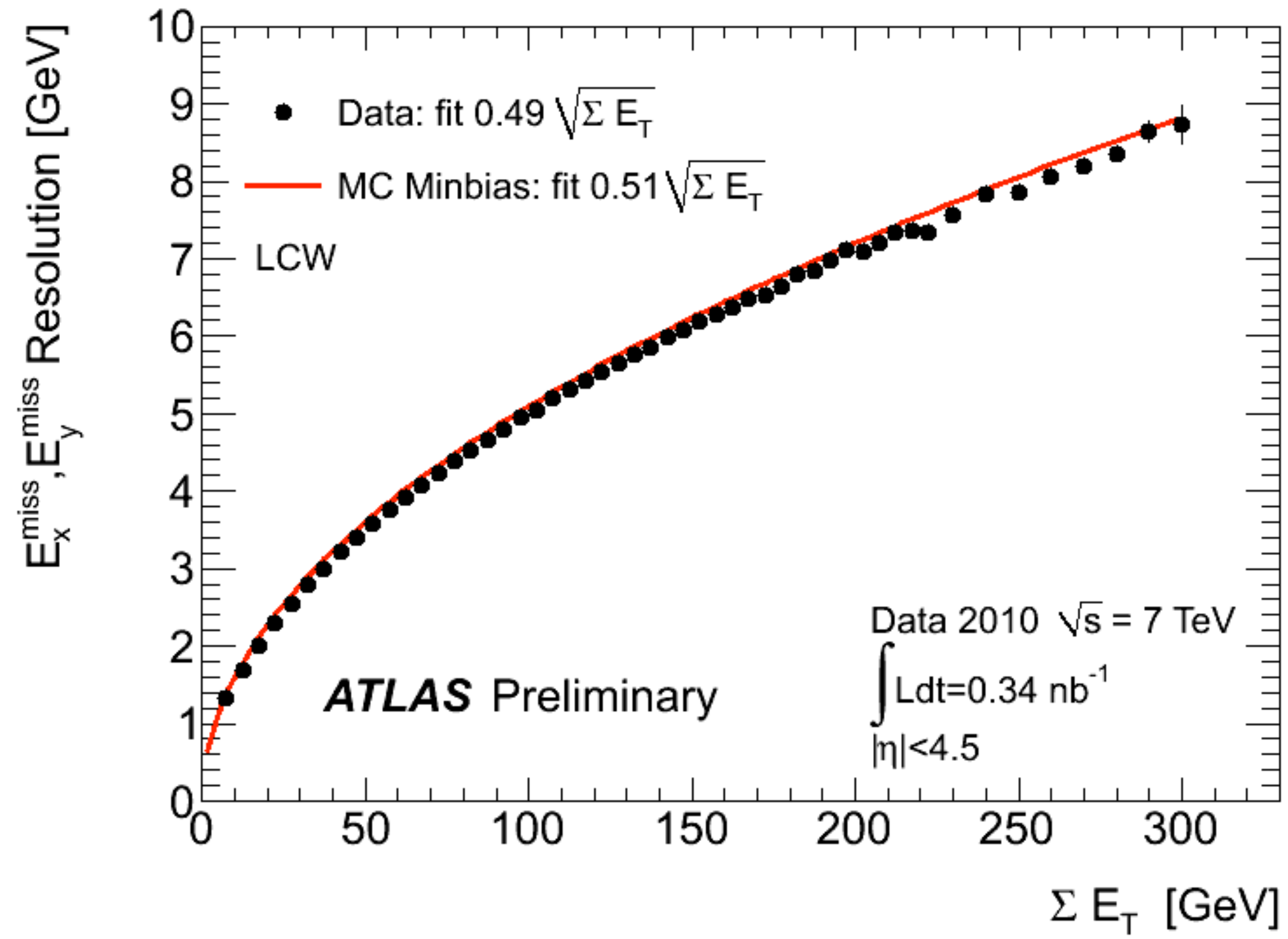


Standard Model physics

arXiv:1009.5908

ATLAS-CONF-2010-057

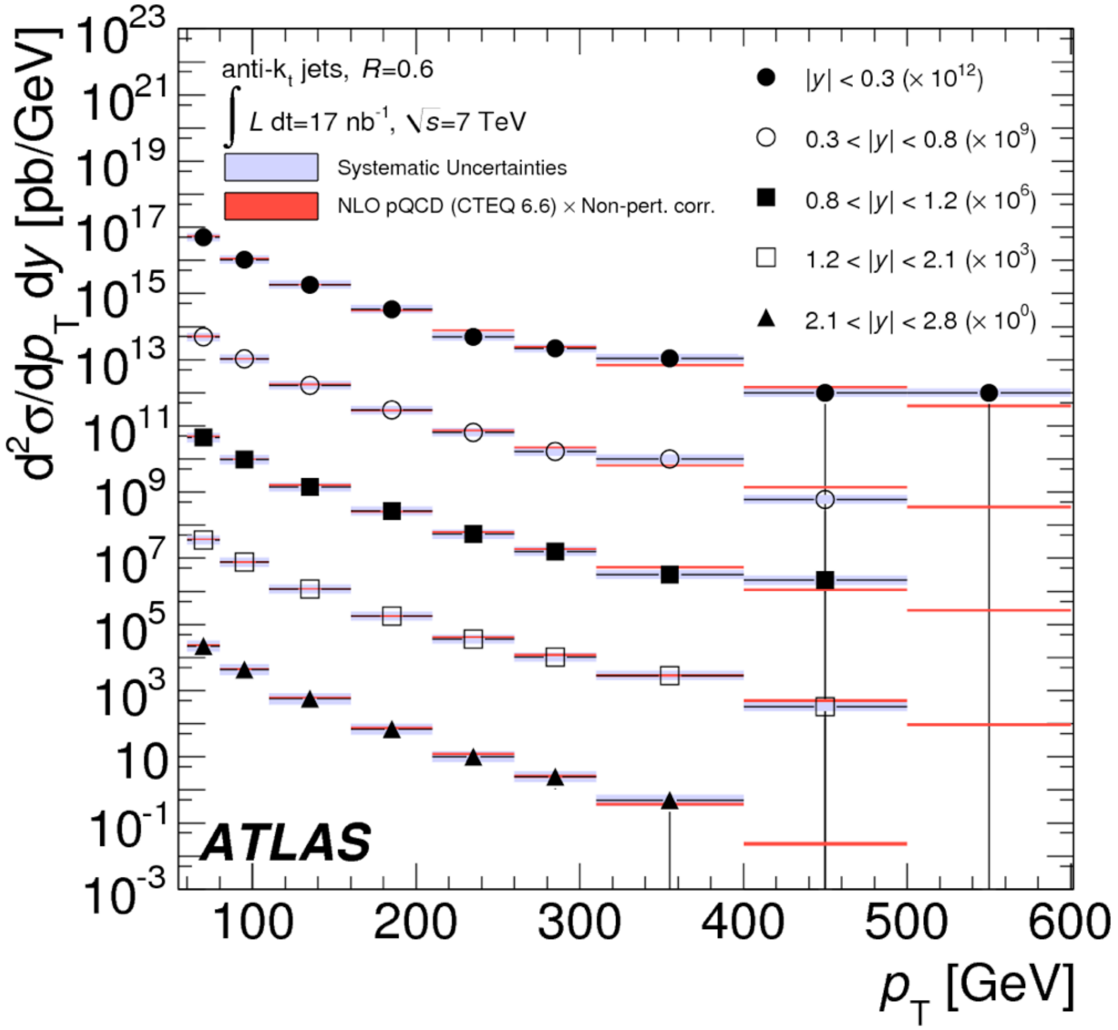




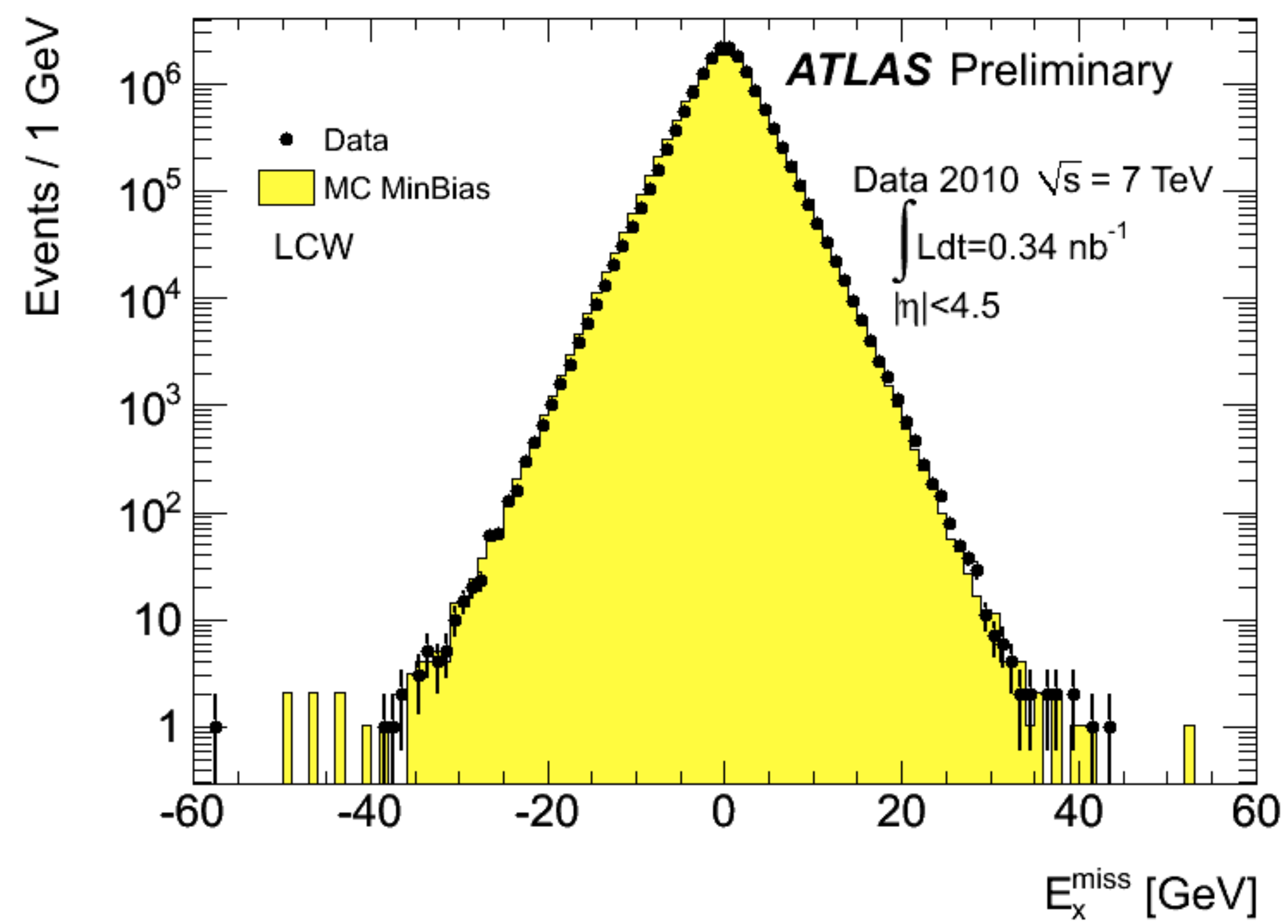
- Measurements of jet cross sections and MET resolution
- Jets and MET in good shape already

Standard Model physics

arXiv:1009.5908



ATLAS-CONF-2010-057



- Measurements of jet cross sections and MET resolution
- Jets and MET in good shape already

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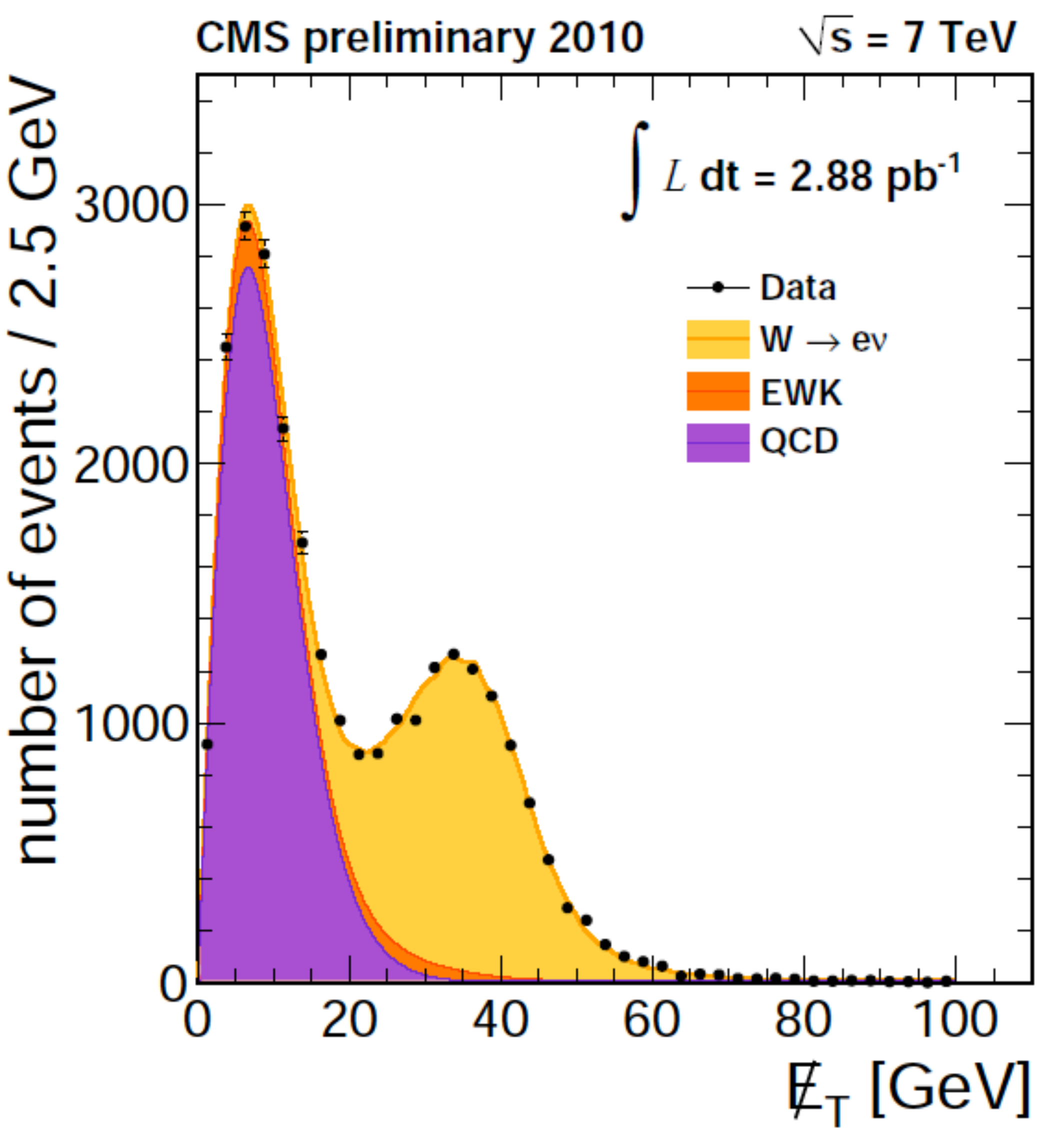
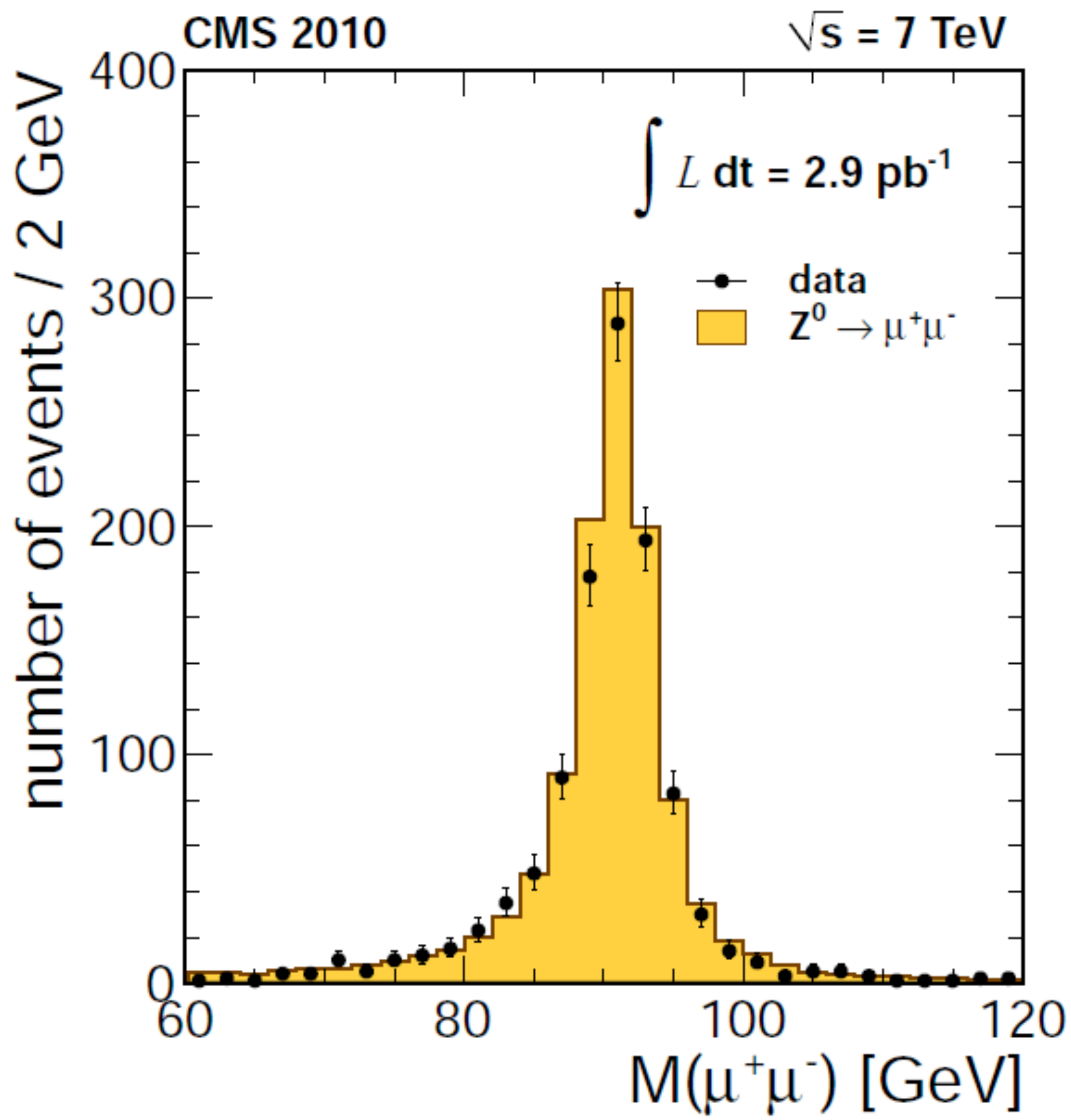
Standard Model physics

CMS EWK-10-002-PAS





- Beautiful reconstruction of W and Z bosons
- Leptons and MET reconstruction performing well

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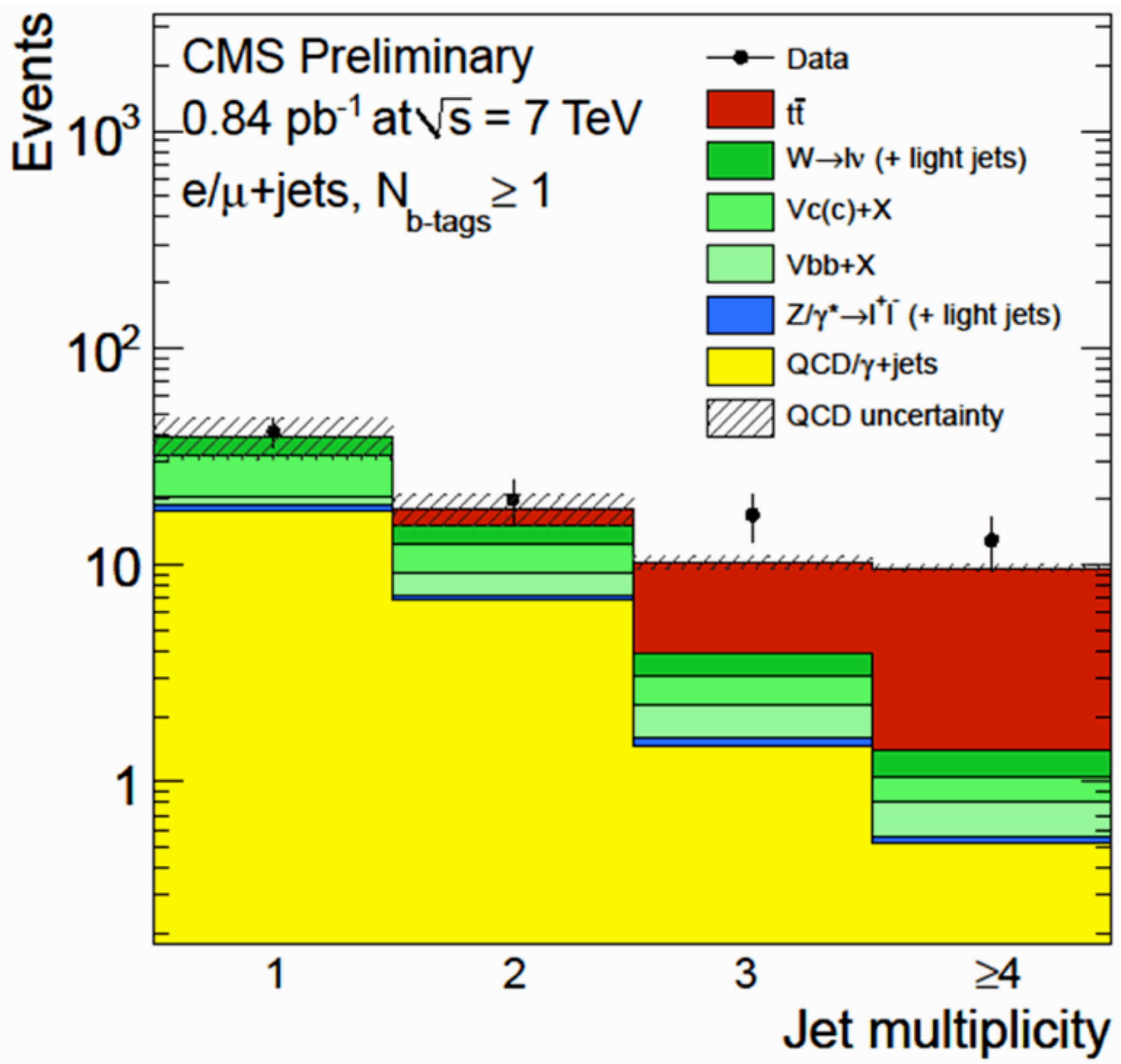
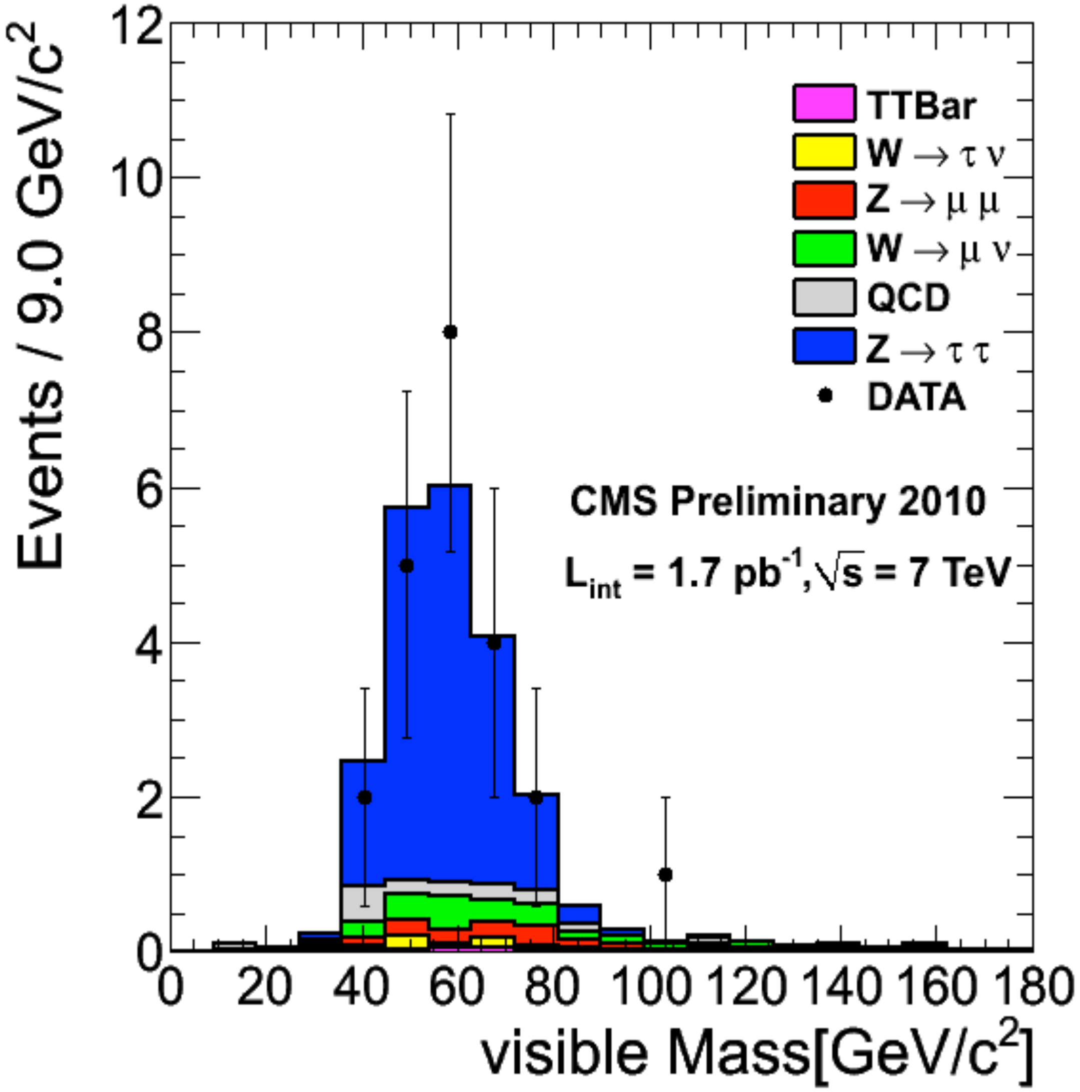
Standard Model physics

CMS PAS-TOP-10-004

CMS PAS-PFT-10-004





- Top-quark pair-production and Z➔ $\tau^+\tau^-$
- b-tagging and τ-tagging performing well already

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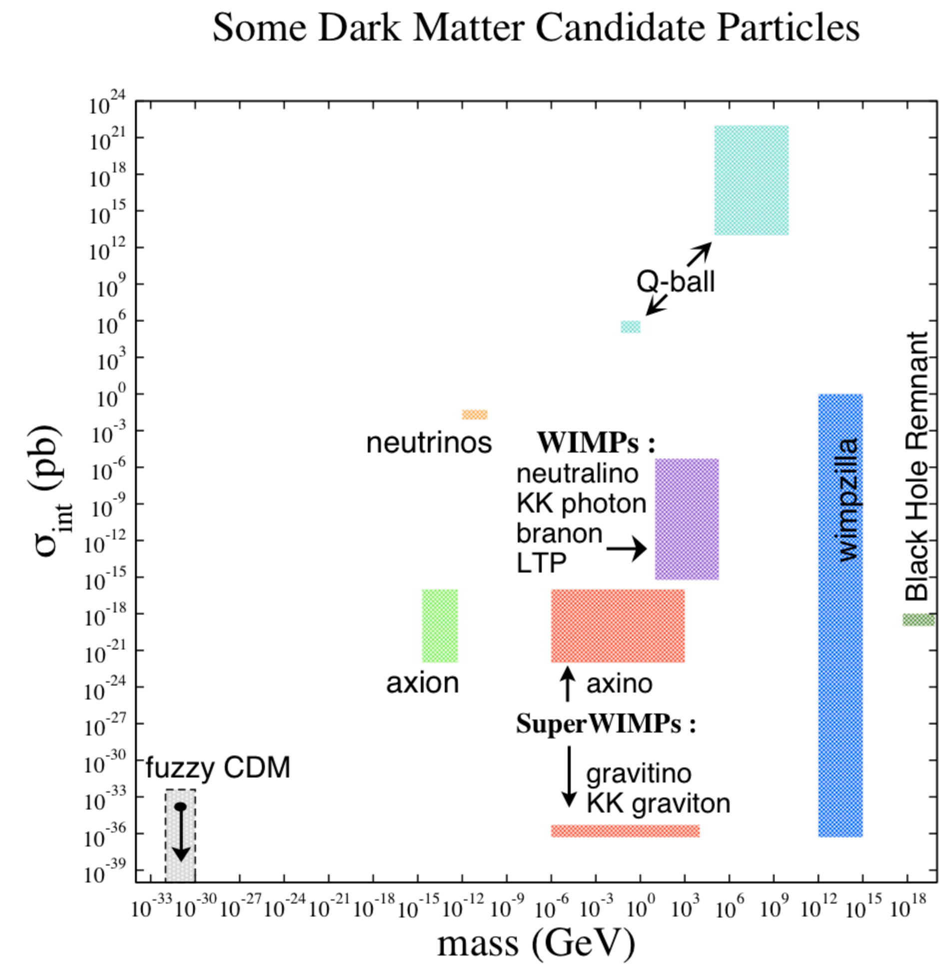
Dark Matter @ LHC

L. Roszkowski, Pramama, 62 (2004) 389

- What can we search for?
  - Detectors designed for discovery of particles in GeV to TeV range
  - Luminosities give lower bound production cross sections



- WIMP dark matter
  - Neutralinos, KK particles, Little Higgs….
  - Missing energy signatures
  - Difficult to distinguish between different types of candidate

- Gravitinos/axinos...
  - Hints possible from long-lived particles
  - Distinctive signatures in detector

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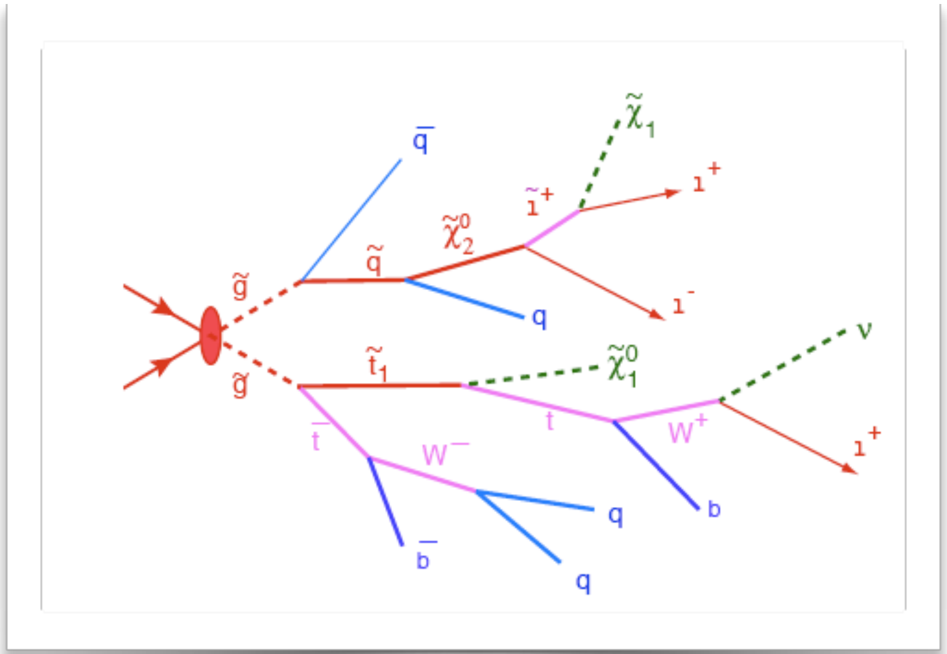
WIMP dark matter

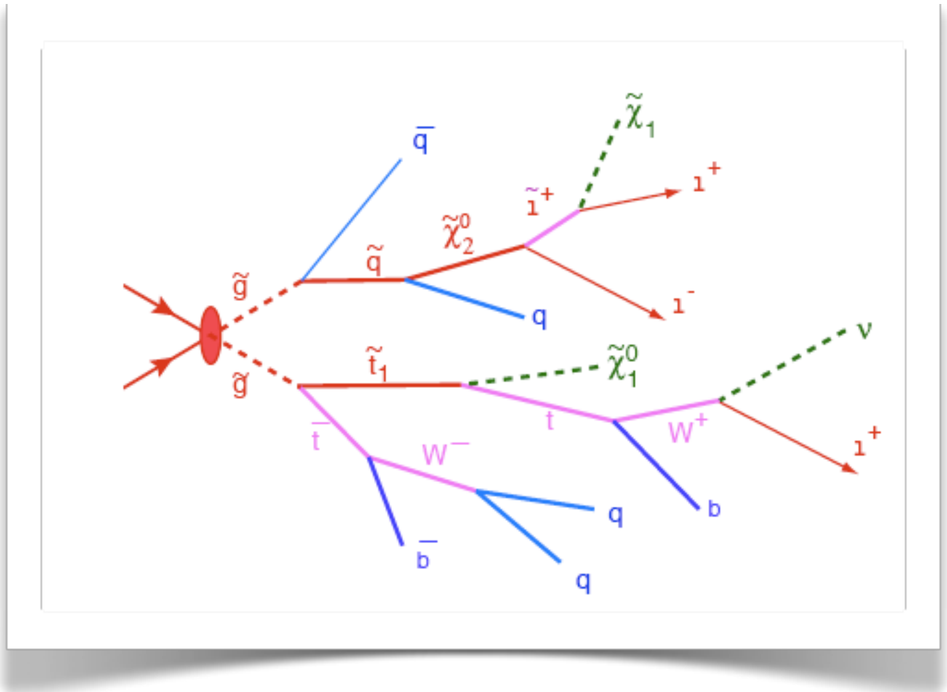
- WIMPS neutral and weakly interacting so difficult to observe
- Direct production has small cross section and no signal in detector
- Production in conjunction with Standard Model particles better option for detection
- Design searches ➔

MET based searches



- Production
  - Pair-produce new heavy particles
  - Strong production so high cross section
  - Cross section depends only on masses
  - Approx. independent of model

MET based searches



- Production
  - Pair-produce new heavy particles
  - Strong production so high cross section
  - Cross section depends only on masses
  - Approx. independent of model
- Decay
  - Details of decay chain depend on model (mass spectra, branching ratios, etc.)
  - Some conserved quantum number needed for dark matter (R-parity, T-parity, KK-parity…)
  - Assume original particles are heavy (since we haven't detected them) ➔ long decay chains
- Signatures
  - **MET** from dark matter candidate, **high-E_T jets** and **leptons** from long decay chain
- Focus on robust and simple signatures
  - Common to wide variety of models

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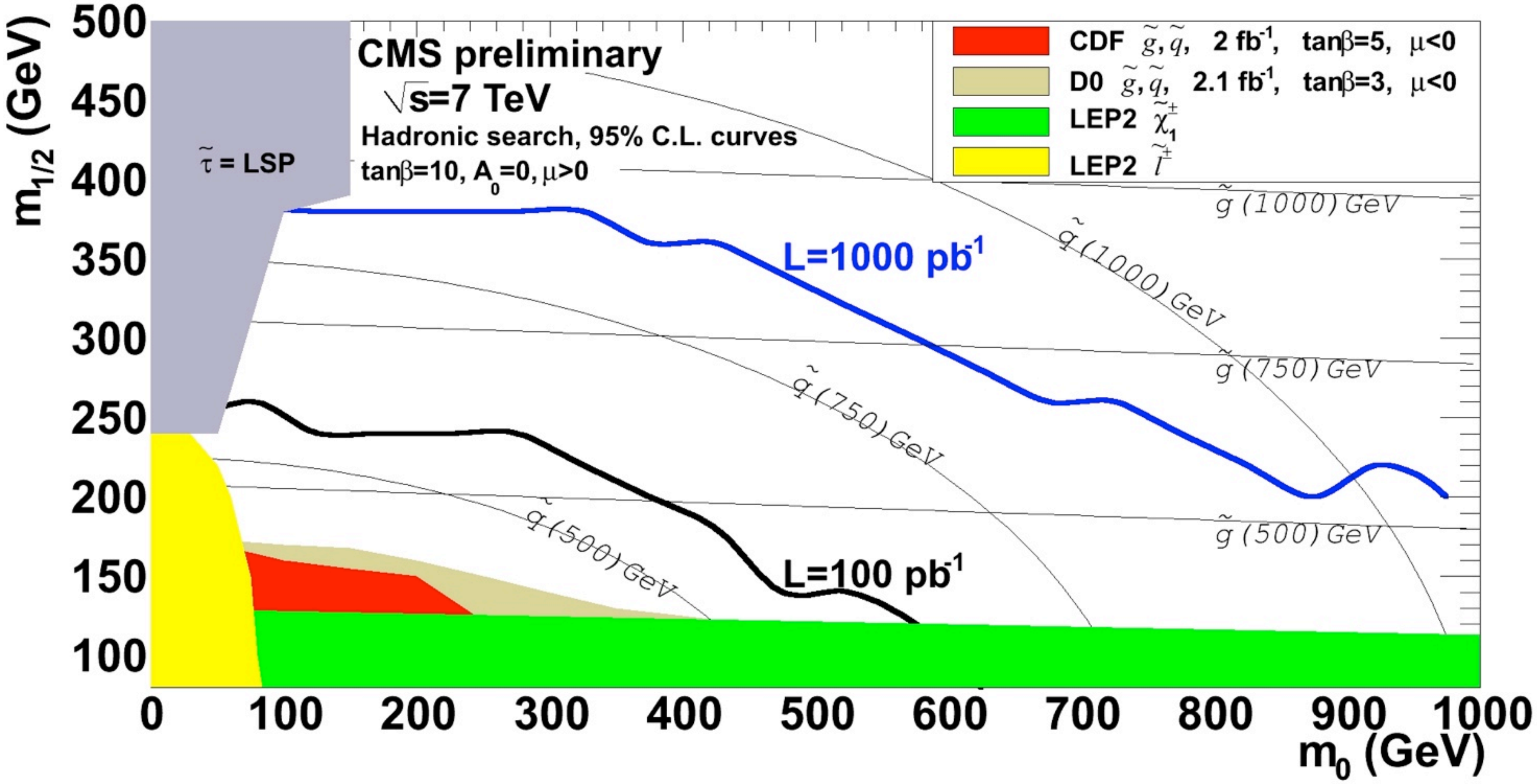
Jets + MET searches

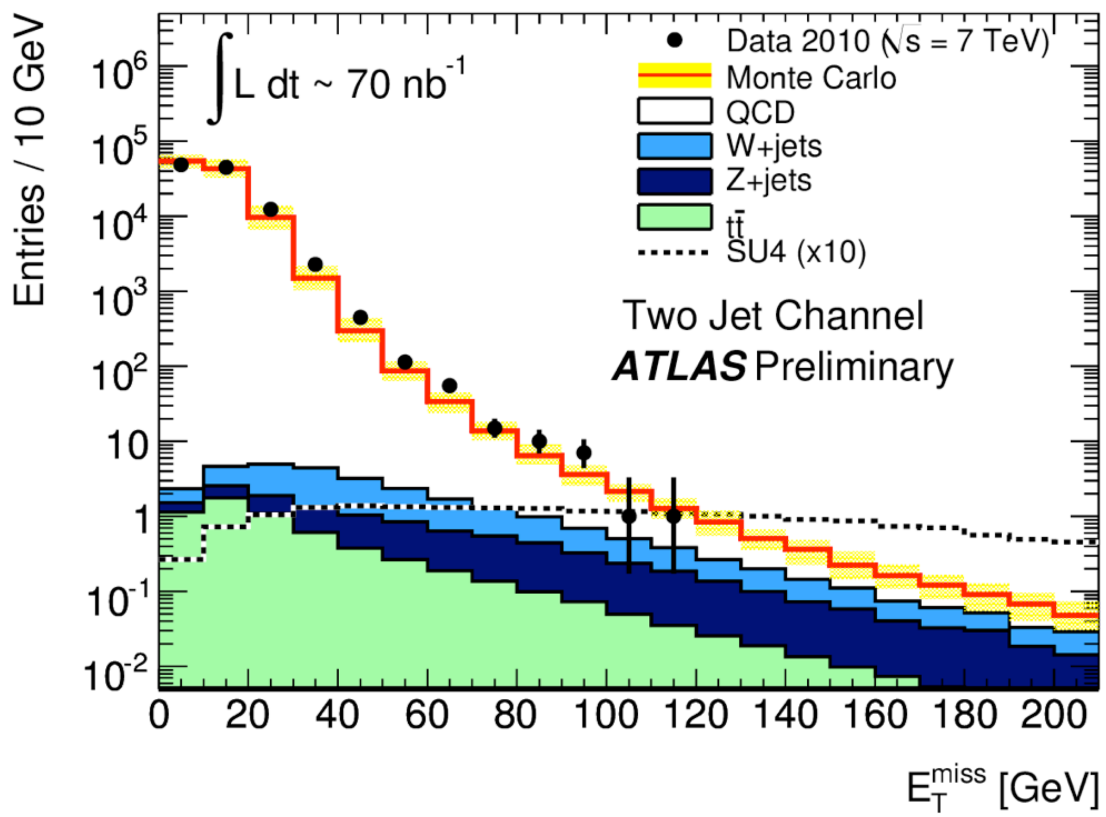
CMS-NOTE-2010-008

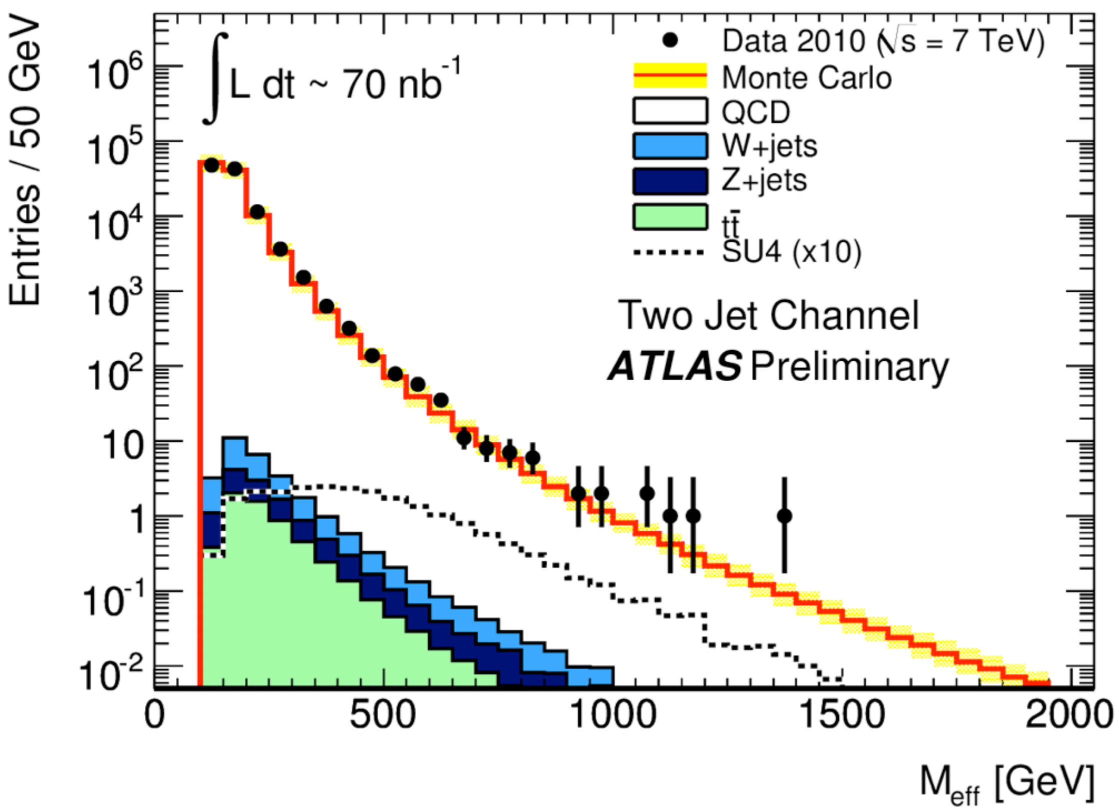


- All-hadronic search highly sensitive, but suffers from many backgrounds
- Reach beyond Tevatron with 2010 data
- Reach up to masses of ~800 GeV with 1 fb^{-1}

Jets + MET searches

ATLAS-CONF-2010-065





- Simple (ignoring lots of things) jet cuts (anti-k_T R=0.4)
  - Leading jet E_T>70 GeV
  - Other jets E_T>30 GeV
- Veto isolated leptons (P_T>10 GeV)
- QCD MC normalised to data in two jet channel (uncertainty neglected)

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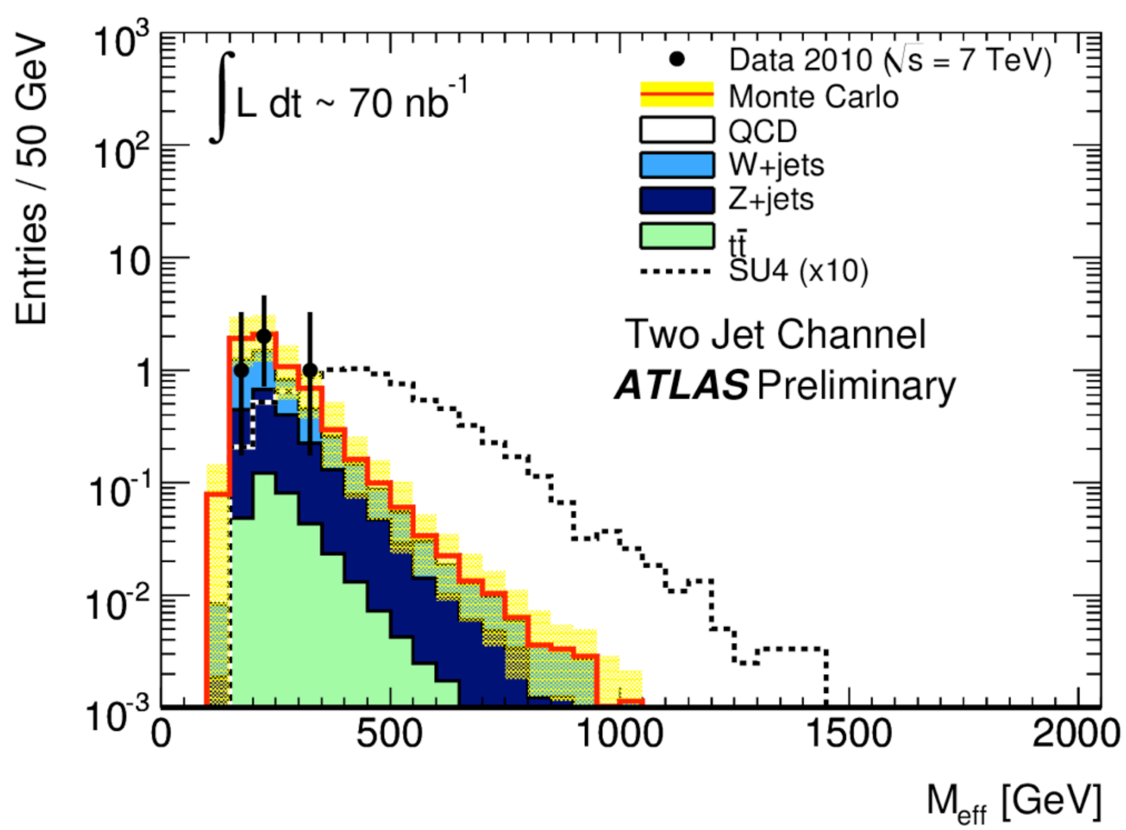
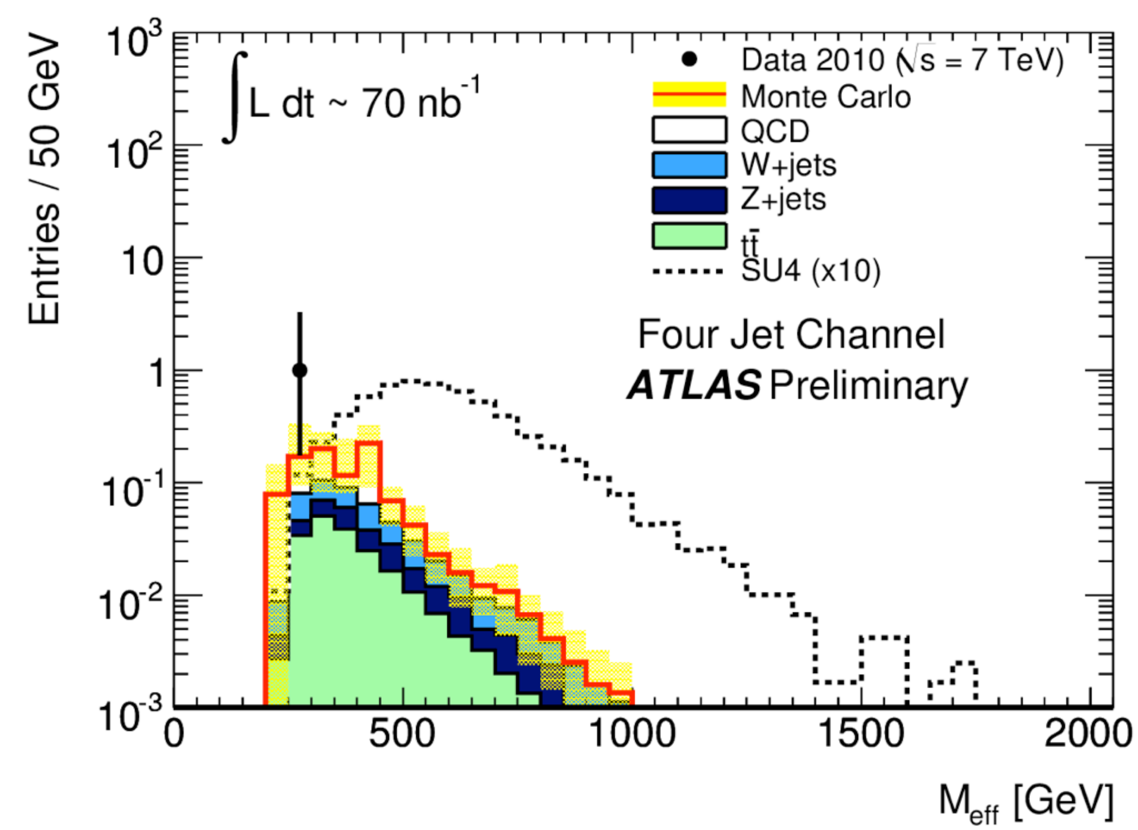
Jets + MET searches

ATLAS-CONF-2010-065

- Further selection
  - MET>40 GeV
  - MET/M_{eff}>0.3(0.2)

	Monojet		≥ 2 jets		≥ 3 jets		≥ 4 jets	
	Data	Monte Carlo	Data	Monte Carlo	Data	Monte Carlo	Data	Monte Carlo
After jet cuts	21 227	23000^{+7000}_{-6000}	108 239	108000^{+31000}_{-25000}	28 697	31000^{+10000}_{-8000}	5329	5600^{+2300}_{-1600}
$\cap\ E_T^{miss}$ cut	73	46^{+22}_{-14}	650	450^{+190}_{-120}	325	230^{+100}_{-70}	116	84^{+45}_{-30}
$\cap\ \Delta\phi$ and E_T^{miss} cuts	–	–	280	200^{+110}_{-65}	136	100^{+55}_{-30}	54	43^{+26}_{-16}
$\cap\ E_T^{miss}/M_{eff}$, $\Delta\phi$ and E_T^{miss} cuts	–	–	4	6.6 ± 3	0	1.9 ± 0.9	1	1.0 ± 0.6





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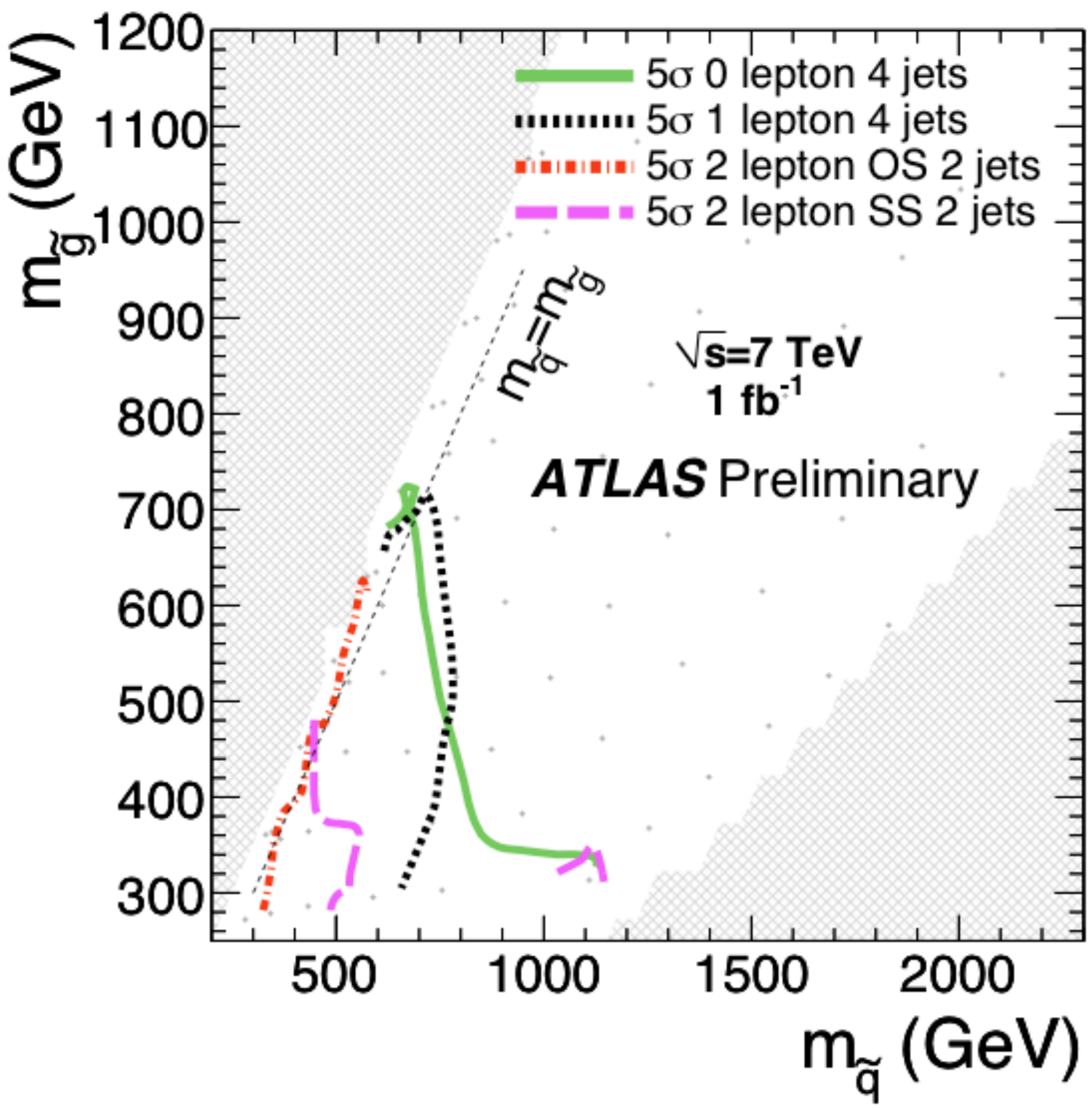
Single-lepton + MET search

ATL-PHYS-PUB-2010-010



- Requiring one lepton (e or μ) suppresses QCD background powerfully
- Highly sensitive to SUSY
- Backgrounds come from Standard Model processes with neutrinos ➔ real MET
- In particular top and W decays

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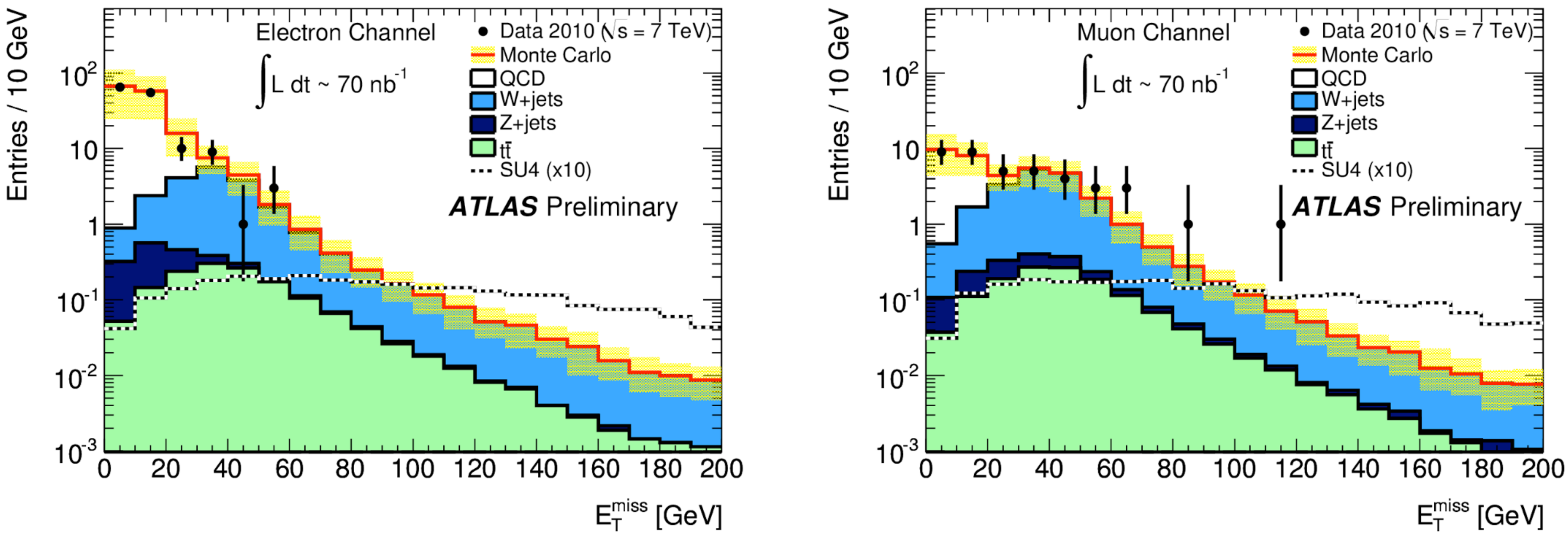
Single-lepton + MET search

ATLAS-CONF-2010-066



- Simple cuts (once again too lazy to list cleaning, triggers...)
  - One isolated lepton with P_T>20 GeV
  - At least two jets E_T>30 GeV
- QCD MC normalised to data at MET < 40 GeV and M_T < 40 GeV
- Uncertainty 50% from fake rate study comparison with data

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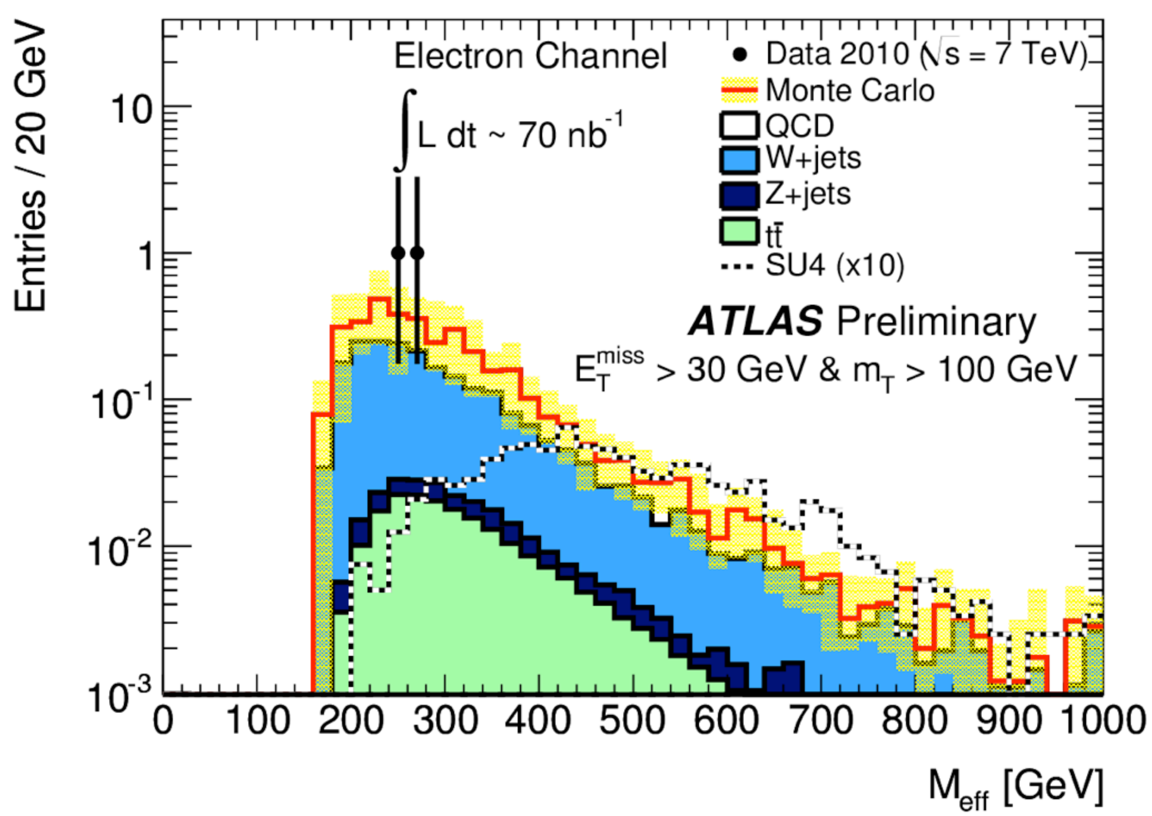
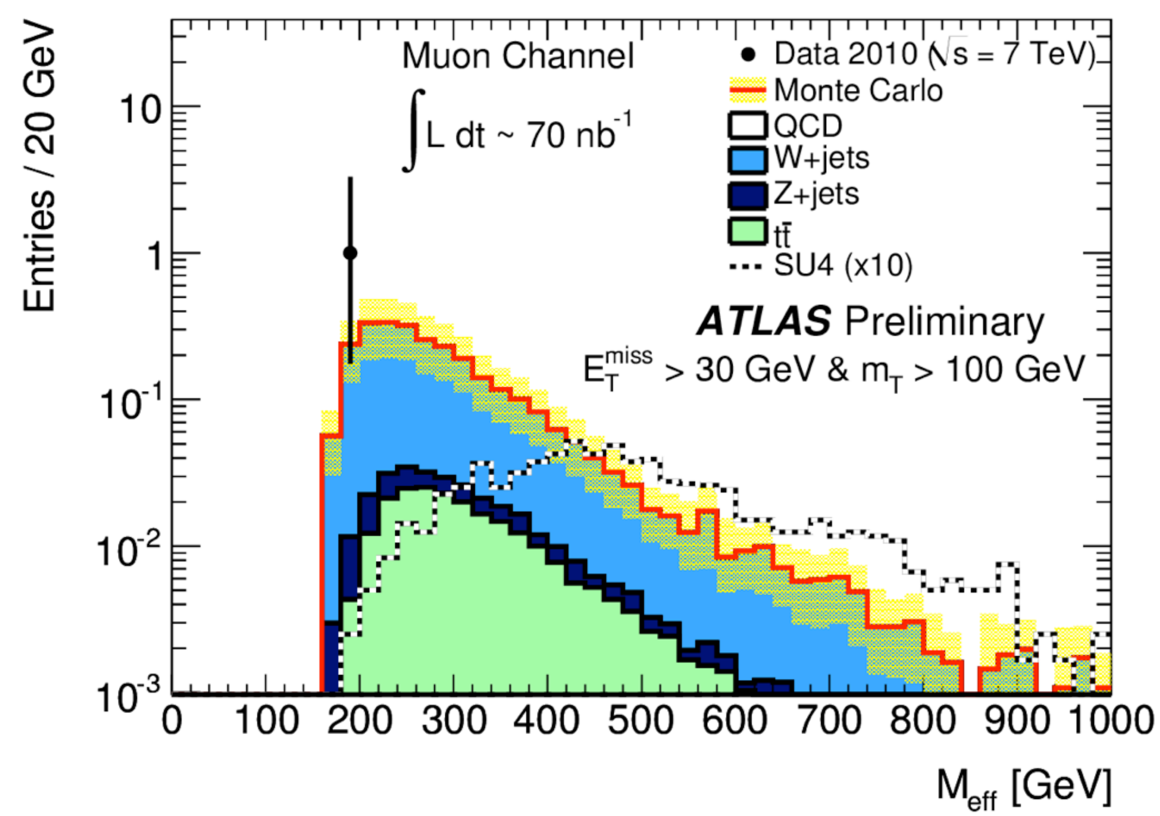
Single-lepton + MET search

ATLAS-CONF-2010-066

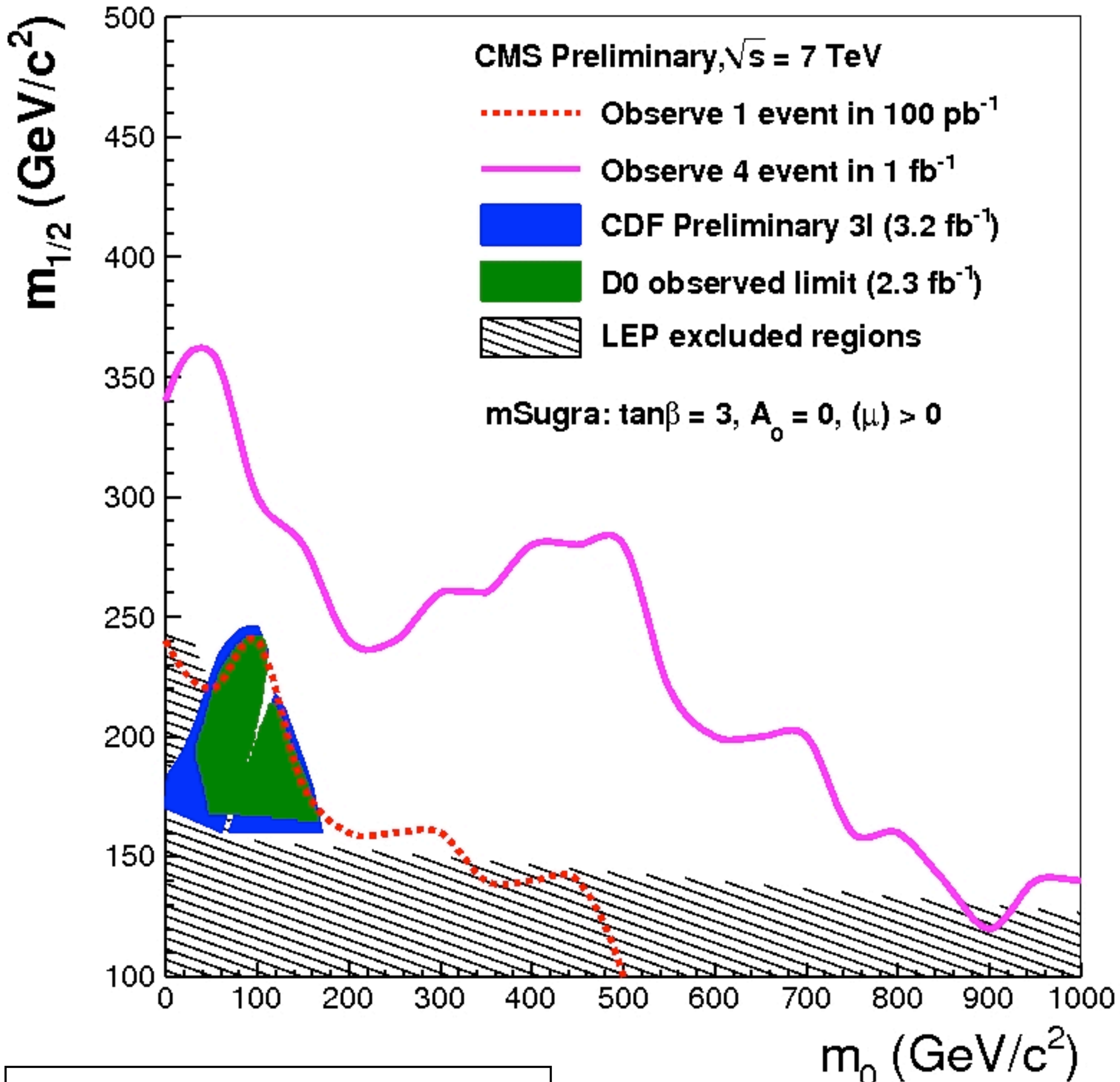
- Further selection
  - MET>30 GeV
  - M_T>100 GeV

Selection	Electron channel Data	Electron channel Monte Carlo	Muon channel Data	Muon channel Monte Carlo
$p_T(\ell) > 20$ GeV $\cap$ ≥ 2 jets with $p_T > 30$ GeV	143	157 ± 85	40	37 ± 14
$\cap\ E_T^{miss} > 30$ GeV	13	16 ± 7	17	15 ± 7
$\cap\ m_T > 100$ GeV	2	3.6 ± 1.6	1	2.8 ± 1.2





Di-lepton + MET searches



CMS-NOTE-2010-008

- Low yields but very interesting properties
- Same sign searches
  - Very low Standard Model background rate
  - Backgrounds from charge mis-identified top events (QCD in τ channel)
- Opposite sign
  - Use opposite-sign, opposite-flavour sample to subtract SM background

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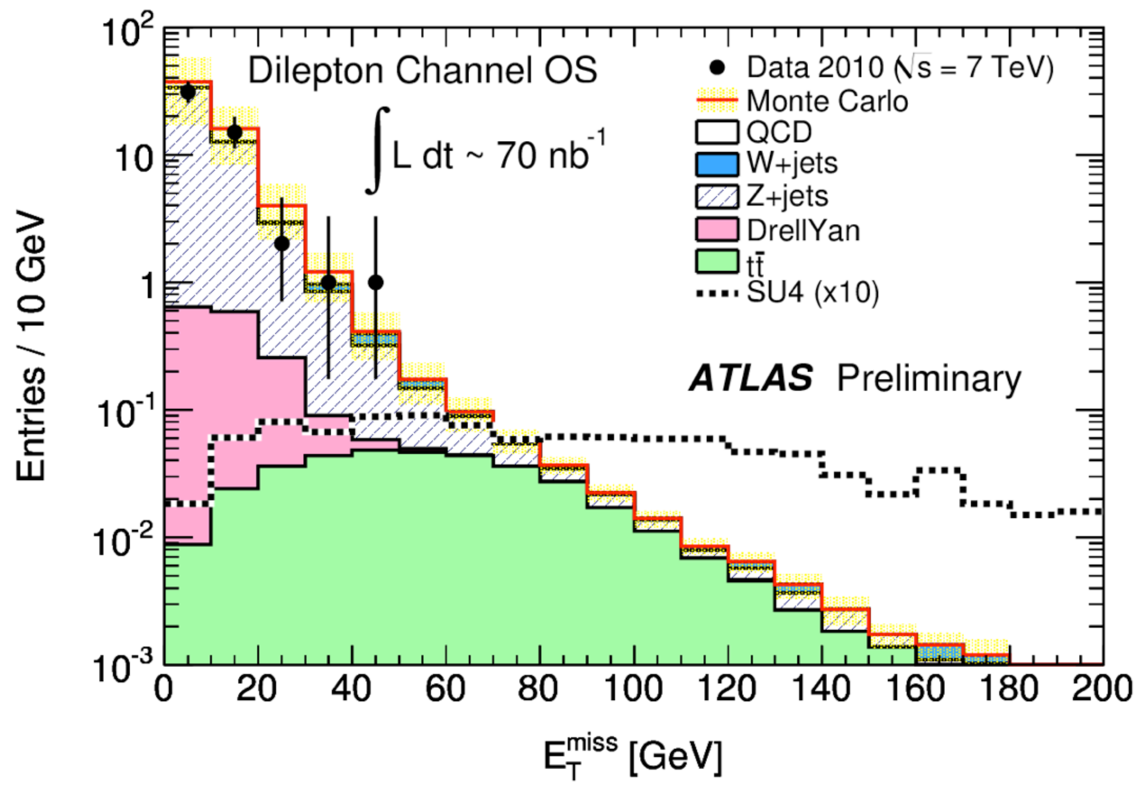
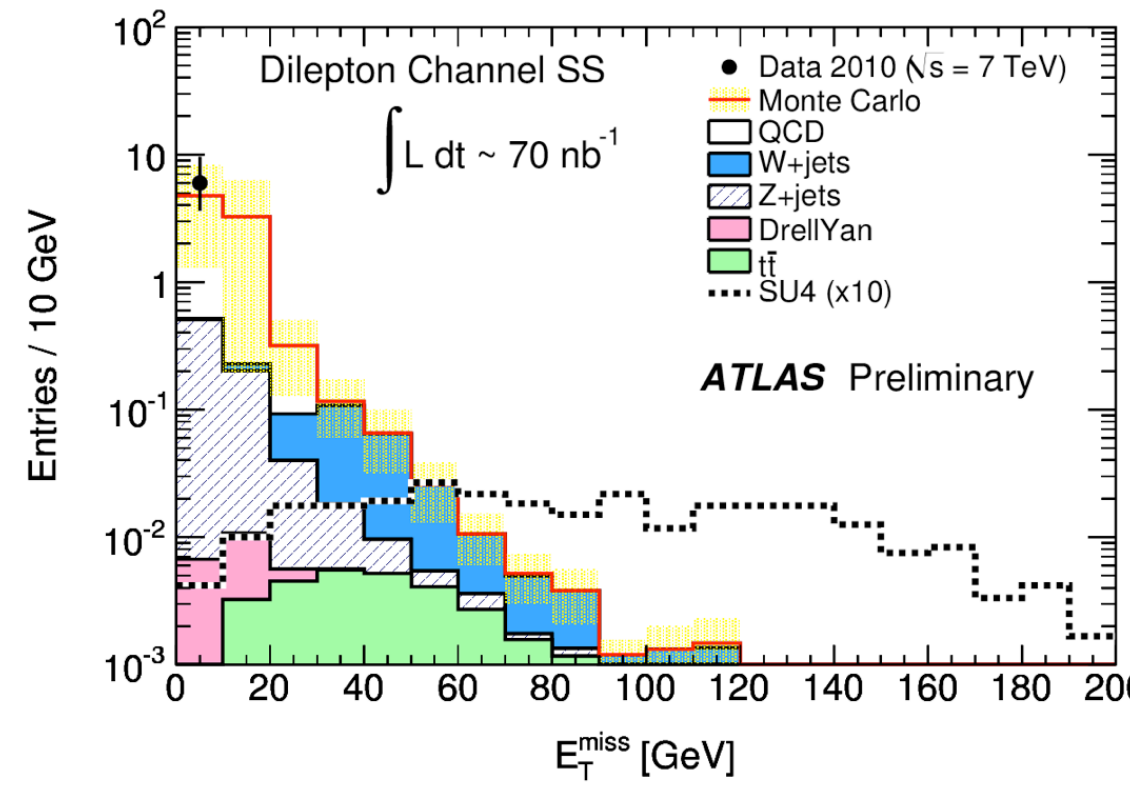
Di-lepton + MET searches

ATLAS-CONF-2010-066





- First look at the MET distributions for di-leptons
- At least two muons P_{T1}>20 GeV P_{T2}>10 GeV M_{ll}>5 GeV
- Normalise QCD MC to data in 5 < M_{ll} < 15 GeV and MET < 15 GeV
- 100% uncertainty assumed on W and QCD backgrounds and 60% for Z
- Good description by Monte Carlo

Long-lived particle searches

- Long-lived particles possible in many theories
  - Indirect support for some dark matter candidates
  - For example many SUSY models with stau NLSP with Gravitino LSP
    ➔ Gravitino LSP could be contribution to dark matter

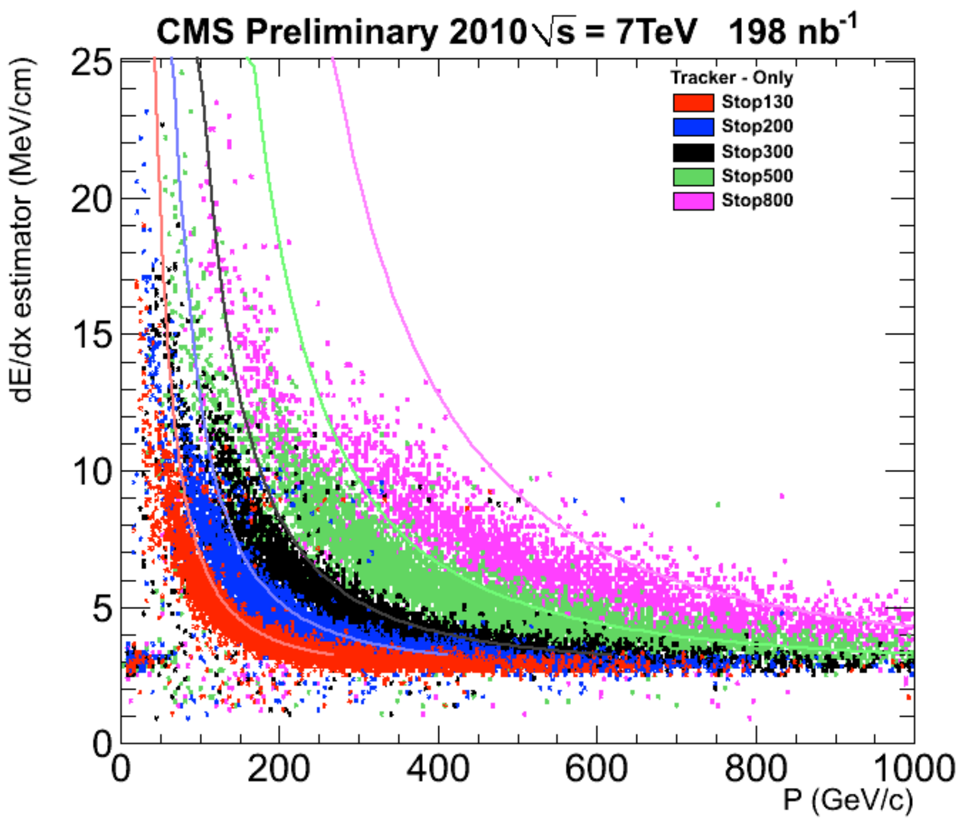
- Long-lived charged particles with lifetimes of O(1000) s could explain the discrepancy between Li abundance and BBN

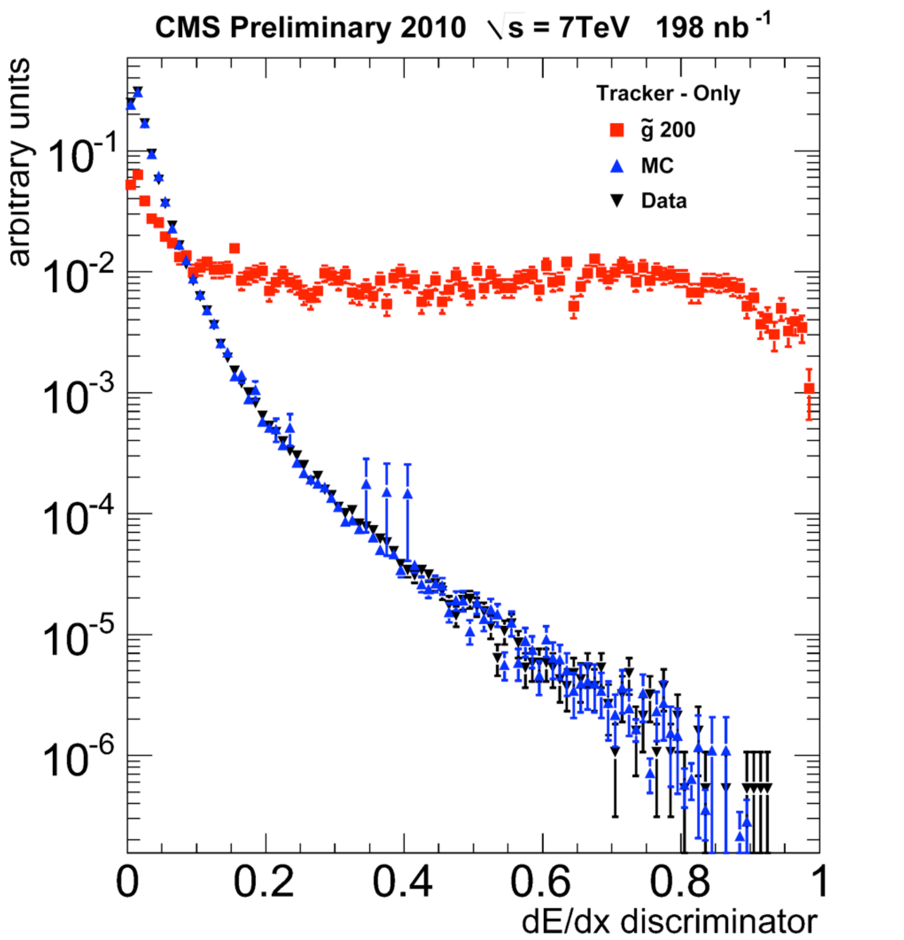
- Two complementary approaches:
  - High momentum tracks with large dE/dx E loss
  - Stopped particles may decay any time ➔ signal out-of-time with LHC beam

HSCP searches

CMS PAS-EXO-10-004

- Heavy stable charged particles (HSCP) escape detector
  - Muon-like signature in muon chambers
- Slow moving, high momentum particles
  - Large ionisation energy loss
- dE/dx (TOF in future)





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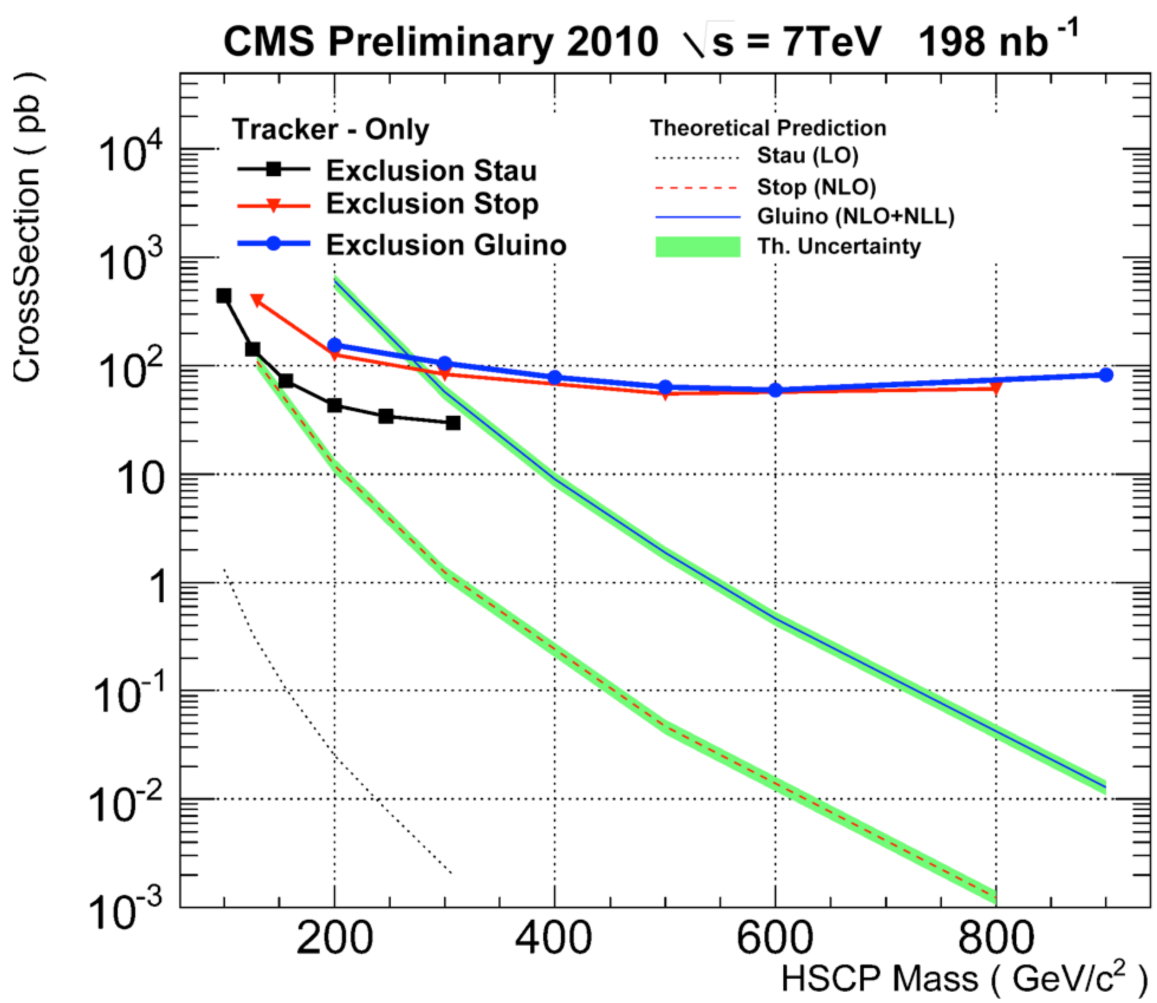
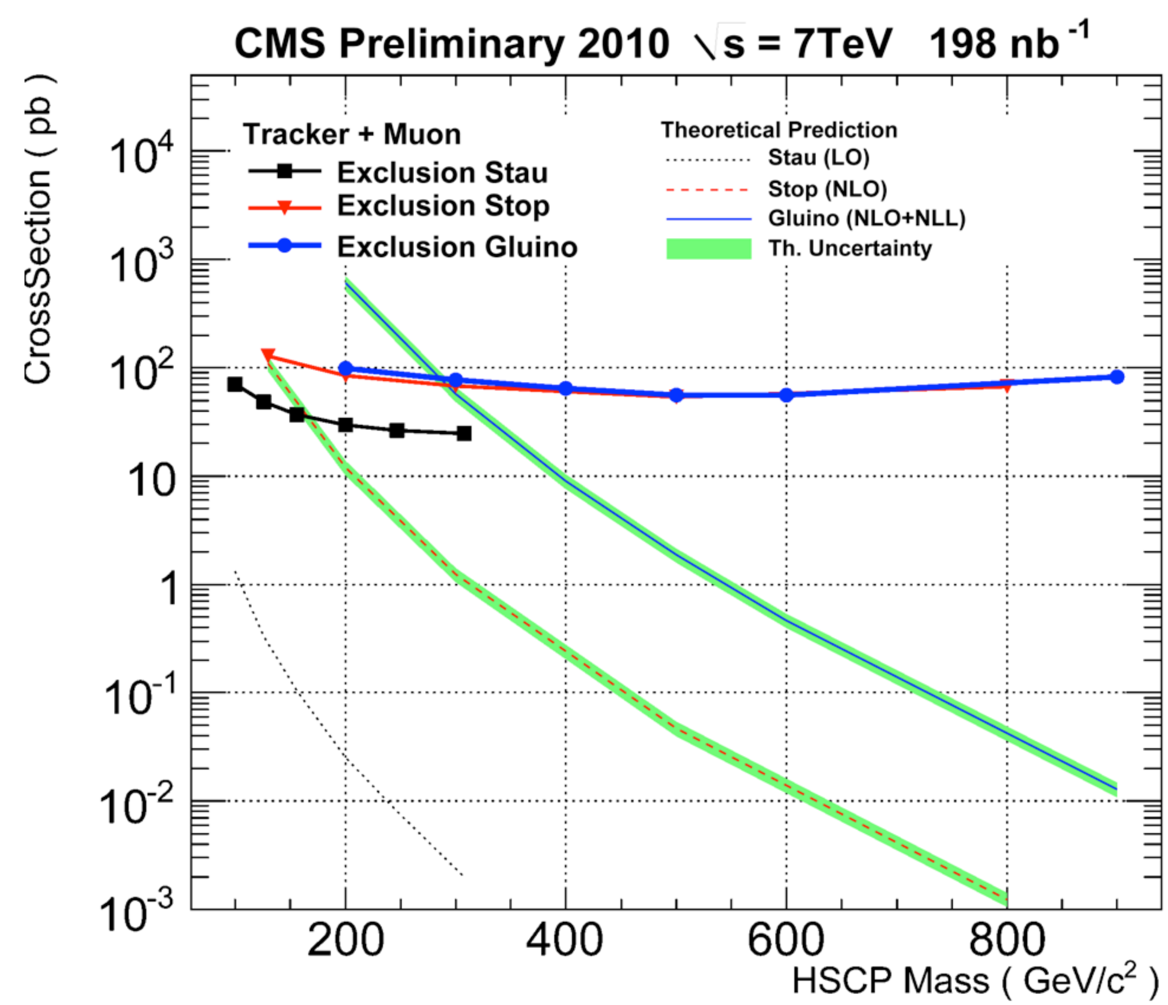
HSCP searches

CMS PAS-EXO-10-004

- Exclusion limits for stau, stop and gluino
  - Tracker only and tracker & muon chambers covers different models





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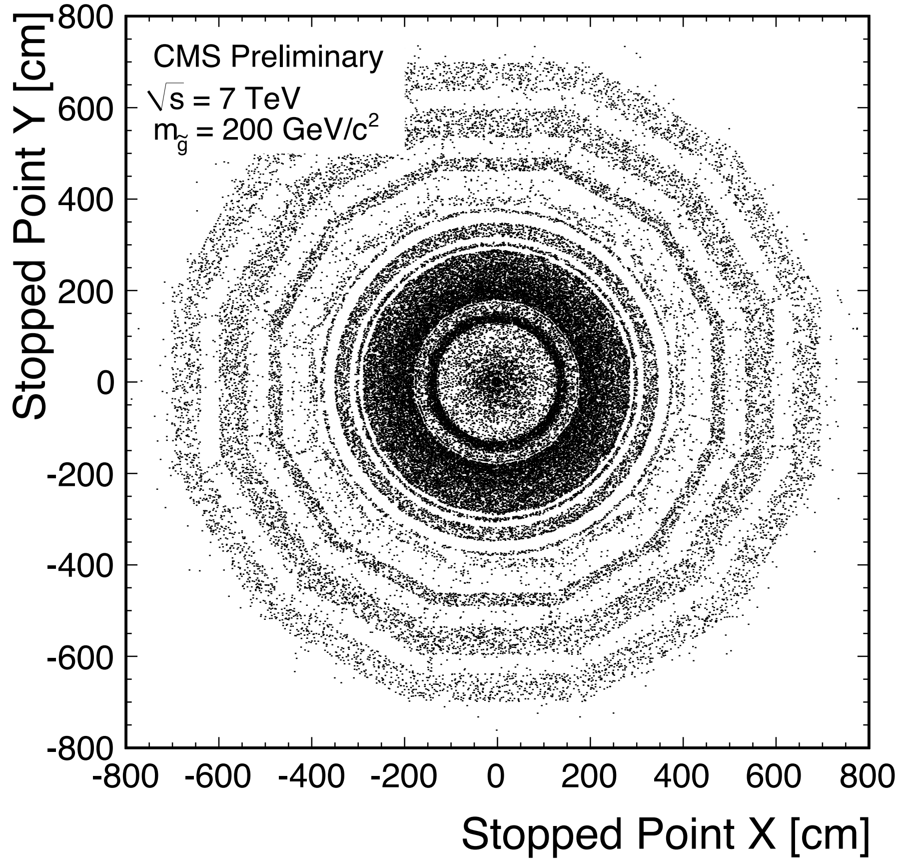
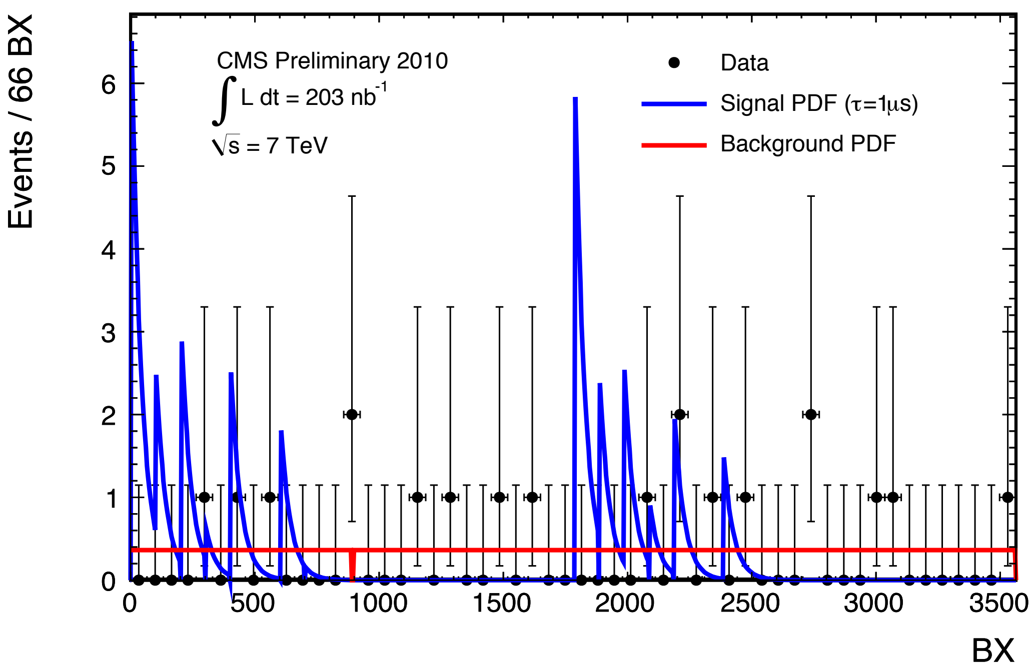
Stopped particle searches

CMS PAS-EXO-10-003



- Long-lived particles produced in pp collisions
- Particles stop in detector in brass absorber in barrel hadronic calorimeter
- Search for decays during non-collision times (between bunches, orbits and fills)
- Counting experiment in lifetime bins ➔



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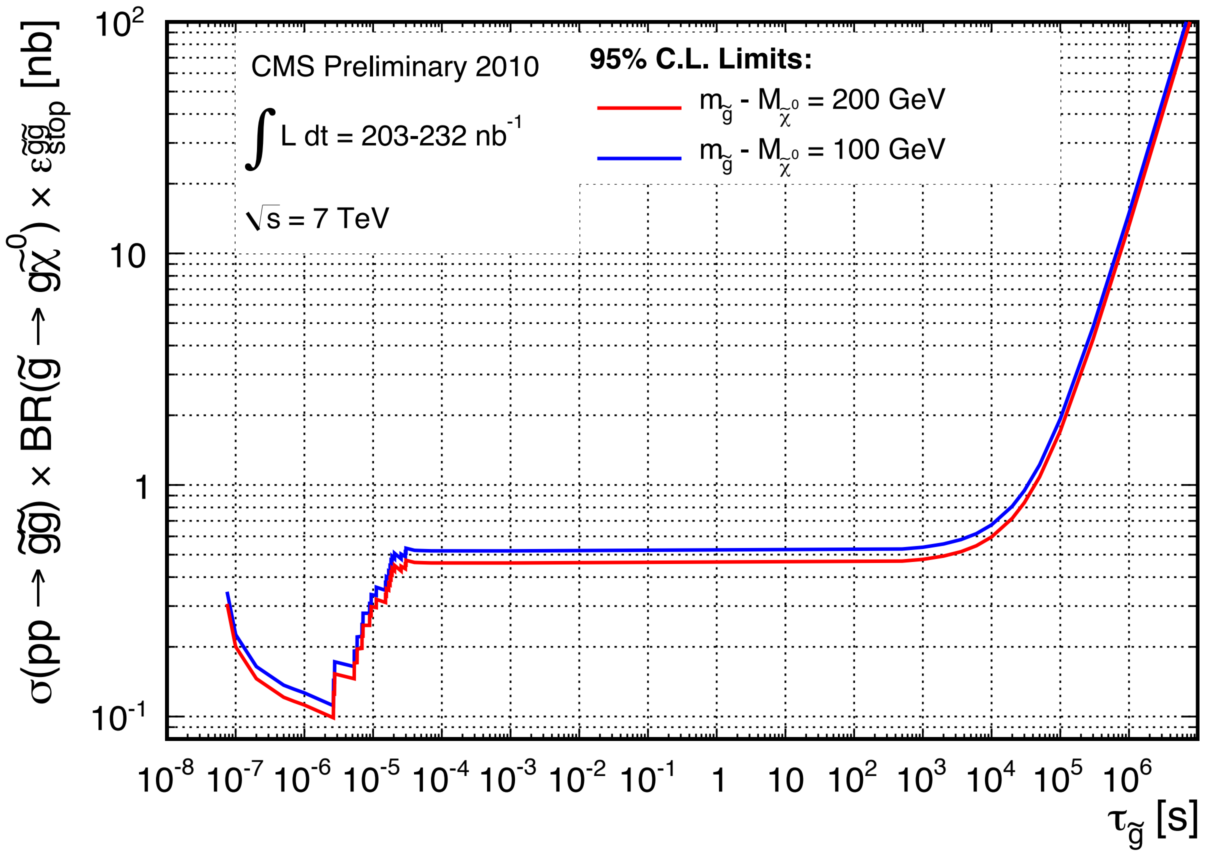
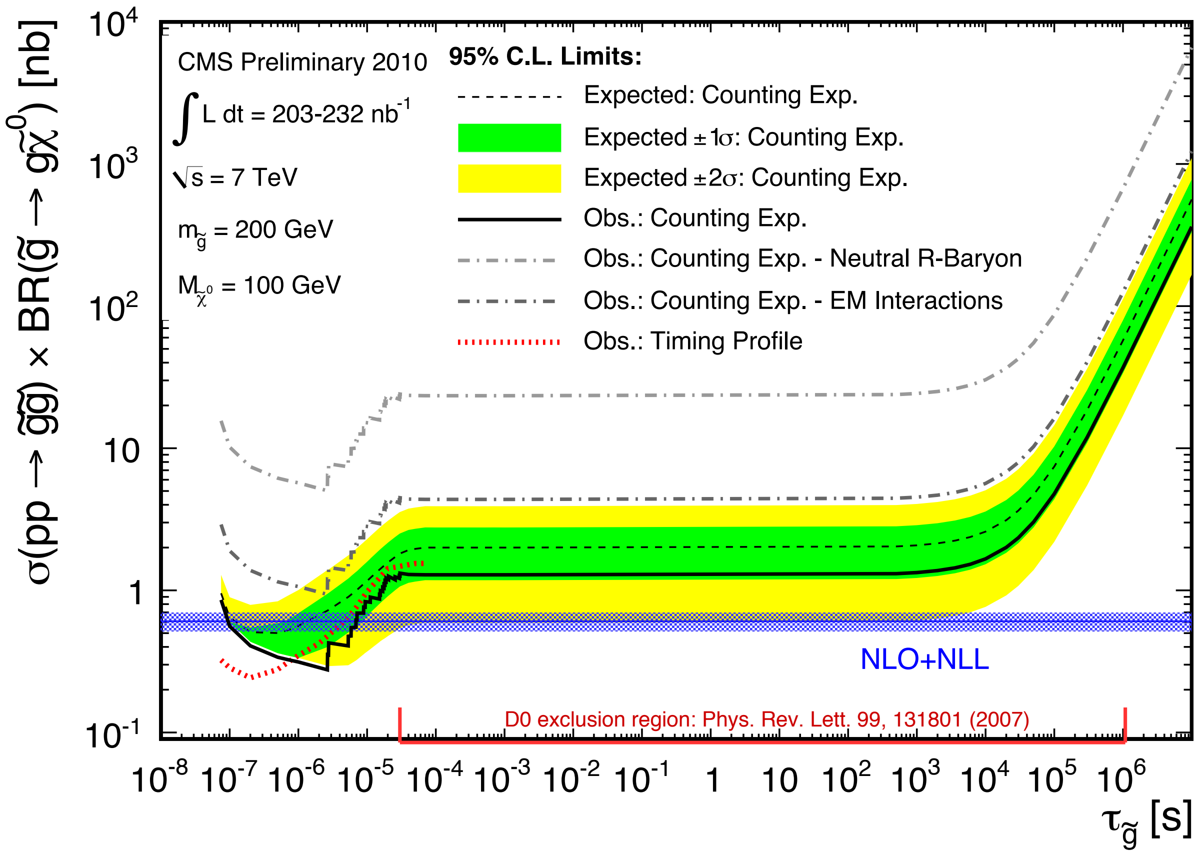
Stopped particle searches

CMS PAS-EXO-10-003





- So far limits on stopped gluinos ➔ technique could be used to set limits on stopped staus with more data

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Future prospects

- Taken the first steps towards searches ➔ What might happen?

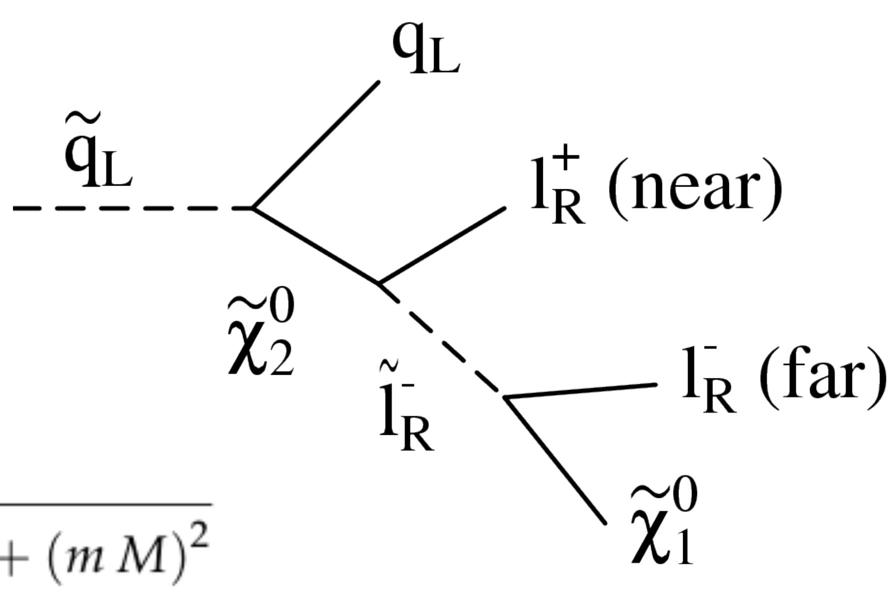
- Discovery with 2010-2011 data sample if M<800 GeV
  - First inclusive studies and indication of mass scale
  - Constraint within models example coming up ➔

- High luminosity required for “precision” measurements
  - Masses, spins, cross sections, branching ratios
  - As more parameters are determined, relax model assumptions to achieve more general results for dark matter

- Will always need direct detection measurements

Mass determination example

- Two undetected LSPs per event
  - No mass peaks
  - Constraints from edges and endpoints in kinematic distributions
  - Two-body $$\left(m_{ll}^{max}\right)^2 = \frac{\left(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{l}}\right)\left(m^2_{\tilde{l}} - m^2_{\tilde{\chi}^0_1}\right)}{m^2_{\tilde{l}}}$$
  - Three-body $$S(m_{ll}) = \frac{1}{\sqrt{2\pi}\sigma}\int_0^{m_{cut}} dy \cdot y \frac{\sqrt{y^4 - y^2\left(m^2 + M^2\right) + (m\,M)^2}}{\left(y^2 - m_Z^2\right)^2} \times \left(-2y^4 - y^2\left(m^2 + 2M^2\right) + (m\,M)^2\right) e^{\frac{-(m_{ll}-y)^2}{2\sigma^2}}$$



- Simplest example - many others with endpoints, thresholds and other variables (M_{T2} and friends)
- Vast literature (recommended review Barr & Lester arXiv:1004.2732)

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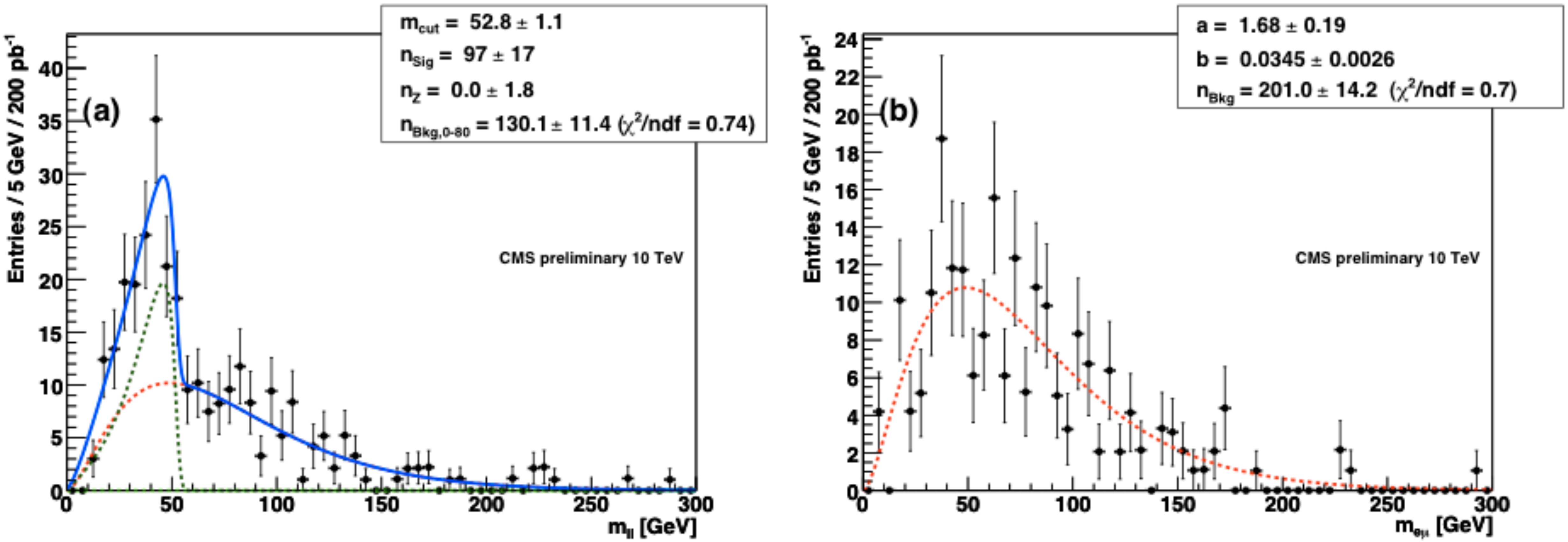
Mass determination example

CMS PAS-SUS-09-002



- Fit ee, μμ and eμ distributions simultaneously
  - Resolution function and efficiencies from data
  - Monte Carlo study for 200 pb^{-1} @ 10 TeV (600-700 pb^{-1} @ 7 TeV)
  - Di-leptonic end-point $m_{ll,max}$=51.3 ± 1.5 (stat.) ± 0.9 (syst.) GeV [52.7 GeV]
- Nice example of what could be done with modest dataset

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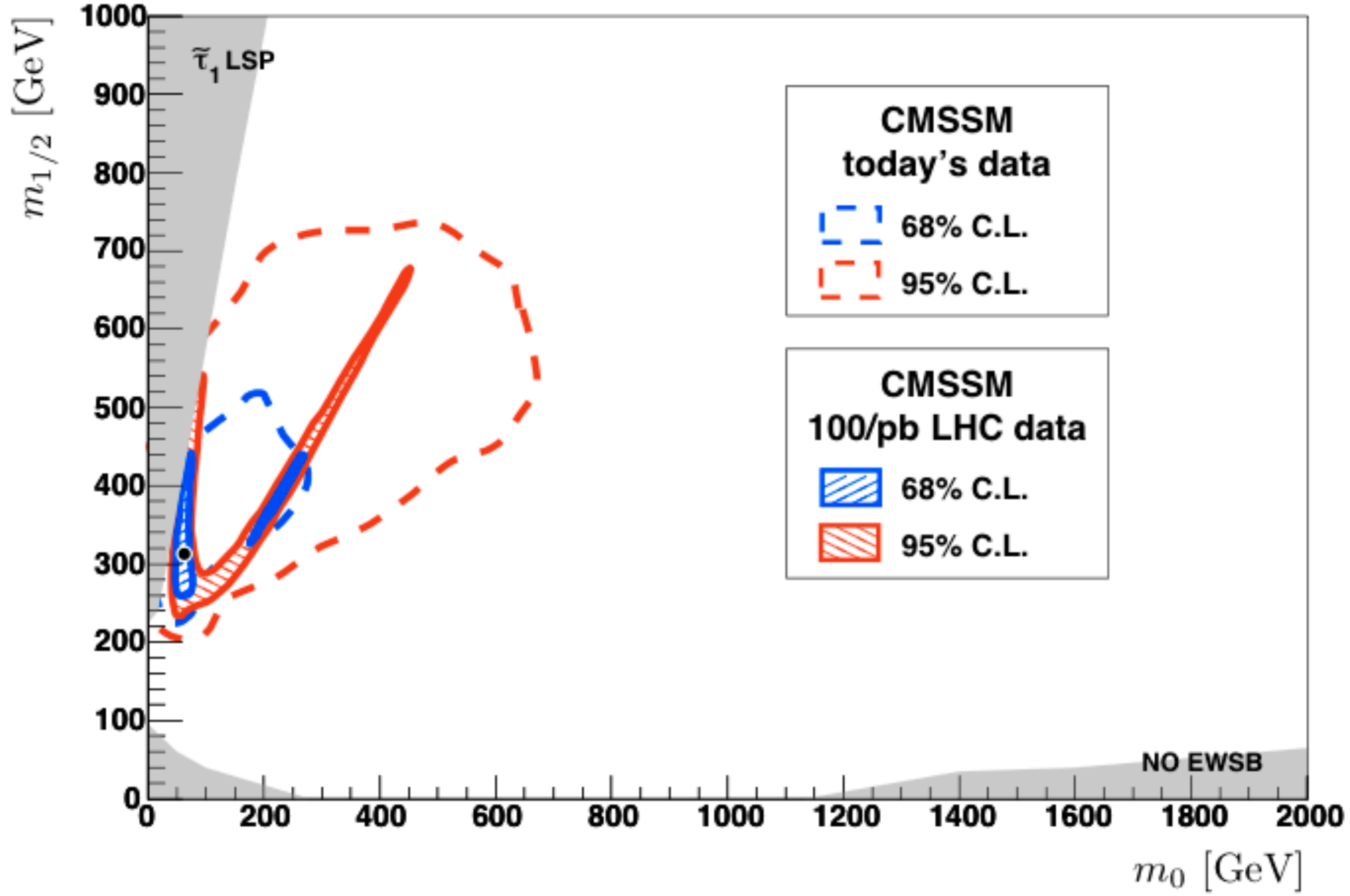
Interpreting mass example

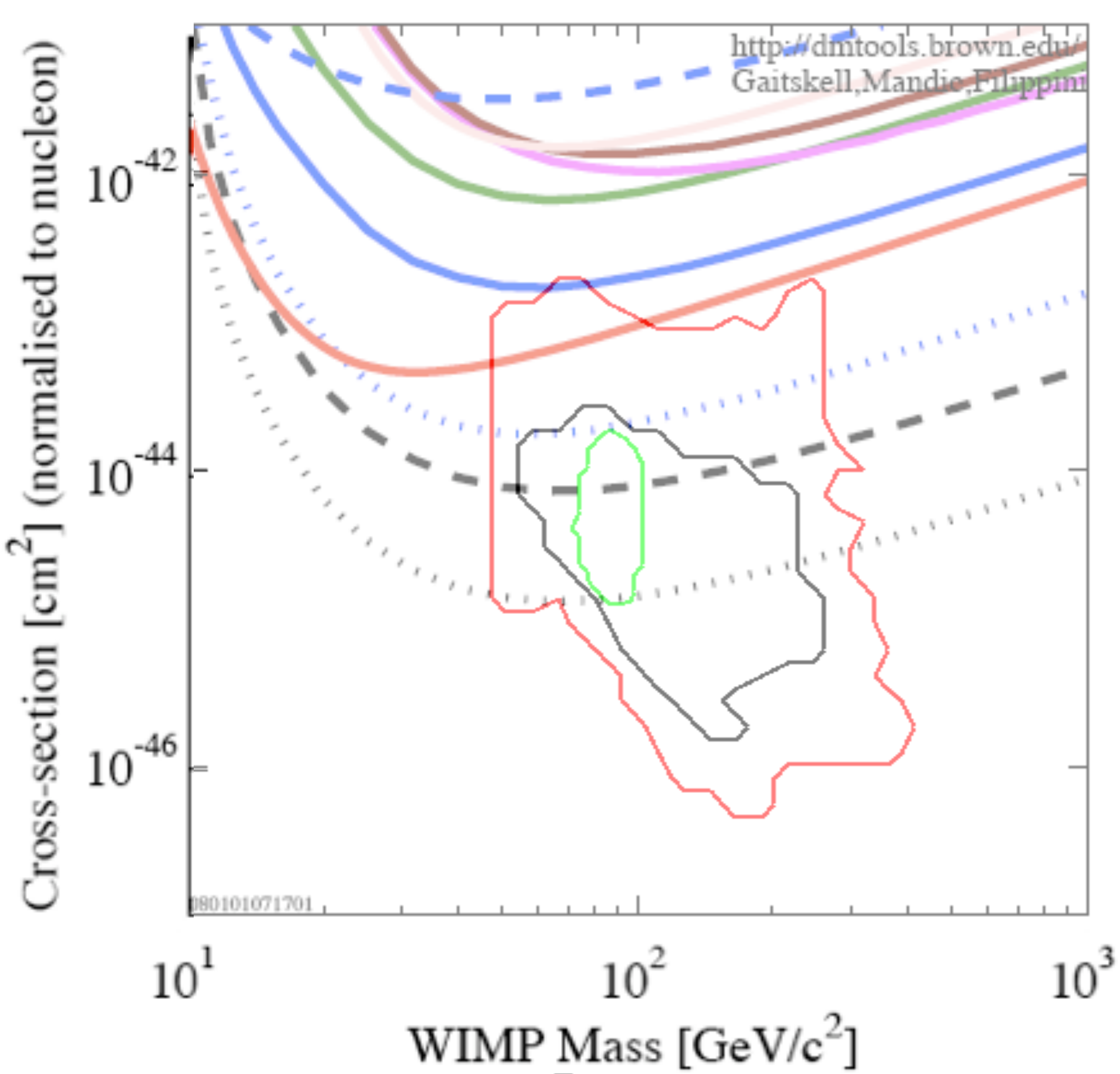
JHEP 0809:117, 2008

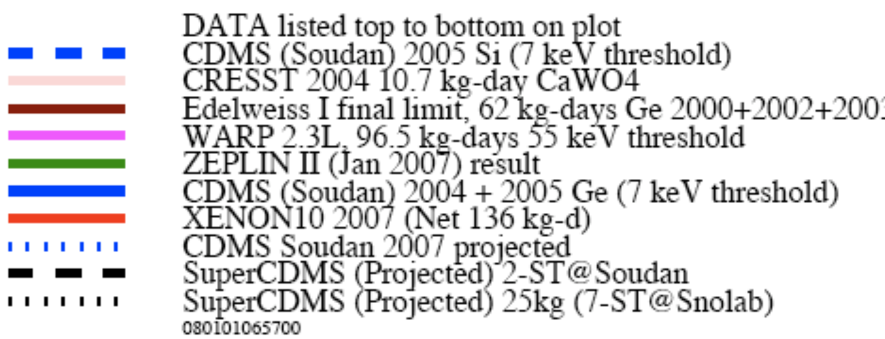


- R. Lafaye, M. Rauch, T. Plehn, D. Zerwas (SFITTER)
- H. Flächer, M. Goebel, J. Haller, A. Höcker, K. Mönig, J. Stelzer (GFITTER)
- P. Bechtle, K. Desch, M. Uhlenbrock, P. Wienemann (FITTINO)
- O. Buchmueller, R. Cavanaugh, A. De Roeck, J.R. Ellis, H.Flacher, S. Heinemeyer, G. Isidori, K.A. Olive, F. J. Ronga, G. Weiglein (MasterCode)
- L. Roszkowski, R. Ruiz de Austri, R. Trotta (SuperBayes)
- S.S. AbdusSalam, B.C. Allanach, M.J. Dolan, F. Feroz, M.P. Hobson

- Including current limits, precision EW HEP data and WMAP constraints in constrained SUSY model
- Include opposite-sign di-lepton edge measurement
- 1 fb^{-1} @ 14 TeV with 3 GeV experimental and theoretical uncertainties

Connection to cosmology





CMSSM NOW (95% CL)

Potential 2011 (95% CL)
OSDL edge

- Spin-independent elastic cross section per nucleon (old plot sorry...)
- Convenient illustration of direct and indirect WIMP searches

Summary and outlook

- Searches for dark matter at the LHC have begun!
- With the 7 TeV run might already make a discovery with impact on dark matter
- Future data will allow the LHC experiments to determine some of the properties of any discovery but will be a huge challenge requiring the ultimate performance of the accelerator and detectors
- Complementary measurements necessary to reveal the true nature of dark matter in detail

Backup: Bibliography

- Documents for ICHEP on preparations for SUSY searches at LHC

  - ATLAS Collab., Early supersymmetry searches in channels with jets and missing transverse momentum with the ATLAS Detector (ATLAS-CONF-2010-065)
  - ATLAS Collab., Early supersymmetry searches with jets, missing transverse momentum and one or more leptons with the ATLAS Detector (ATLAS-CONF-2010-066)
  - CMS Collab., Performance of Methods for Data-Driven Background Estimation in SUSY Searches (CMS-SUS-10-001)
  - Early supersymmetry searches in events with missing transverse energy and b-jets with the ATLAS detector (ATLAS-CONF-2010-079)
  - Prospects for Supersymmetry discovery based on inclusive searches at a 7 TeV centre-of-mass energy with the ATLAS detector (ATL-PHYS-PUB-2010-010)
  - The CMS physics reach in searches at 7 TeV (CMS-NOTE-2010-008)

Backup: Links

- ATLAS latest results
  - https://twiki.cern.ch/twiki/bin/view/Atlas/AtlasResults
- ATLAS Physics TDR
  - http://cdsweb.cern.ch/record/1125884?ln=en
- CMS latest results
  - https://twiki.cern.ch/twiki/bin/view/CMS/PhysicsResults
- CMS Physics TDR
  - http://cmsdoc.cern.ch/cms/cpt/tdr/

Backup: Benchmark points

Low mass (LM) mSUGRA benchmarks

Benchmark	m0	m1/2	A0	tanb	sgn(mu)	Notes
LM0	200	160	-400	10	1	
LM1	60	250	0	10	+	
LM2	185	350	0	35	+	
LM2mhf360	185	360	0	35	+	
LM3	330	240	0	20	+	
LM4	210	285	0	10	+	
LM5	230	360	0	10	+	
LM6	85	400	0	10	+	
LM7	3000	230	0	10	+	
LM8	500	300	-300	10	+	
LM9	1450	175	0	50	+	
LM9p	1450	230	0	10	+	
LM9t175	1450	175	0	50	+	mtop = 175
LM10	3000	500	0	10	+	
LM11	250	325	0	35	+	
LM12						TBD
LM13						focus point, TBD

High mass (HM) mSUGRA benchmarks

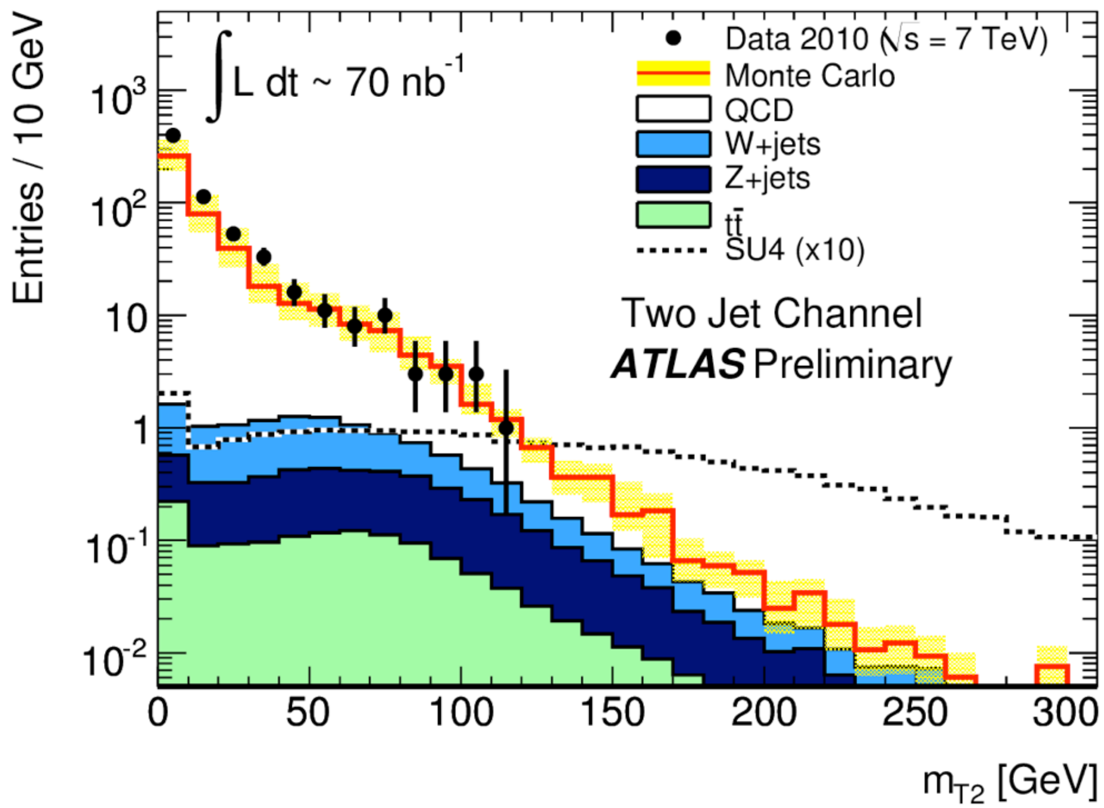
Benchmark	m0	m1/2	A0	tanb	sgn(mu)	Notes
HM1	180	850	0	10	+	
HM2	350	800	0	35	+	
HM3	700	800	0	10	+	
HM4	1350	600	0	10	+	

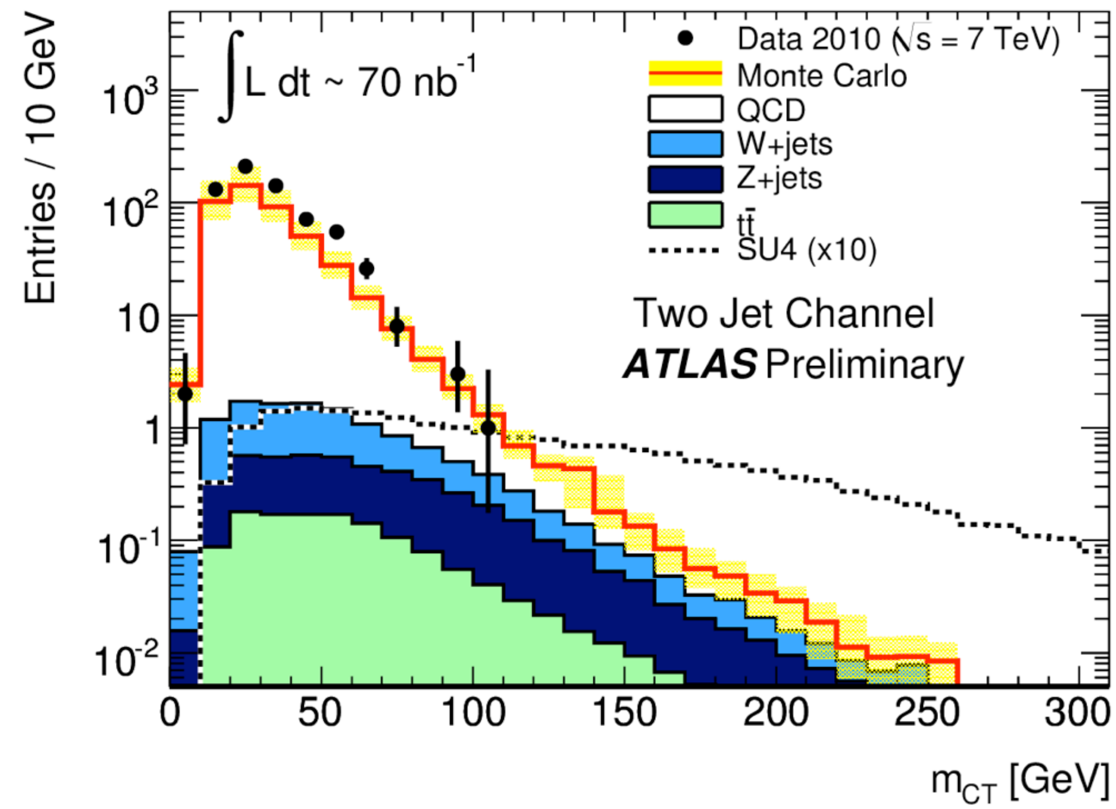
GMSB (GM) benchmarks

Benchmark	Lambda	M_mess	N5	C_Grav	tanb	sgn(mu)	Notes
GM1b	80	160	1	1	15	+	
GM1c	100	200	1	1	15	+	
GM1d	120	240	1	1	15	+	
GM1e	140	280	1	1	15	+	
GM1f	160	320	1	1	15	+	
GM1g	180	360	1	1	15	+	

Particle	SU1	SU2	SU3	SU4	SU6	SU8.1	SU9
$\tilde{d}_L$	764.90	3564.13	636.27	419.84	870.79	801.16	956.07
$\tilde{u}_L$	760.42	3563.24	631.51	412.25	866.84	797.09	952.47
$\tilde{b}_1$	697.90	2924.80	575.23	358.49	716.83	690.31	868.06
$\tilde{t}_1$	572.96	2131.11	424.12	206.04	641.61	603.65	725.03
$\tilde{d}_R$	733.53	3576.13	610.69	406.22	840.21	771.91	920.83
$\tilde{u}_R$	735.41	3574.18	611.81	404.92	842.16	773.69	923.49
$\tilde{b}_2$	722.87	3500.55	610.73	399.18	779.42	743.09	910.76
$\tilde{t}_2$	749.46	2935.36	650.50	445.00	797.99	766.21	911.20
$\tilde{e}_L$	255.13	3547.50	230.45	231.94	411.89	325.44	417.21
$\tilde{\nu}_e$	238.31	3546.32	216.96	217.92	401.89	315.29	407.91
$\tilde{\tau}_1$	146.50	3519.62	149.99	200.50	181.31	151.90	320.22
$\tilde{\nu}_\tau$	237.56	3532.27	216.29	215.53	358.26	296.98	401.08
$\tilde{e}_R$	154.06	3547.46	155.45	212.88	351.10	253.35	340.86
$\tilde{\tau}_2$	256.98	3533.69	232.17	236.04	392.58	331.34	416.43
$\tilde{g}$	832.33	856.59	717.46	413.37	894.70	856.45	999.30
$\tilde{\chi}_1^0$	136.98	103.35	117.91	59.84	149.57	142.45	173.31
$\tilde{\chi}_2^0$	263.64	160.37	218.60	113.48	287.97	273.95	325.39
$\tilde{\chi}_3^0$	466.44	179.76	463.99	308.94	477.23	463.55	520.62
$\tilde{\chi}_4^0$	483.30	294.90	480.59	327.76	492.23	479.01	536.89
$\tilde{\chi}_1^+$	262.06	149.42	218.33	113.22	288.29	274.30	326.00
$\tilde{\chi}_2^+$	483.62	286.81	480.16	326.59	492.42	479.22	536.81
h^0	115.81	119.01	114.83	113.98	116.85	116.69	114.45
H^0	515.99	3529.74	512.86	370.47	388.92	430.49	632.77
A^0	512.39	3506.62	511.53	368.18	386.47	427.74	628.60
H^+	521.90	3530.61	518.15	378.90	401.15	440.23	638.88
t	175.00	175.00	175.00	175.00	175.00	175.00	175.00

Backup: Mass determination





Stransverse mass The m_{T2} variable is the generalization of the transverse mass to pair decays [32]. For a final state consisting of two visible objects with transverse momenta $\mathbf{p}_T^{(1)}$ and $\mathbf{p}_T^{(2)}$ respectively, and with missing transverse momentum $\not{\mathbf{p}}_T$, it is defined by

$$m_{T2}\left(\mathbf{p}_T^{(1)}, \mathbf{p}_T^{(2)}, \not{\mathbf{p}}_T\right) \equiv \min_{\not{\mathbf{q}}_T^{(1)}+\not{\mathbf{q}}_T^{(2)}=\vec{E}_T^{\text{miss}}} \left\{\max\left(m_T\left(\mathbf{p}_T^{(1)}, \not{\mathbf{q}}_T^{(1)}\right), m_T\left(\mathbf{p}_T^{(2)}, \not{\mathbf{q}}_T^{(2)}\right)\right)\right\} \quad (4)$$

where m_T is the transverse mass [5)]

$$m_T^2\left(\mathbf{p}_T^{(i)}, \not{\mathbf{q}}_T^{(i)}\right) \equiv 2|\mathbf{p}_T^{(i)}||\not{\mathbf{q}}_T^{(i)}| - 2\mathbf{p}_T^{(i)} \cdot \not{\mathbf{q}}_T^{(i)}, \quad (5)$$

and the minimization is over all values of the two undetectable particles' possible missing transverse momenta $\not{\mathbf{q}}_T^{(1,2)}$ consistent with the $\vec{E}_T^{\text{miss}}$ constraint. This variable represents an event-by-event lower bound on the mass of any pair-produced semi-invisibly decaying particle which could have resulted in the observed state [34] .

Contransverse mass This variable is useful in events in which a pair of identical parent particles has decayed semi-invisibly producing visible daughters (with momenta $j^{(1,2)}$). The contransverse mass is defined by [35]

$$m_{CT}^2\left(j^{(1)}, j^{(2)}\right) \equiv 2E_T^{(1)}E_T^{(2)} + 2\mathbf{p}_T^{(1)} \cdot \mathbf{p}_T^{(2)}. \quad (6)$$

It is invariant under back-to-back boosts of the parent particles, and provides a lower bound on a combination of the masses of the parent and undetectable daughter particles. The contransverse mass is sensitive to the boost of the centre-of-momentum frame of the parent particles in the laboratory transverse plane and must therefore be corrected using the procedure described in [36].

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