Dark Matter at the LHC

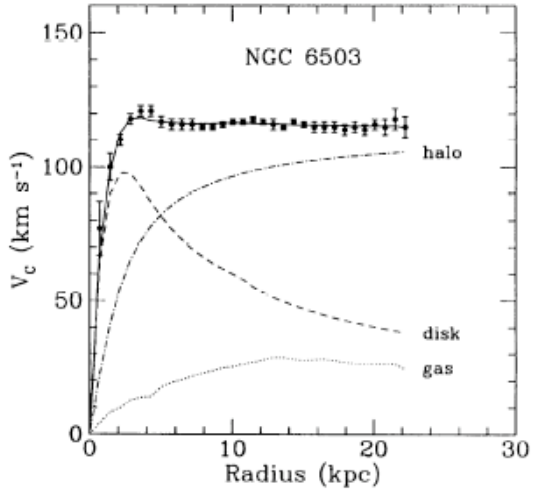
The road is long, but at least we started driving …

Filip Moortgat (ETH Zurich)

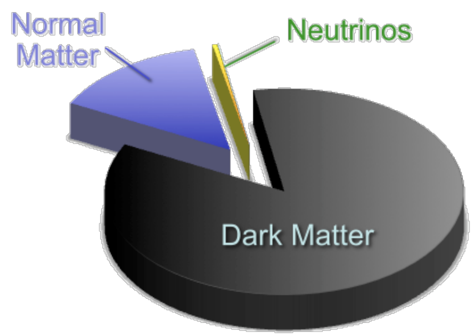
Evidence for Dark Matter

- Rotation curves
- Gravitational lensing
- Hot gas in clusters
- Bullet cluster

→ Existence of DM established!



Quantify?



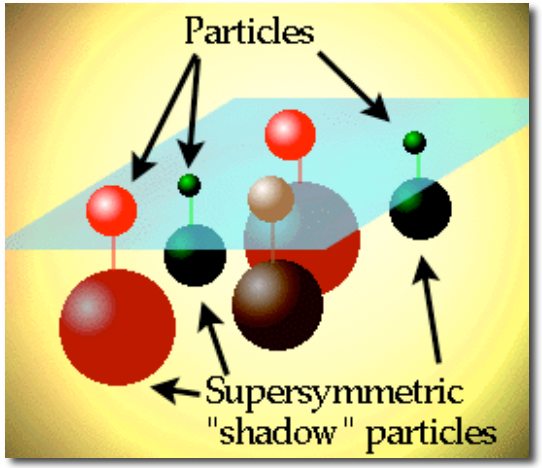
From Cosmic Microwave Background measurements + large scale structures + Big Bang Nucleosynthesis:

~ 80% of matter in Universe is Dark Matter!

→ need new form of matter, that is neutral, stable and (at most) weakly interacting …

SUSY & Dark Matter

Connection to particle physics:



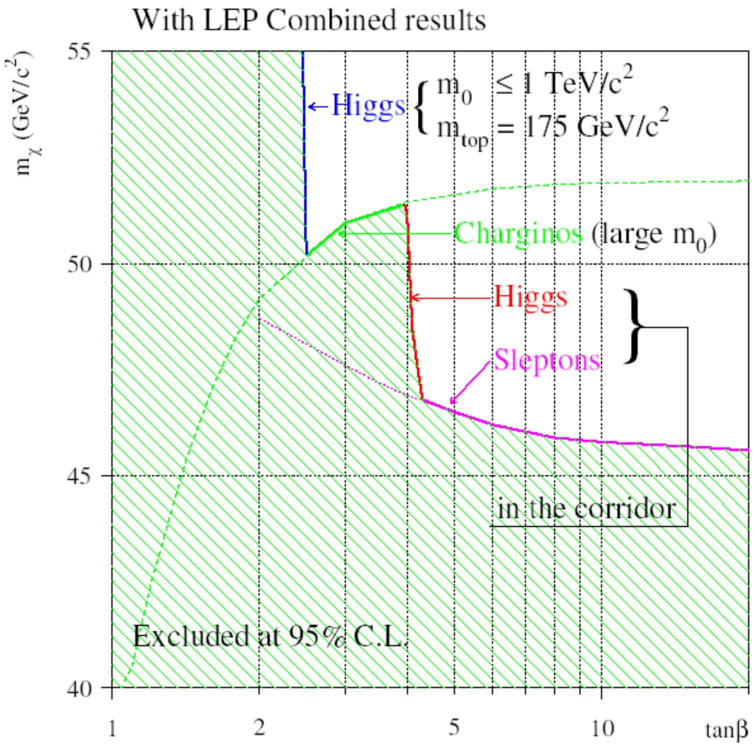
Supersymmetry is a popular extension of the Standard Model of Particle Physics that *naturally* predicts a Lightest Supersymmetric Particle (LSP) with these properties:

Weakly Interacting Massive Particle (WIMP)
with mass up to few 100 GeV gives correct relic density
(present experimental lower limit ~ 50 GeV)

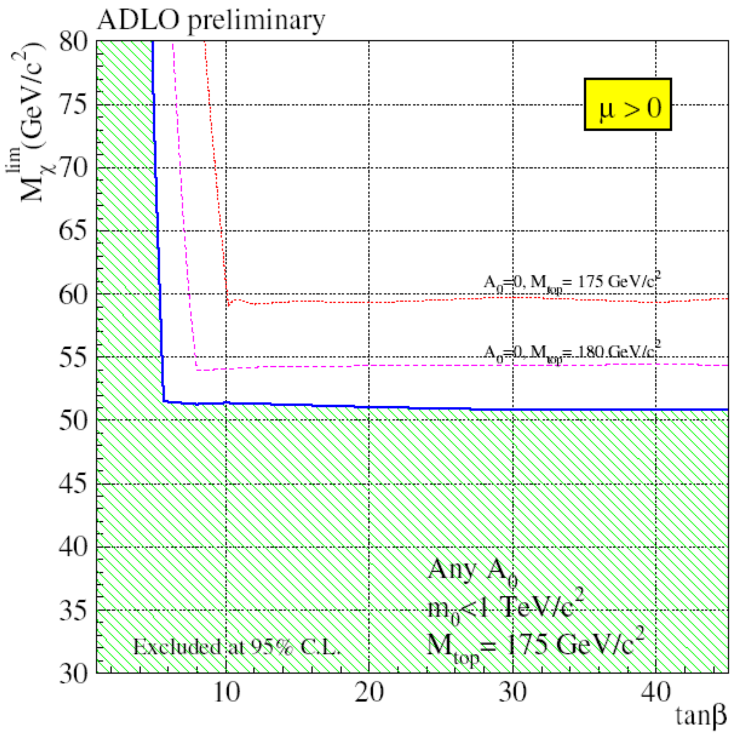
Also: Universal Extra Dimensions, Little Higgs with T-parity, …

Present exp. limits ?

In MSSM:



In MSUGRA:



$M(\chi^0_1\text{=LSP}) > 45\text{- }50$ GeV

Which DM can LHC look for?

CMS

ETH Institute for Particle Physics

Two types of signatures at the LHC:

- Missing Transverse Energy signals: “standard” WIMP dark matter (neutralinos, lightest KK particles, lightest T-odd parity particles, ...)
- long-lived heavy charged particles : stau, R-hadrons (gravitino DM, superwimps, split-susy, ...)

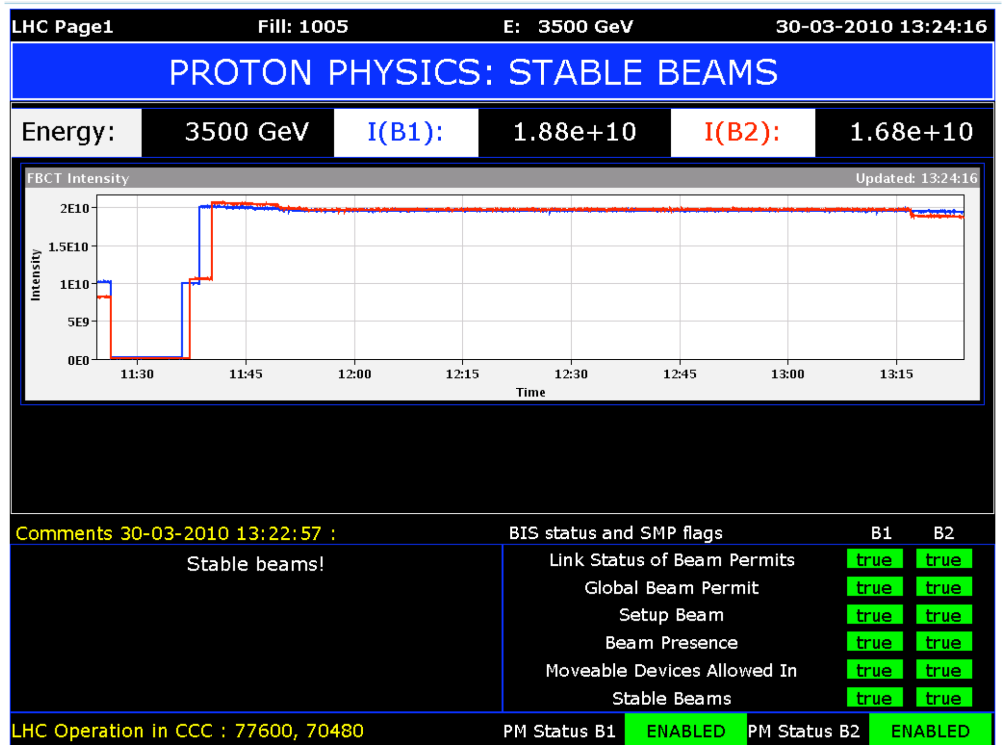
Goal of the LHC:

1) *Discovery*
2) *Measure properties, identify underlying physics*

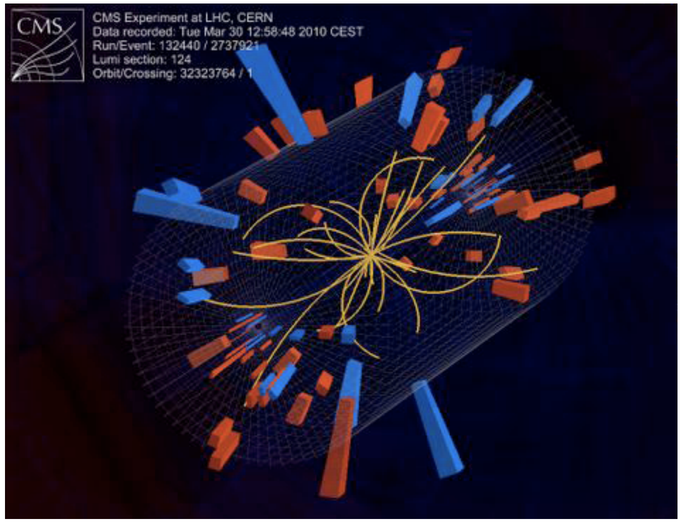
The LHC

First collisions at 900 GeV : 23 November 2009
First collisions at 7 TeV : 30 March 2010

30 March 2010 at 12:58



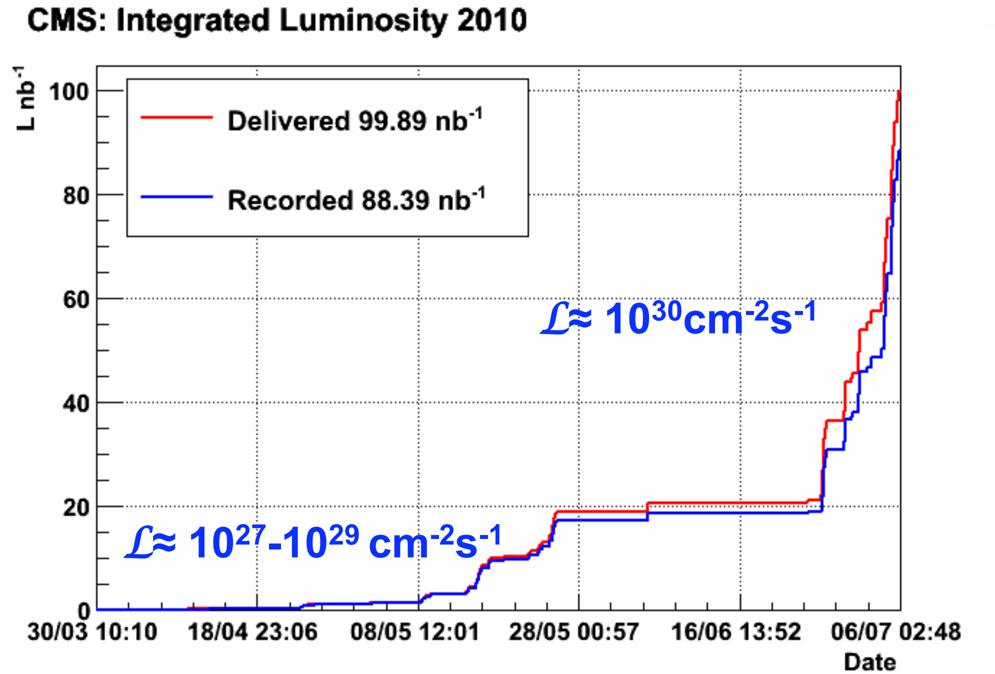
One of the first 7 TeV collisions:



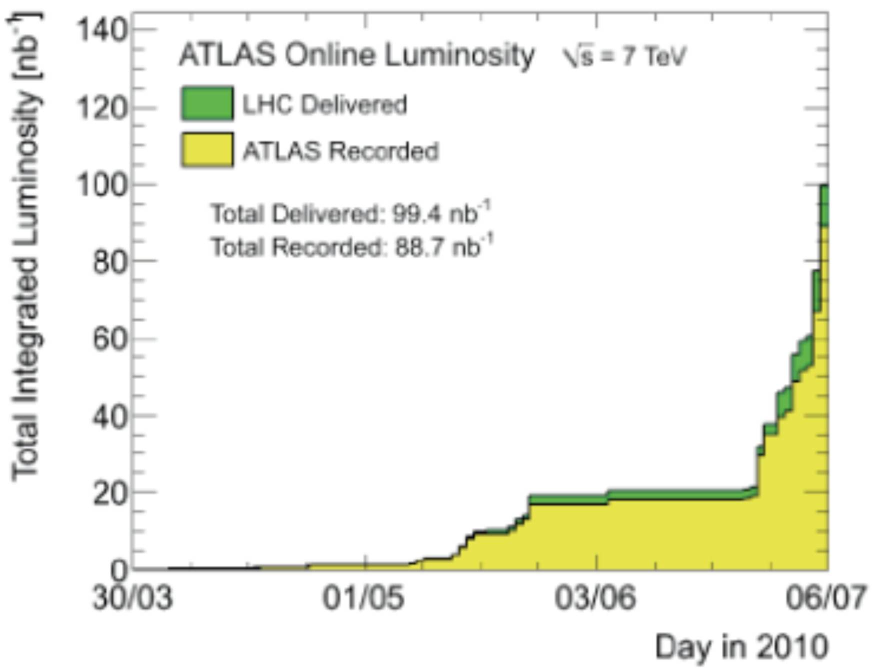
LHC timeline: 2010-2011: 1 fb^{-1} collisions at E_{cm} = 7 TeV
from 2013 onwards: collisions at E_{cm} ~ 14 TeV → discoveries possible soon!

Integrated luminosity

CMS



ATLAS

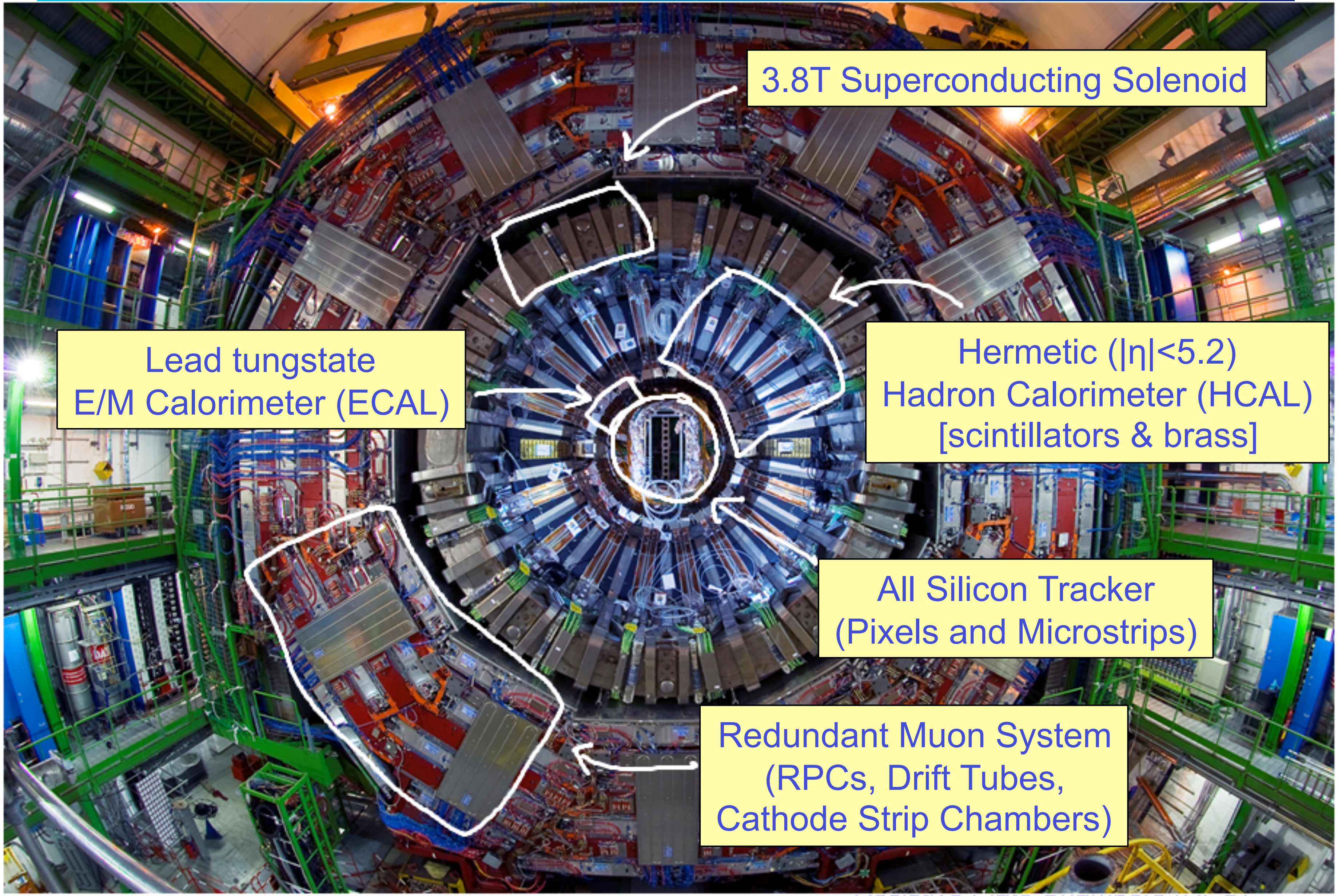


Since end of March (7 TeV):
100 nb^{-1} delivered $^{(*)}$
88 nb^{-1} recorded (~88%)

Overall data taking efficiency: ~ 89%

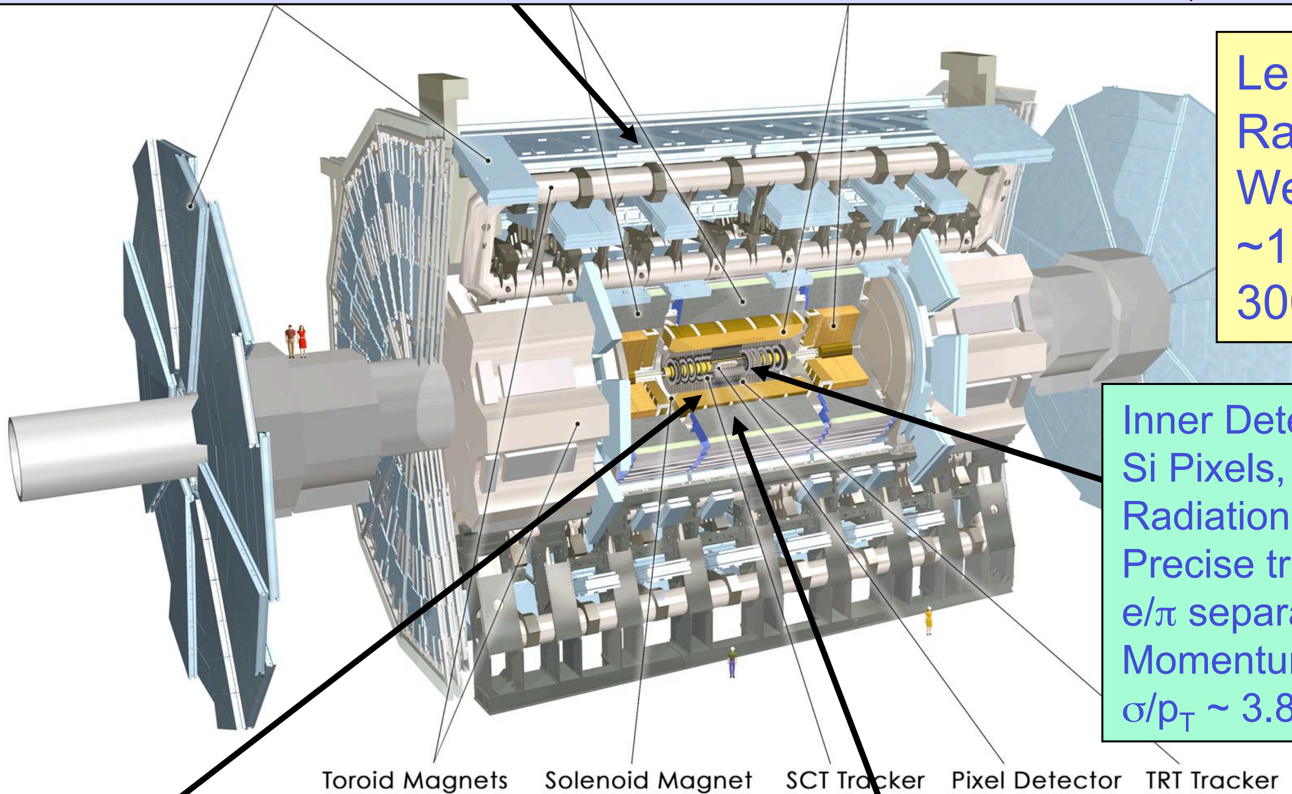
(*) Stable beams only

The CMS detector



The ATLAS detector

Muon Spectrometer ($|\eta|<2.7$) : air-core toroids with gas-based muon chambers
Muon trigger and measurement with momentum resolution < 10% up to E_μ ~ 1 TeV



Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~10^8 electronic channels
3000 km of cables

Inner Detector ($|\eta|<2.5$, B=2T):
Si Pixels, Si strips, Transition Radiation detector (straws)
Precise tracking and vertexing,
e/π separation
Momentum resolution:
$\sigma/p_T \sim 3.8\times10^{-4}\, p_T (\mathrm{GeV}) \oplus 0.015$

EM calorimeter: Pb-LAr Accordion
e/γ trigger, identification and measurement
E-resolution: $\sigma/E \sim 10\%/\sqrt{E}$

HAD calorimetry ($|\eta|<5$): segmentation, hermeticity
Fe/scintillator Tiles (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and missing E_T
E-resolution: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

SM processes in 2010

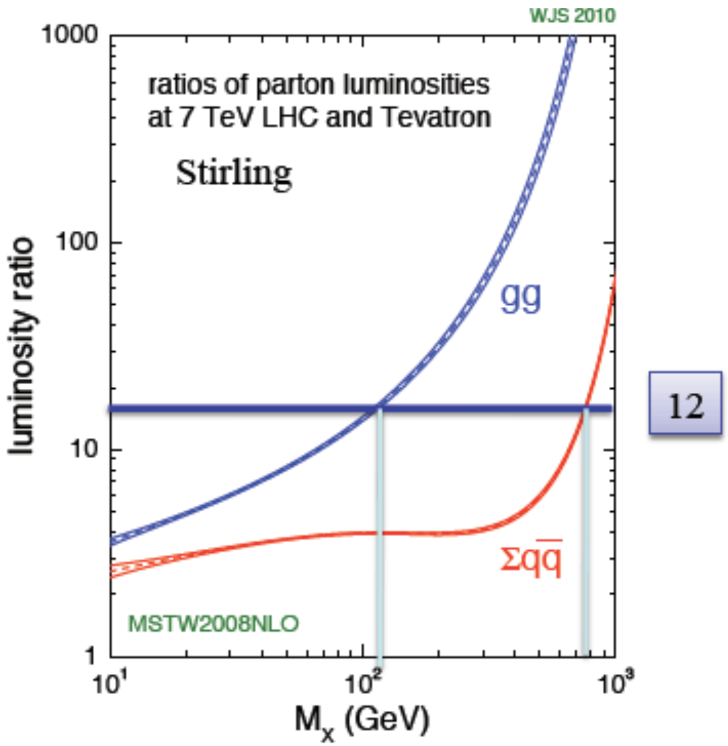
process	Order α_s	14 TeV (pb)	7 TeV (pb)	2 TeV ppbar (pb)	reference
$t\bar{t}$	NLO +NLL	910	170	7.4	arXiv: 0804.2800, arXiv: 0909.0037
Single top	NLO	320			
W->eν or μν	NNLO	22000	8000	2700	arXiv: 0901.0002
Z-> ee or μμ	NNLO	2000	770	250	arXiv: 0901.0002
WW	NLO	112			
WZ		48			
ZZ		15			

Number of events in 1 fb^{-1}: multiply by 1000 and then a typical acceptance of 0.2-0.8.

Also see arXiv:hep-ph/0611148

LHC vs Tevatron

The Tevatron can probe up to $\sqrt{s} = 2$ TeV and currently has 7 fb^{-1} delivered, and may have 12 fb^{-1} by the end of 2011.



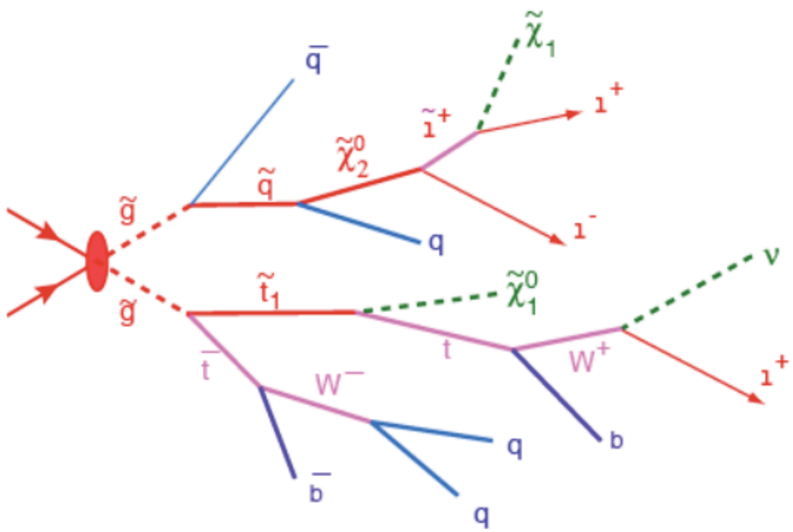
$$\frac{12}{1} = 12$$

Roughly, the tevatron with 12000 pb^{-1} has the same or greater reach than the LHC at 7 TeV and 1000 pb^{-1} for particles with gg initial state and masses less than about 120 GeV. For particles with a qqbar initial state, it has same or greater reach up to 700 GeV.

Basic SUSY signatures

ETH Institute for Particle Physics

Plan for first LHC physics run: coherent survey of simple, inclusive signatures involving MET. But also need to search for “exotic” signatures such as those arising from long-lived NLSP’s.



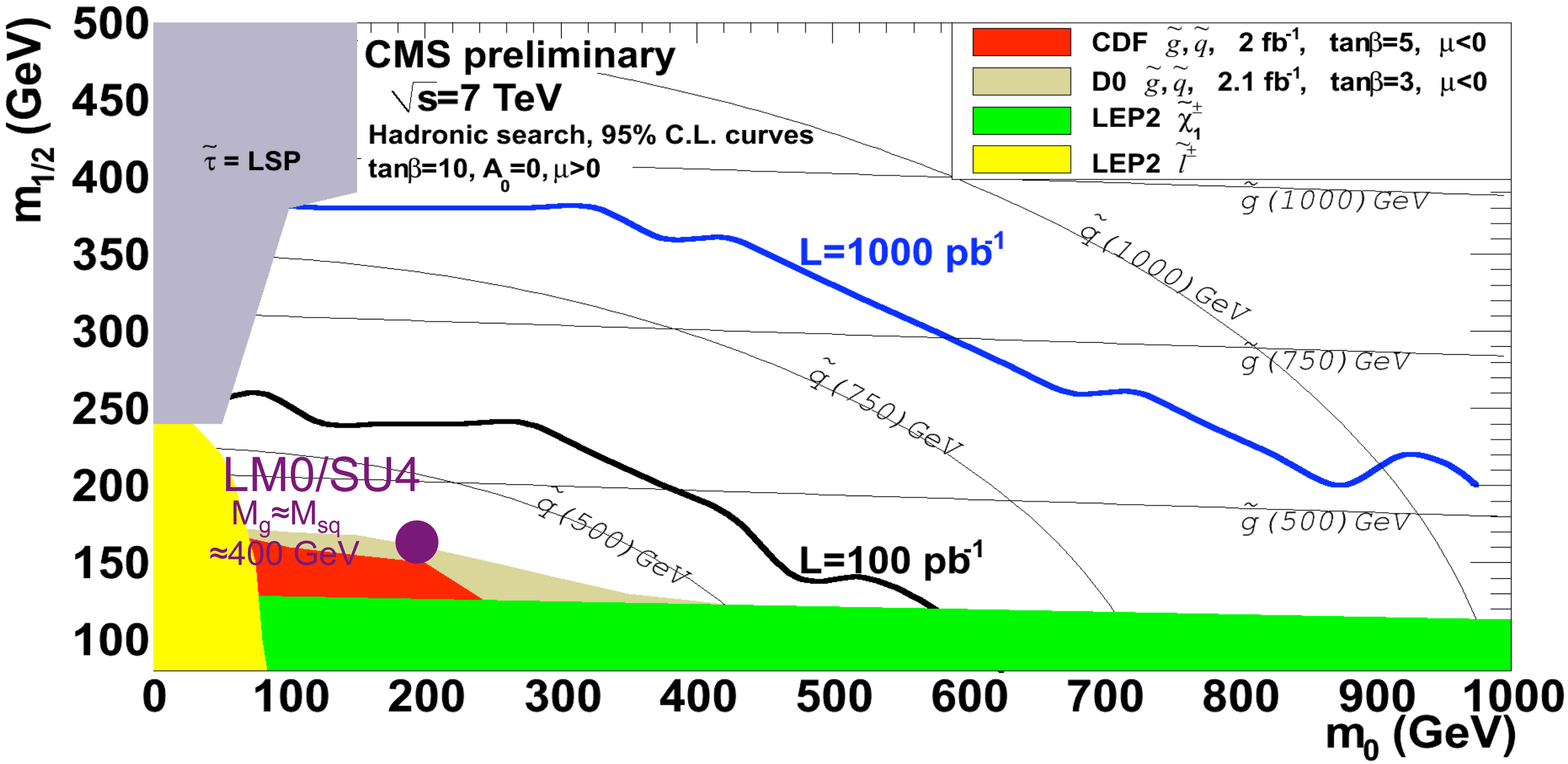
- Establish foundation for more complex searches. Signatures will expand to include b, τ, t.
- Data-driven background methods: pursue multiple approaches, <u>as many cross-checks as possible.</u>

<u>0 leptons</u>	<u>1 lepton</u>	<u>2 leptons</u>	<u>≥3 leptons</u>
• Exclusive jets • Inclusive Jets • Photons + Jets		• Like-sign • Opposite sign	

Approach

- For many background measurements, we (mostly) do not want to rely on
  - Predicted cross sections (especially for QCD)
  - Predicted kinematical distributions
- Major emphasis on "Data-driven background determinations"
  - Rely on control samples in the data, sometimes with some assistance from Monte Carlo
  - May suffer from limitations (statistical or systematic) that reduce the precision of the measurement. Will evolve rapidly w/more data.

Inclusive Jet + MET reach



- 95% CL exclusion for all-hadronic search (≥ 3 jets + MET + e/μ veto)
- Systematic uncertainty of 50% assumed on Standard Model background
- *Sensitivity significantly beyond previous experiments (~50/pb to surpass Tevatron)*

Hadronic SUSY

$N_{leptons}$=0 : largest signal cross section, but beware of QCD!

Efficiency for e.g. SPS1a: 13%

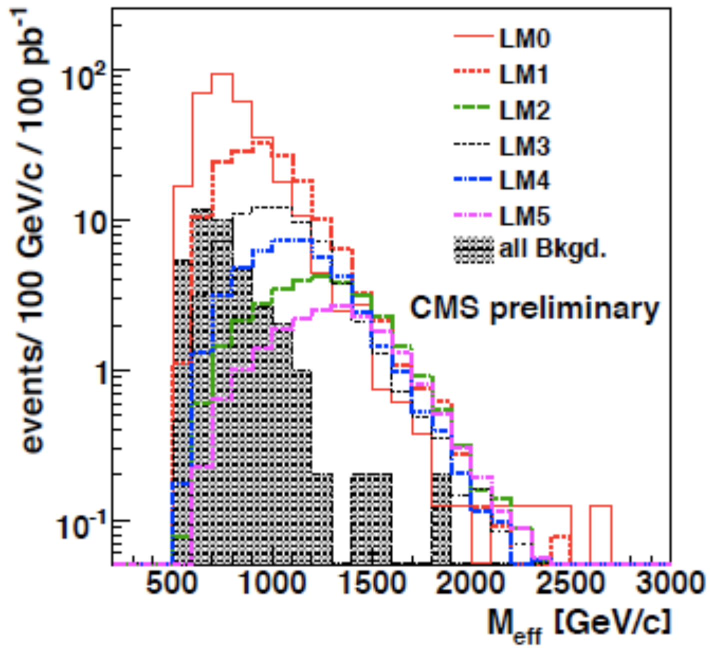
(SPS1a = LM1)

Event Selection:

- MET > 200 GeV
- ≥ 3 jets ($|\eta|$ < 1.7/3/3) with E_T > 180/110/30 GeV
- HT (= $E_{T,j2}+E_{T,j3}+E_{T,j4}$+MET) > 500 GeV
- indirect lepton veto
- cleanup and QCD rejection (see next slide)

Main backgrounds:

- QCD multijets: MET due to mis-measurements or jet resolution
- Z+jets: $Z \rightarrow \nu\nu$ irreducible
- tt+jets: hadronic or lost lepton(s)
- W+jets: hadronic or lost lepton



New variables

CMS PAS SUS-09-001

L. Randall and D. Tucker-Smith, "Dijet Searches for Supersymmetry at the LHC," Phys. Rev. Lett. **101 (2008) 221803.**

- Dijet analysis

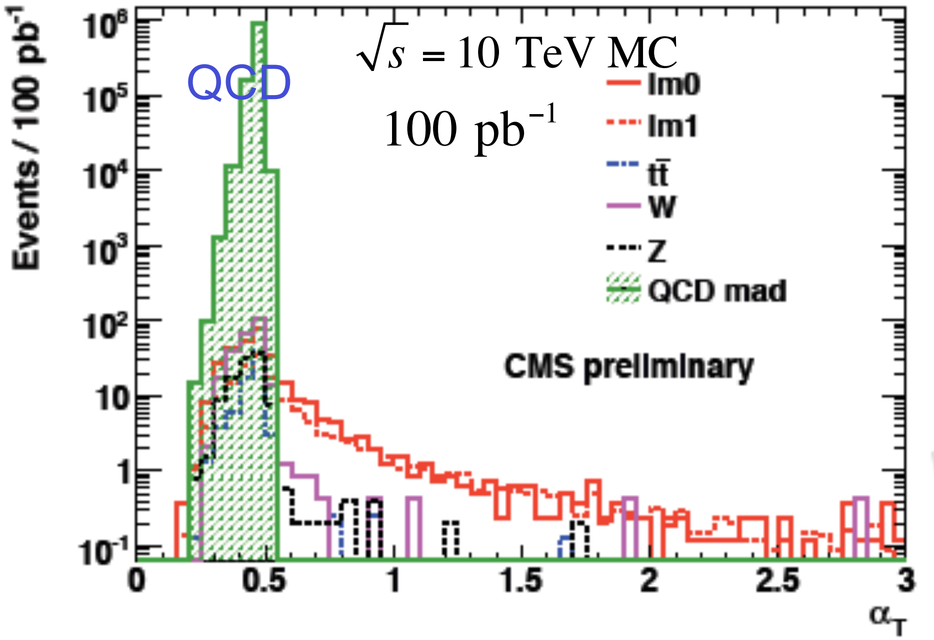
$$\alpha_T \equiv E_T^{j_2} / M_T(j_1 j_2)$$

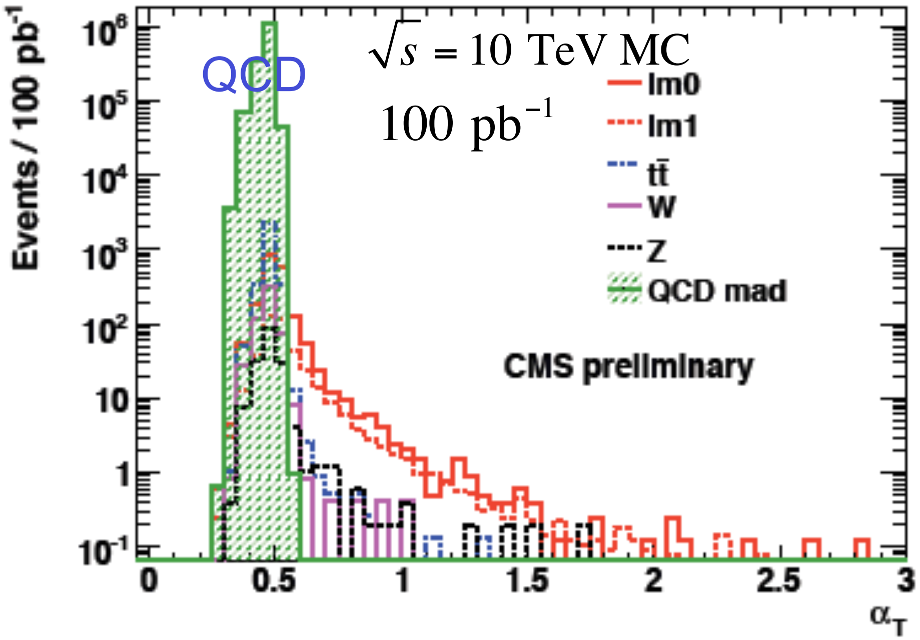
$$= \frac{\sqrt{E_T^{j_2} / E_T^{j_1}}}{\sqrt{2(1-\cos\Delta\varphi)}}$$

- N=3-6 jets: form two pseudo-jets
- minimize

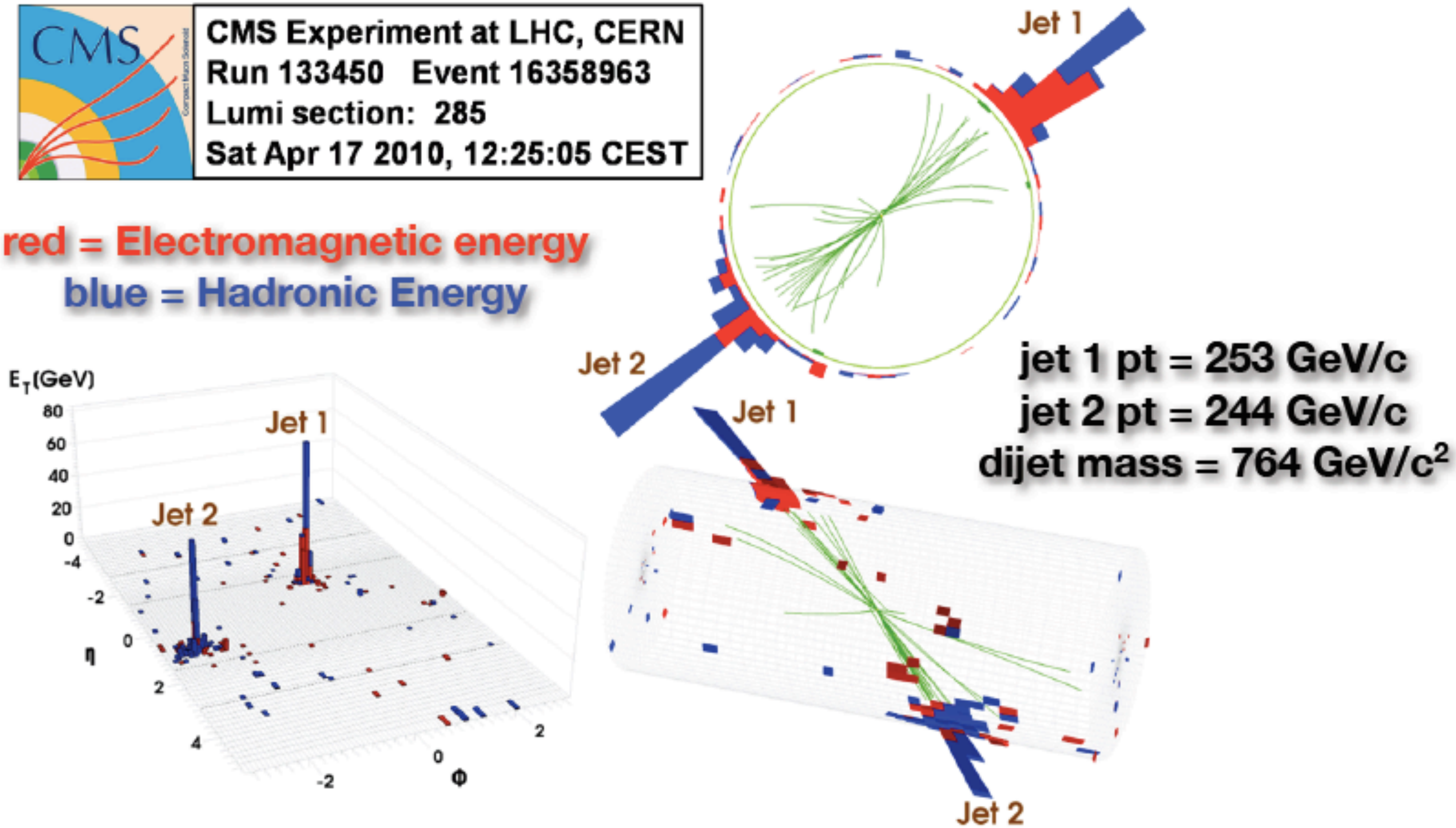
$$\Delta HT = E_T^{pj1} - E_T^{pj2}$$

$$\alpha_T \equiv \frac{1}{2}\frac{HT - \Delta HT}{\sqrt{HT^2 - MHT^2}}$$



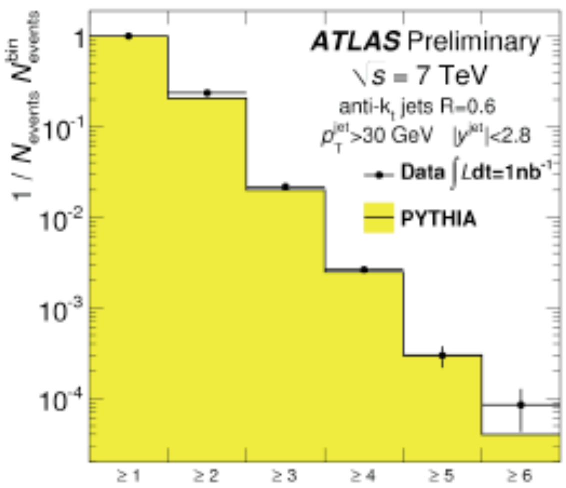


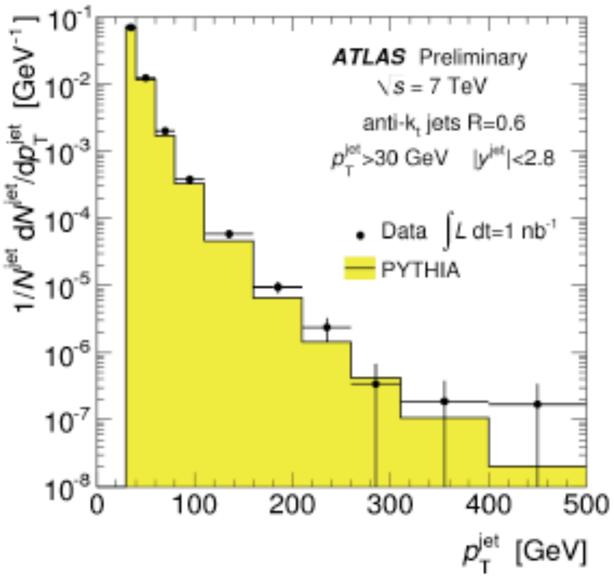
Di-jets

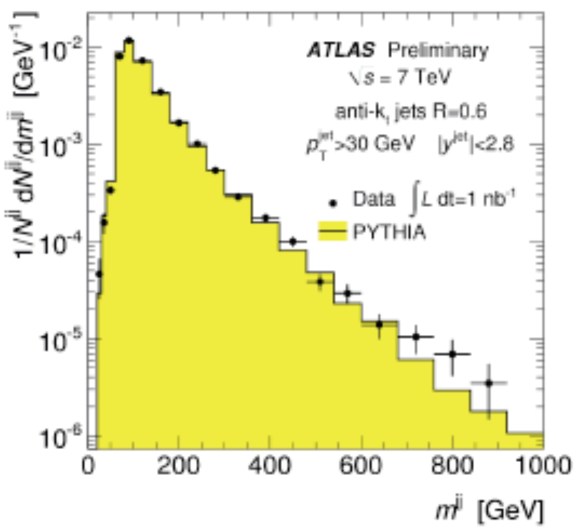


E_T of calorimeter energies in η-Φ space (left) and r-Φ space (right)
Jets reconstructed with anti-k_T algorithm (ΔR=0.7)

Jets in ATLAS





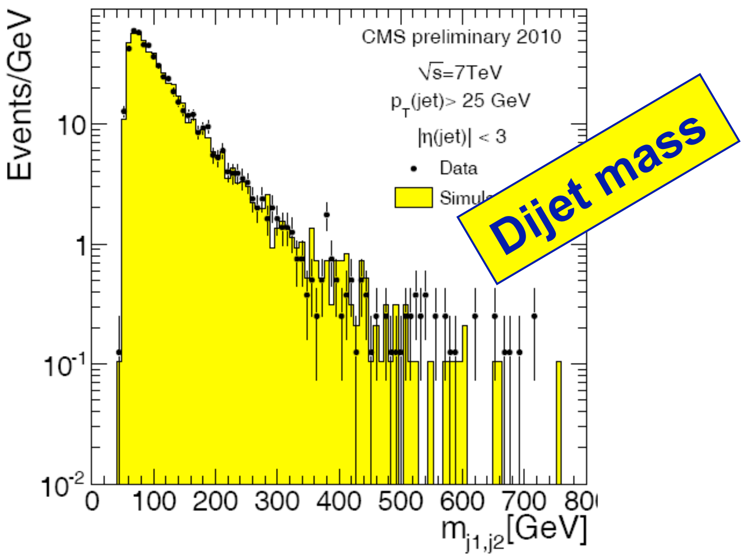


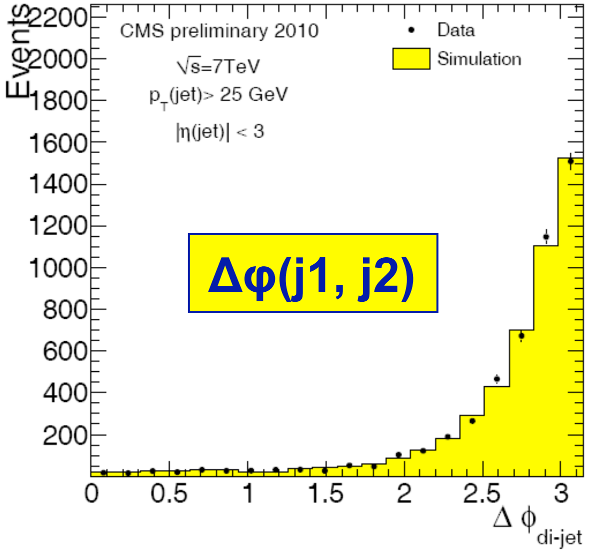
Observed inclusive jet multiplicity distribution (top left plot- black dots), inclusive p_T distribution for jets with $p_T > 30$ GeV and $|y| < 2.8$ (top right plot) and jet-jet mass distributions, compared to PYTHIA Monte Carlo prediction (yellow histogram).

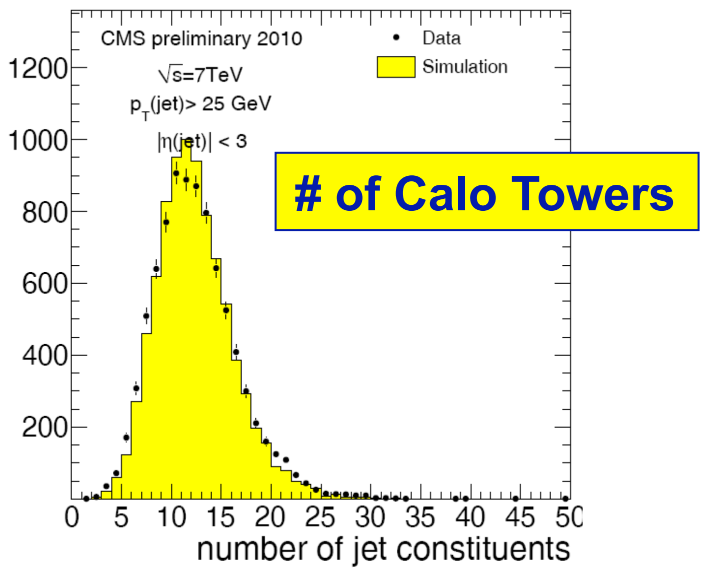
The distributions are normalized to unity and only statistical uncertainties are included.

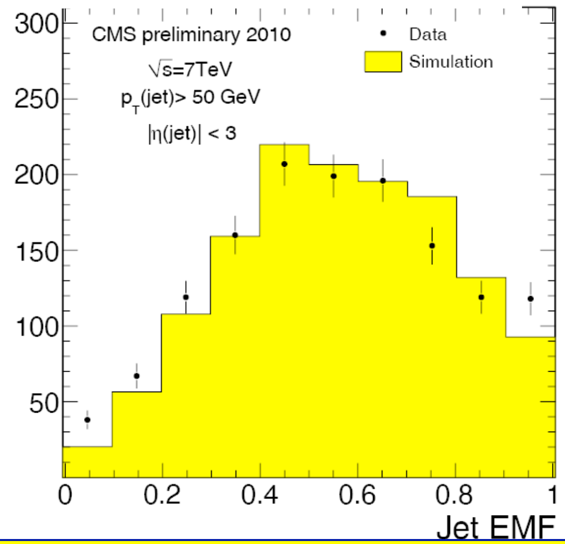
11

Jets in CMS



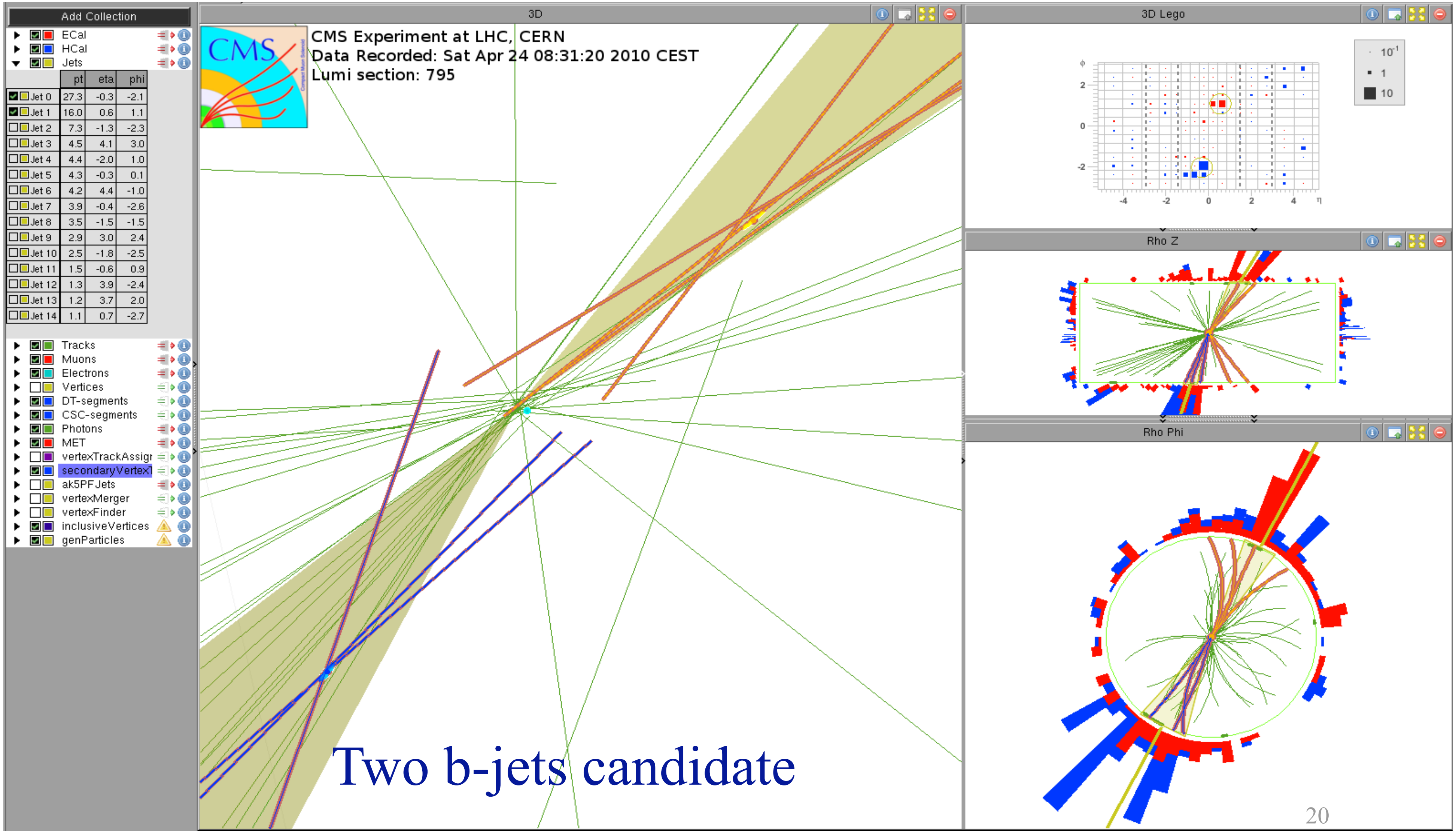






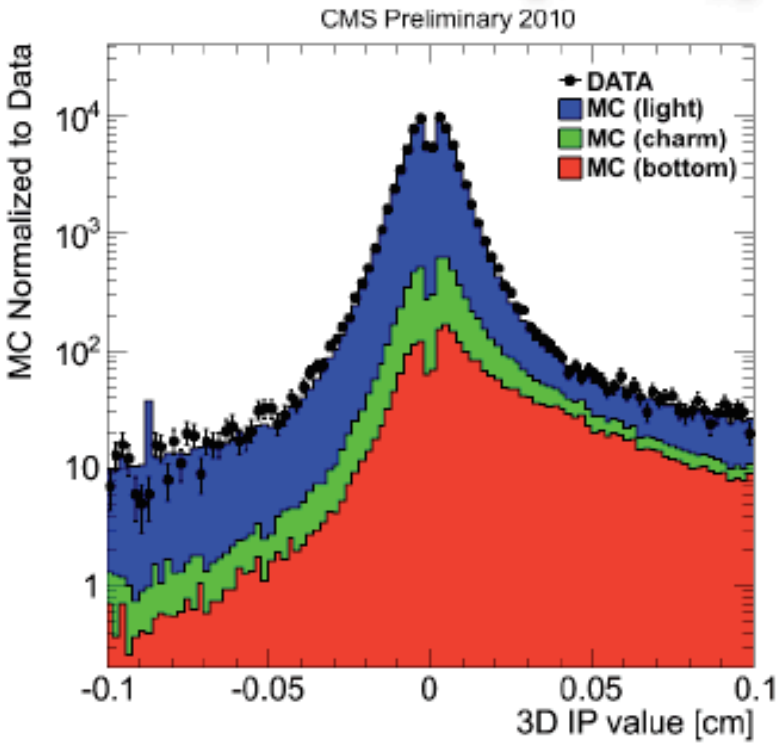
Fraction of EM energy in Calo-Jets

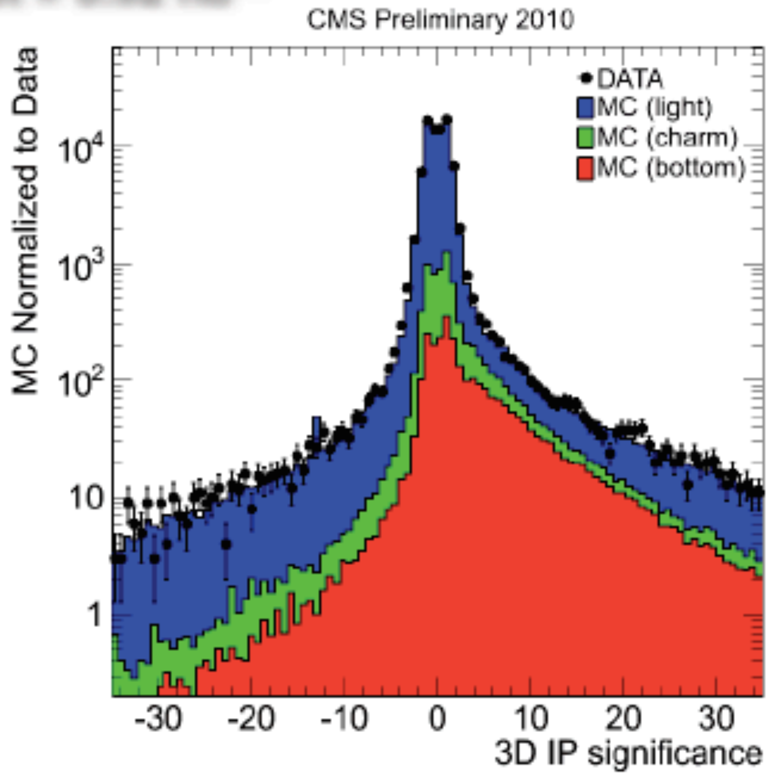
b-jets


Add Collection
ECal
HCal
Jets
pt eta phi
Jet 0 27.3 -0.3 -2.1
Jet 1 16.0 0.6 1.1
Jet 2 7.3 -1.3 -2.3
Jet 3 4.5 4.1 3.0
Jet 4 4.4 -2.0 1.0
Jet 5 4.3 -0.3 0.1
Jet 6 4.2 4.4 -1.0
Jet 7 3.9 -0.4 -2.6
Jet 8 3.5 -1.5 -1.5
Jet 9 2.9 3.0 2.4
Jet 10 2.5 -1.8 -2.5
Jet 11 1.5 -0.6 0.9
Jet 12 1.3 3.9 -2.4
Jet 13 1.2 3.7 2.0
Jet 14 1.1 0.7 -2.7
Tracks
Muons
Electrons
Vertices
DT-segments
CSC-segments
Photons
MET
vertexTrackAssign
secondaryVertex
ak5PFJets
vertexMerger
vertexFinder
inclusiveVertices
genParticles
3D
CMS Experiment at LHC, CERN
Data Recorded: Sat Apr 24 08:31:20 2010 CEST
Lumi section: 795
3D Lego
Rho Z
Rho Phi
Two b-jets candidate
20

B-tagging

$\sqrt{s}$=7 TeV, $\int Ldt$ = 0.92 nb^{-1}



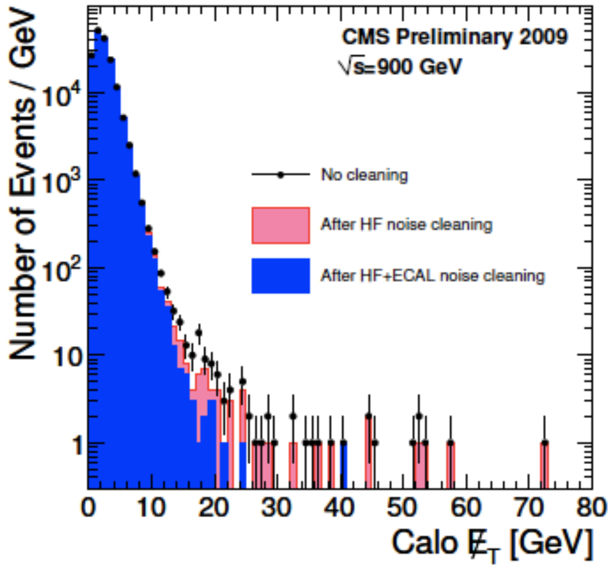


3D impact parameter value (left) and significance (right) for all tracks with p_T>1 GeV/c associated with jets with p_T > 40 GeV/c and |η| < 1.5

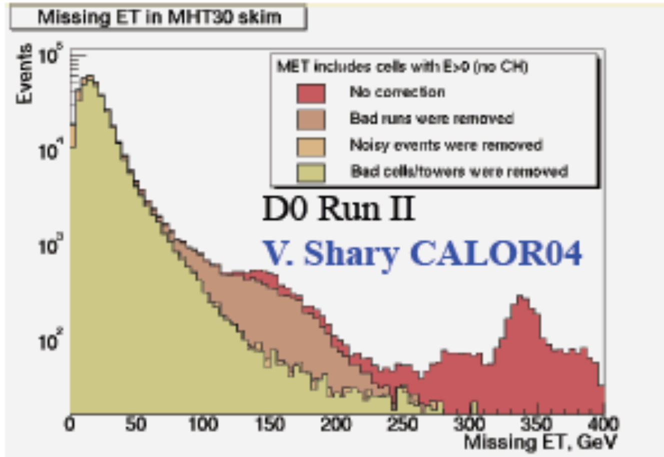
The MET challenge

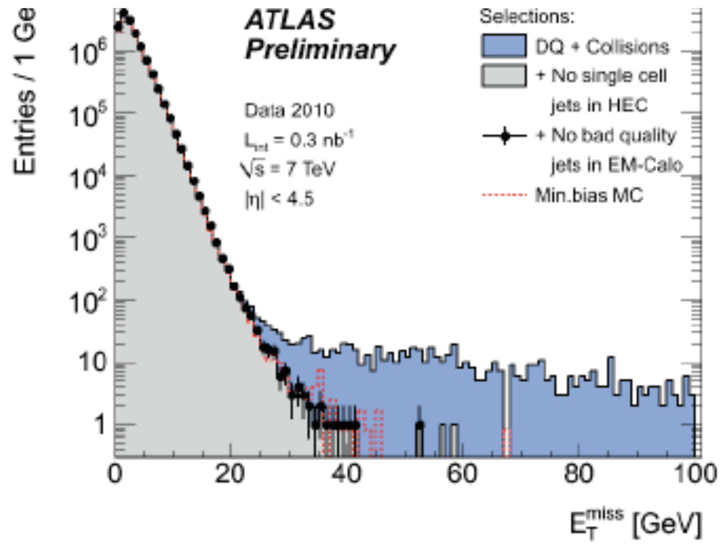
Sources of instrumental noise:

* readout discharge
* electronics noise
* beam halo muons
* cosmics, …

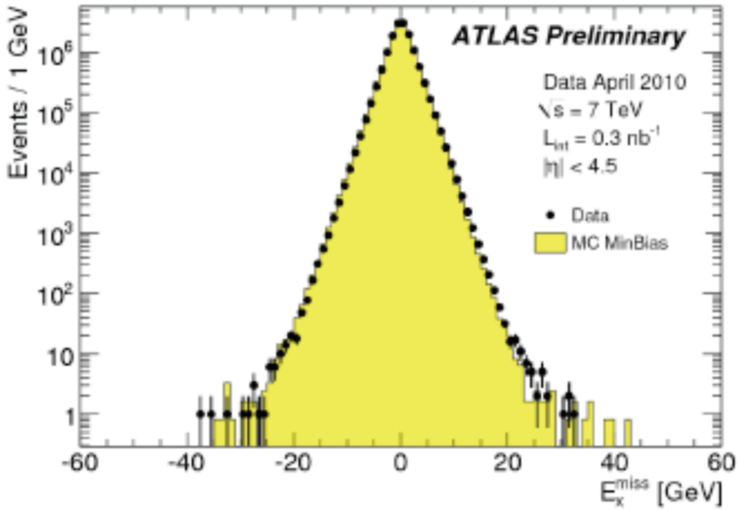


Our expectations from Tevatron:



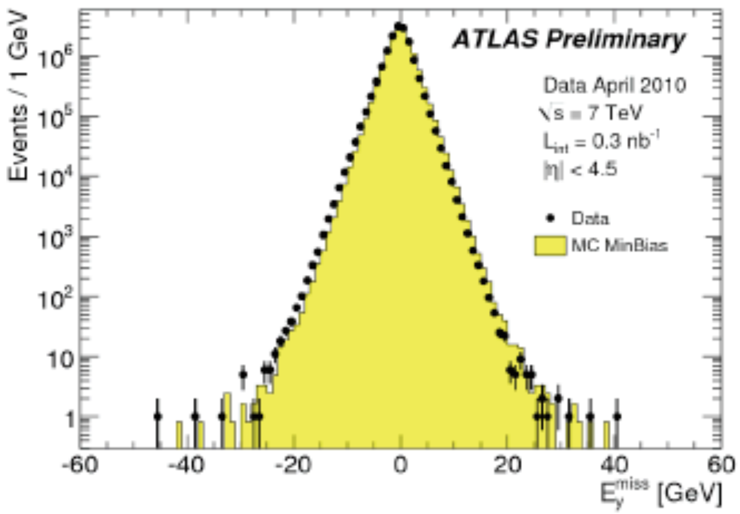


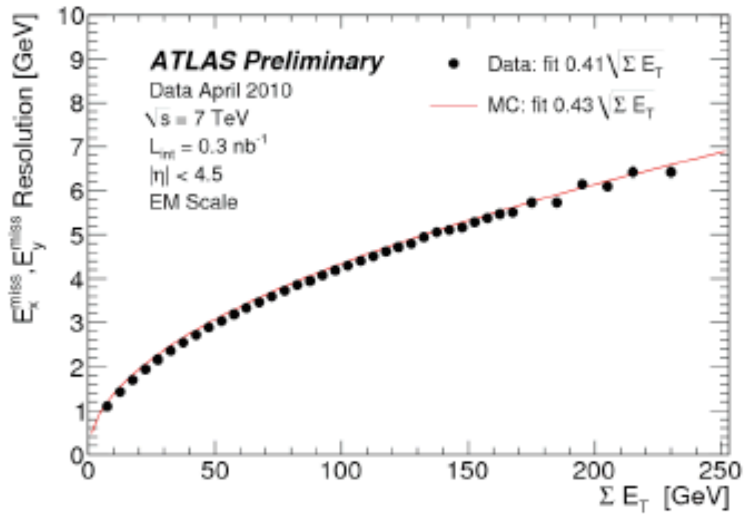
MET in ATLAS



Distribution of E_T^{miss} (x,y) as measured in a data sample of 14.4 million selected minimum bias events (dots) at 7 TeV center-of-mass energy, recorded in April 2010

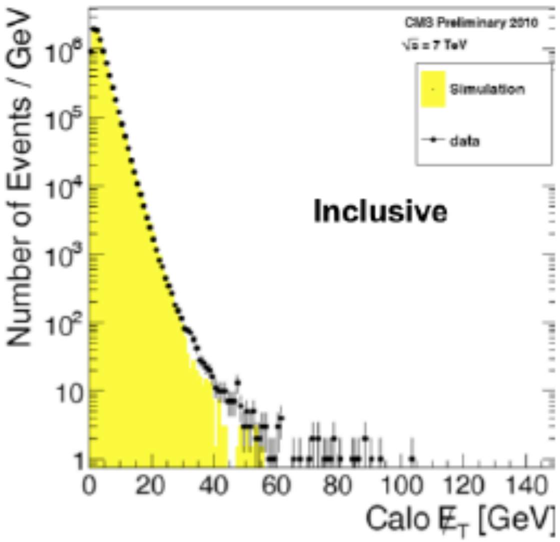
E_T^{miss} (x,y) resolution as a function of the total transverse energy (Sum E_T) for minimum bias events. The line represents a fit to the resolution obtained in the Monte Carlo simulation and the full dots represent the results from data taken √s= 7 TeV.



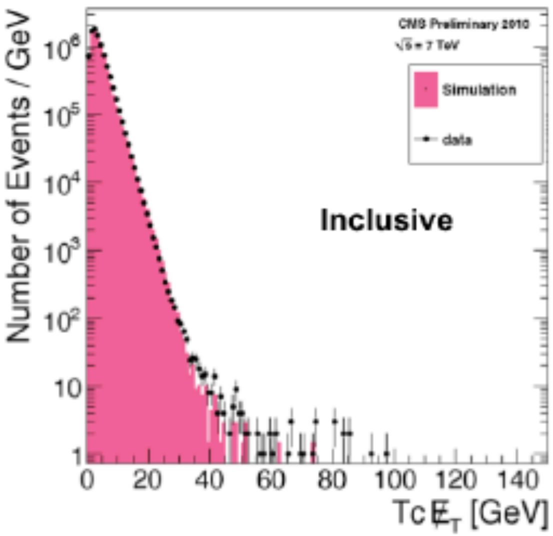


MET in CMS

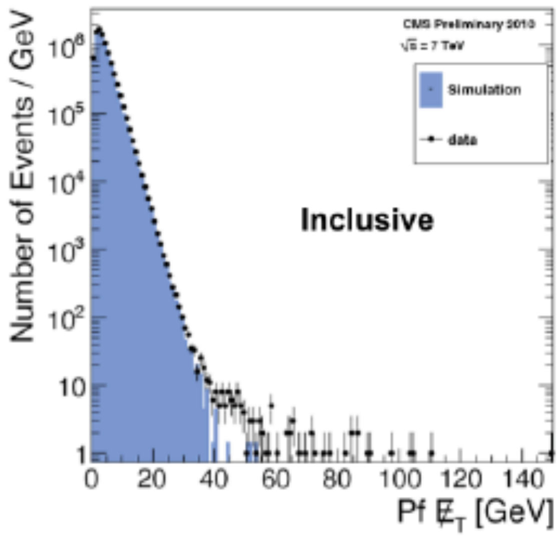
Calorimeter



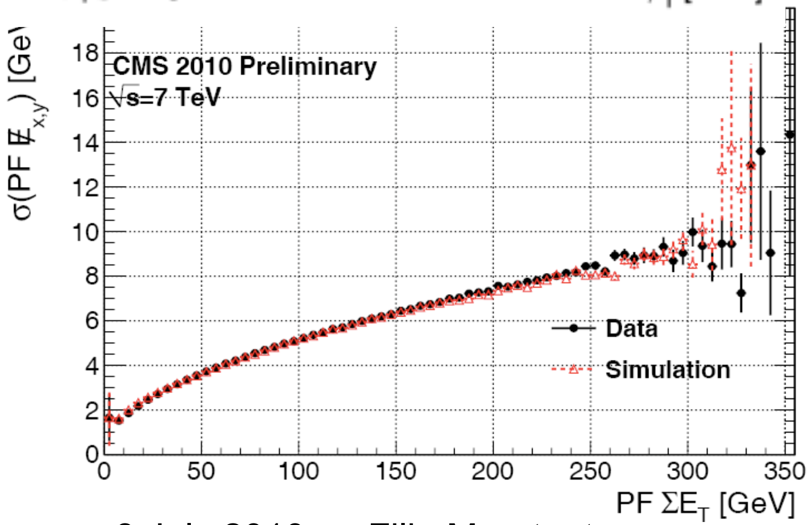
Calorimeter + Tracks



Particle Flow

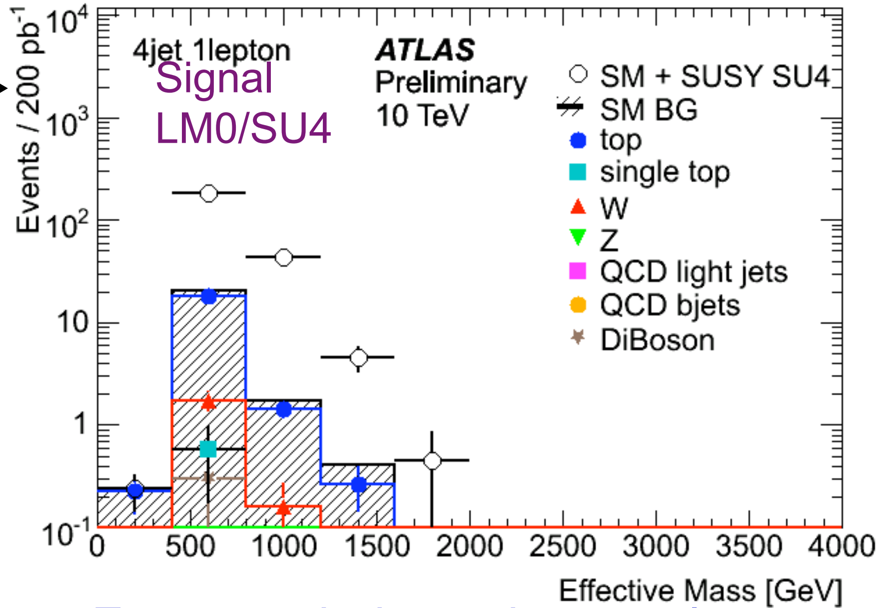


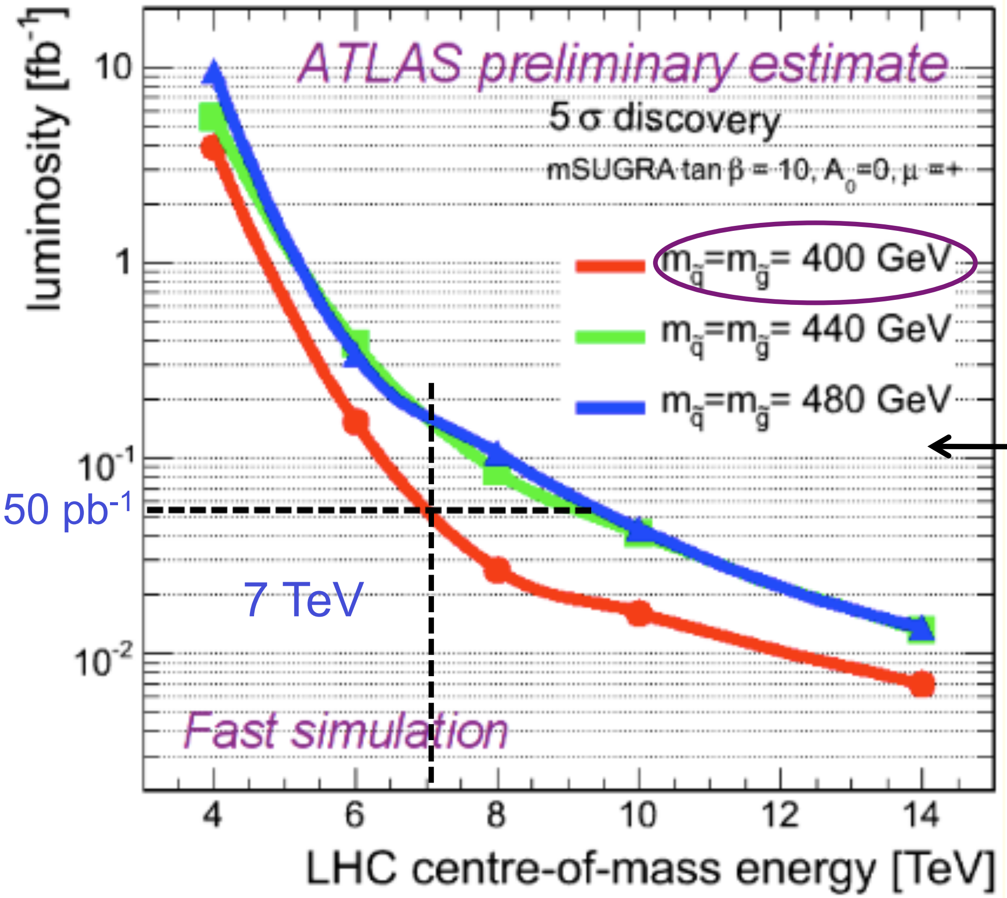
In CMS, particle flow techniques significantly improve the purely calorimetric MET



1 lept + jet + MET

Example: 200 pb^{-1} @10 TeV
(~ 700 pb^{-1} @ 7 TeV)



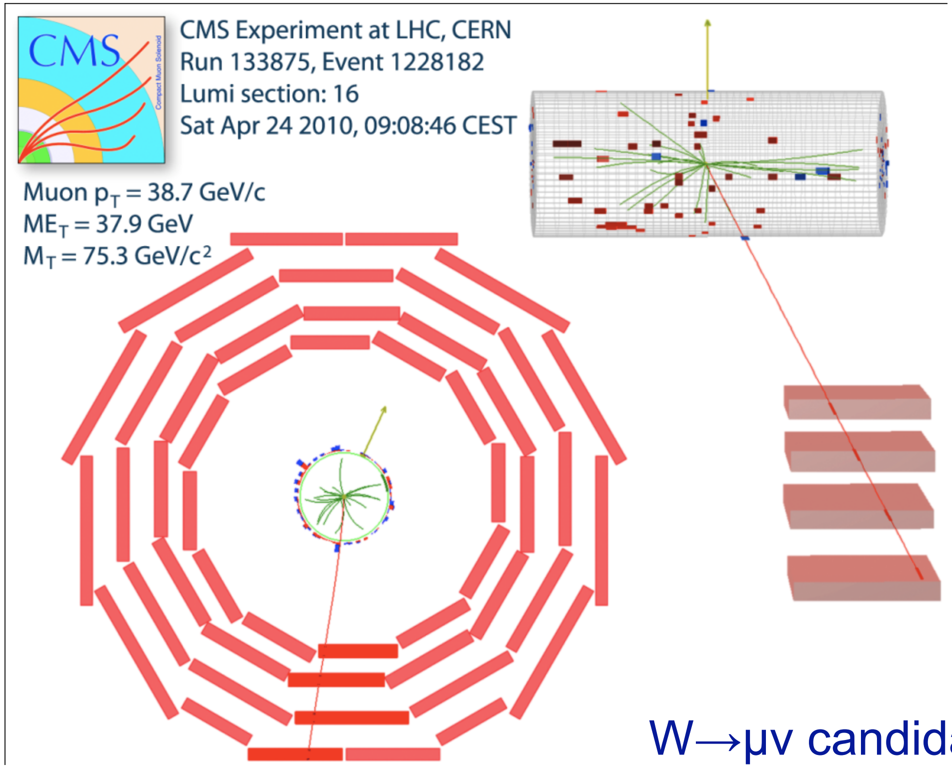


- Exact reach depends strongly on assumed systematic – here 100%
- Discovery sensitivity beyond Tevatron from 50 pb^{-1} onwards.
- Channels combined discovery up to squark masses of ~750 GeV with 1 fb^{-1}

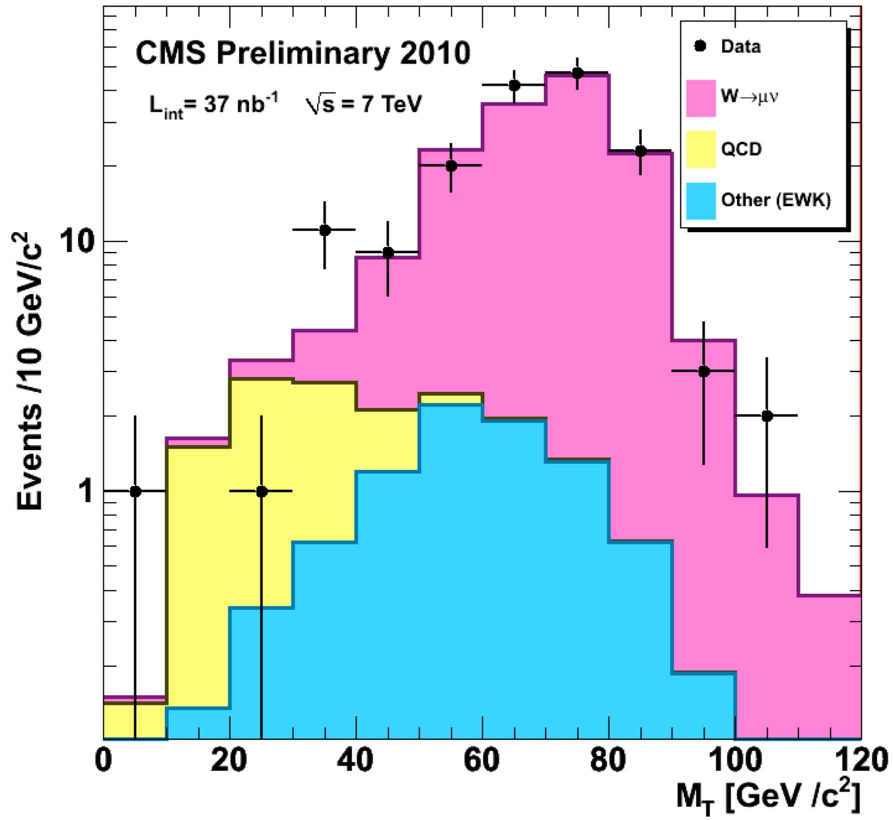
W± →μ±ν observation

- Event selection:
  - ➢ Muon id cuts
  - ➢ Isolation, p_T and MET cuts
- Monte Carlo: Event count normalized to integrated luminosity

37 nb^{-1}

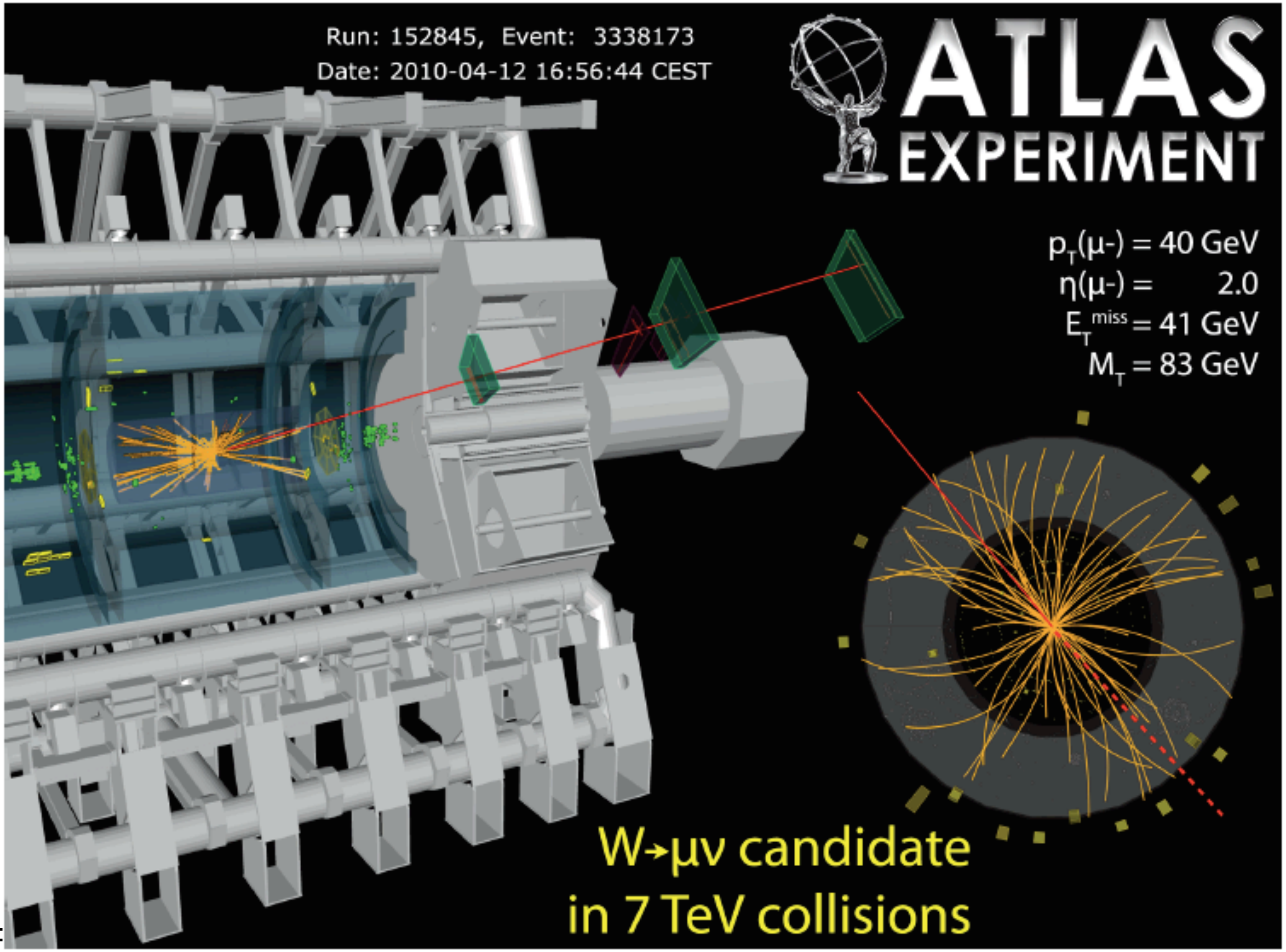


W→μν candidate



# of candidate (M_T > 50 GeV) = 137
# of expected signal (M_T > 50 GeV) = 128
# of expected background (M_T > 50 GeV) = 7

W candidate in ATLAS

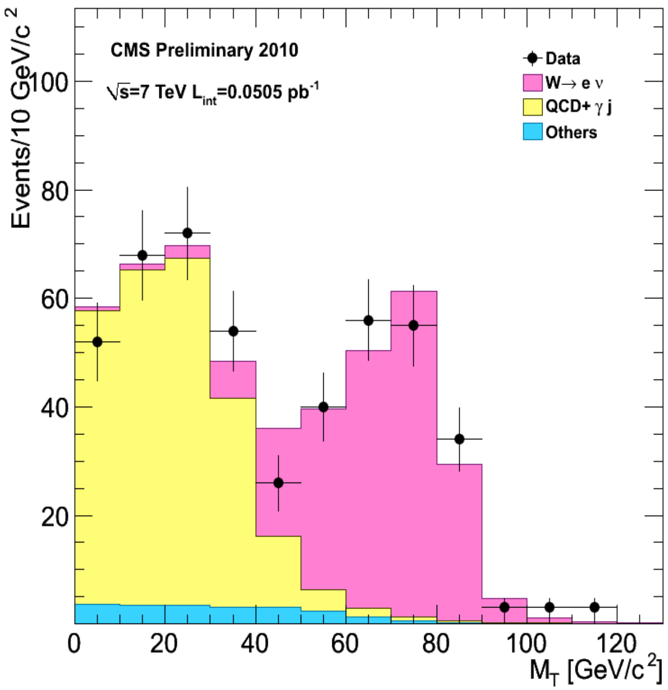


W± →e±ν observation

51 nb^{-1}

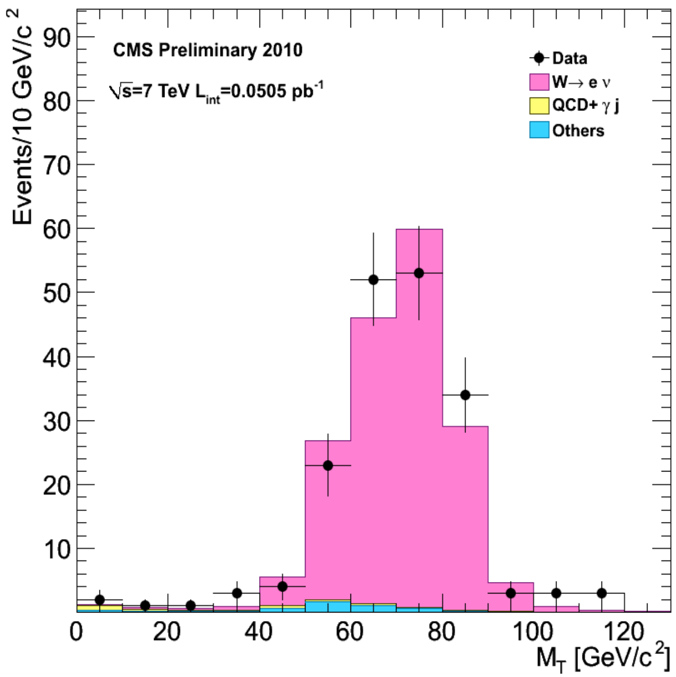
Two event selections:

- Basic electron ID, no MET cuts



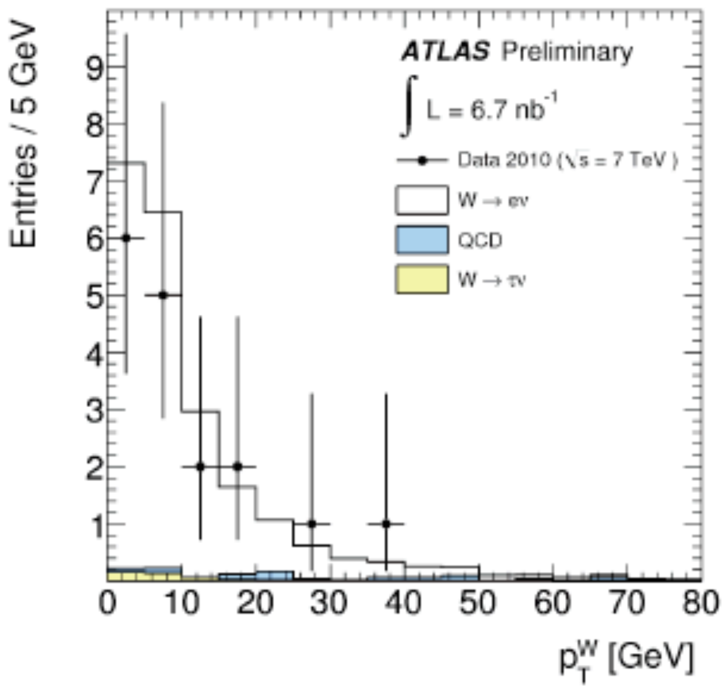
196 candidates with M_T > 50 GeV
MC: Sig =176, Bkg =11

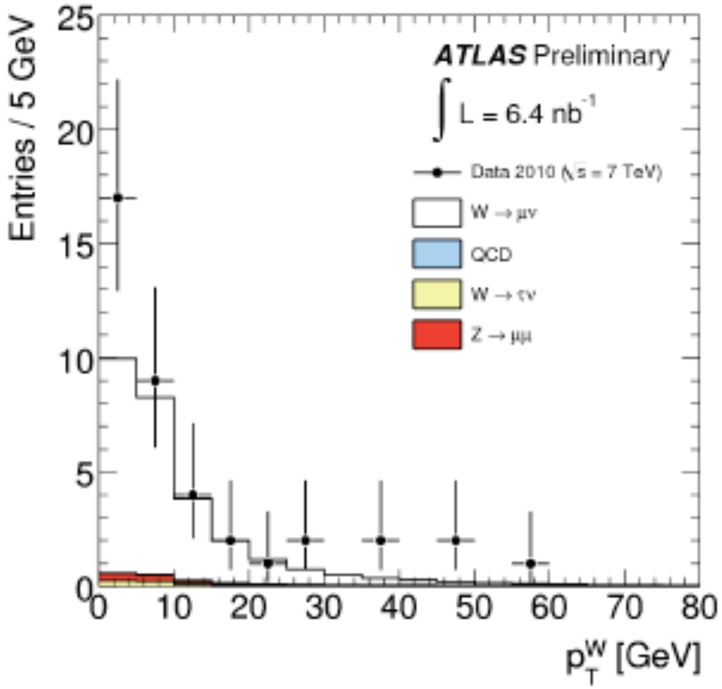
- More advanced electron ID, cuts on E_T, MET, ΣE_T



173 candidates with M_T > 50 GeV
MC: Sig=163, Bkg=5

W properties





Electron channel:
17 candidates
11 W+
6 W-

Muon channel:
40 candidates
25 W+
15 W-

SM W+/W- ~ 1.4

2l OS SUSY

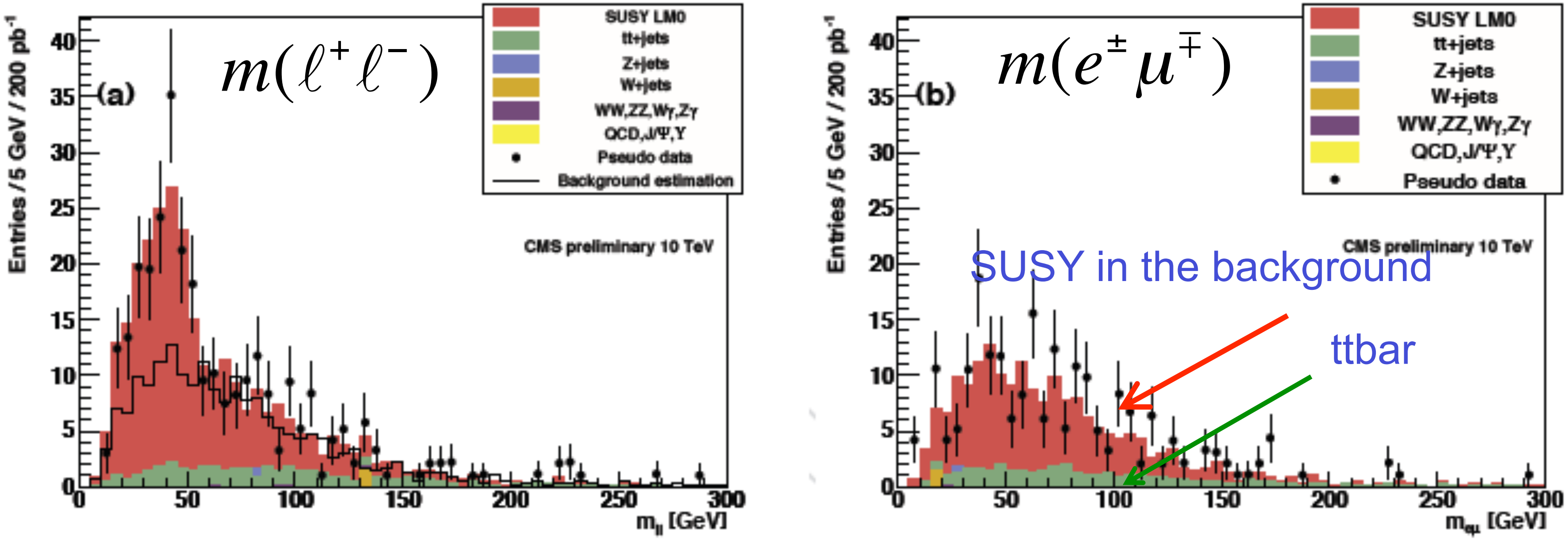
- Traditional approach: search for opp. sign, same flavor leptons from correlated SUSY production:

$$\tilde{\chi}_2^0 \rightarrow \ell^+ \tilde{\ell}^-; \quad \tilde{\ell}^- \rightarrow \ell^- \tilde{\chi}_1^0$$

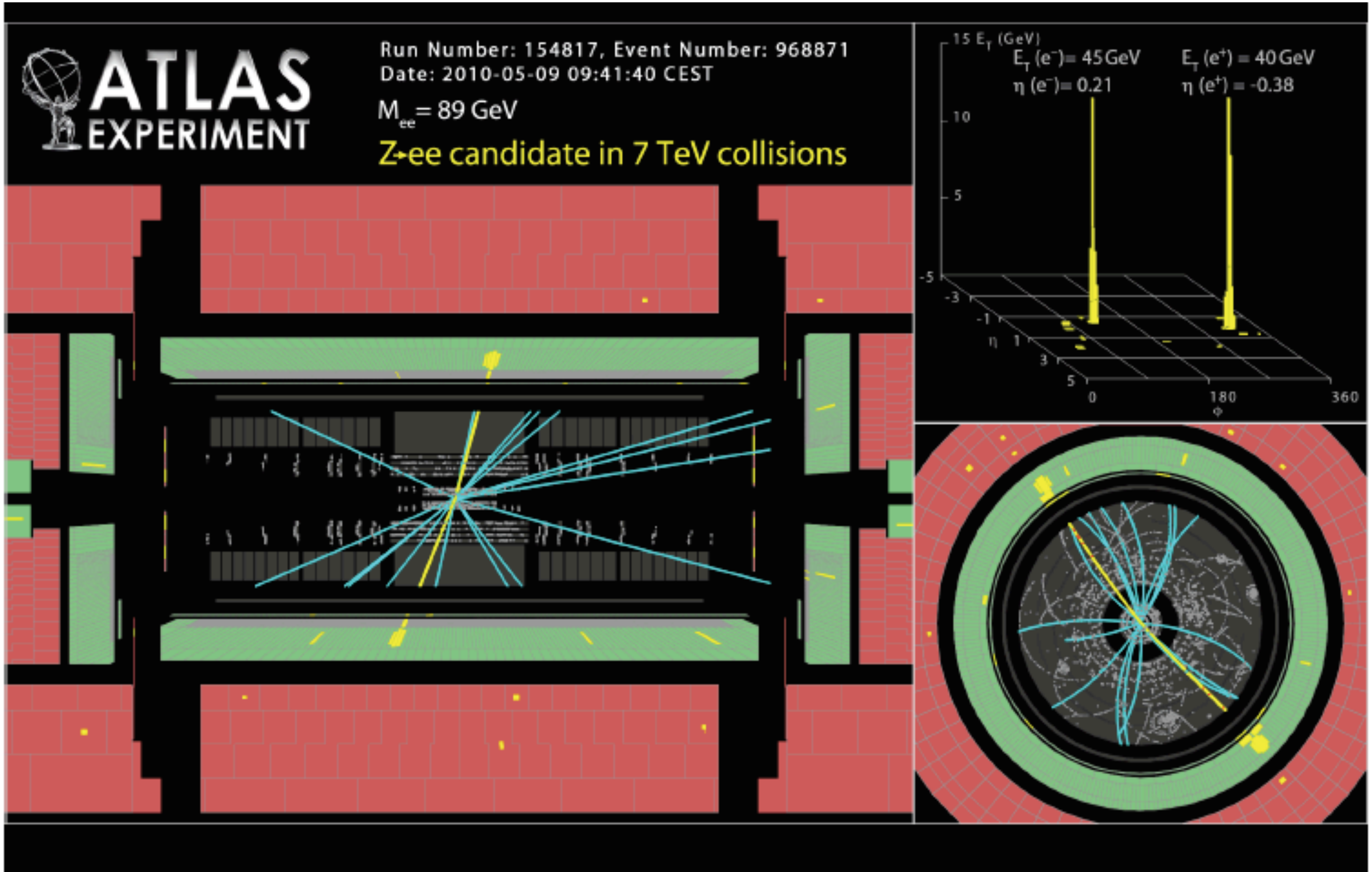
slepton on-shell: seq. 2-body decays
slepton off-shell: 3-body decay

- Background estimations from eμ control sample.

Same flavor; opposite sign leptons | Opposite flavor; opposite sign leptons



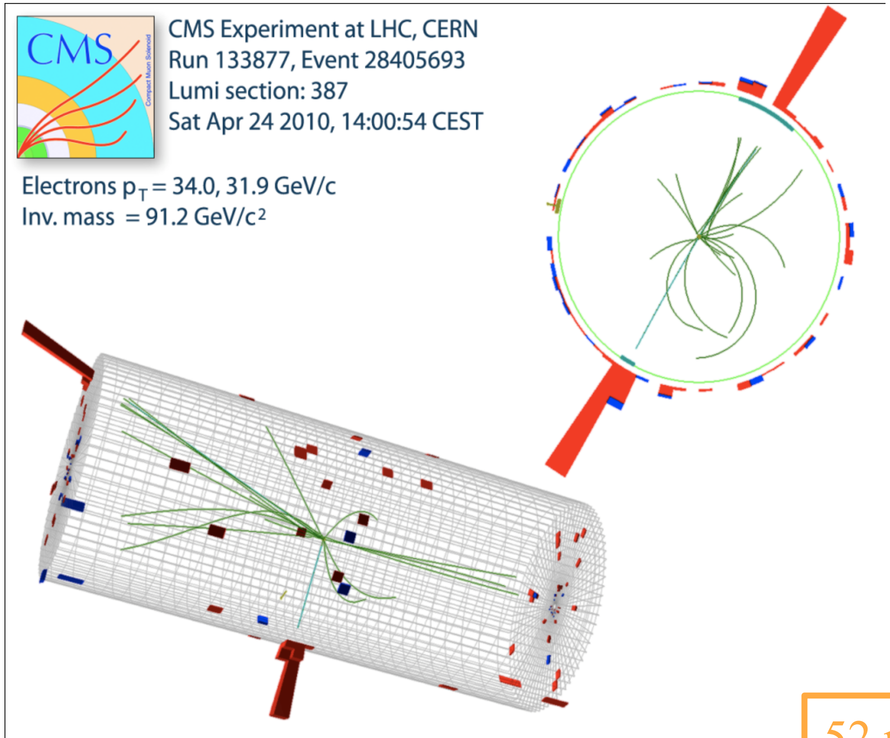
Z candidate



ATLAS EXPERIMENT
Run Number: 154817, Event Number: 968871
Date: 2010-05-09 09:41:40 CEST
M_ee = 89 GeV
Z→ee candidate in 7 TeV collisions
E_T (e⁻)= 45 GeV
η (e⁻)= 0.21
E_T (e⁺) = 40 GeV
η (e⁺) = -0.38

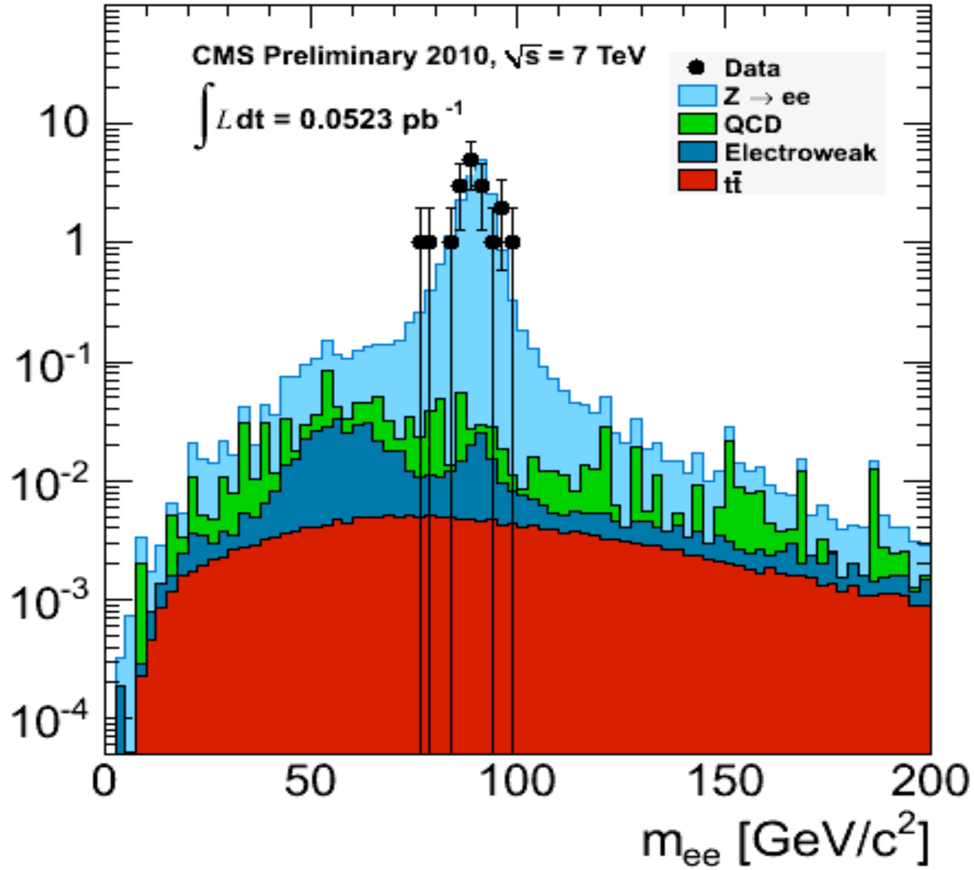
Z →e+e− observation

- Event selection:
  - ➢ Two electrons with $E_T > 20$ GeV
- Monte Carlo: Event count normalized to integrated luminosity



Z→ee candidate

52 nb^{-1}

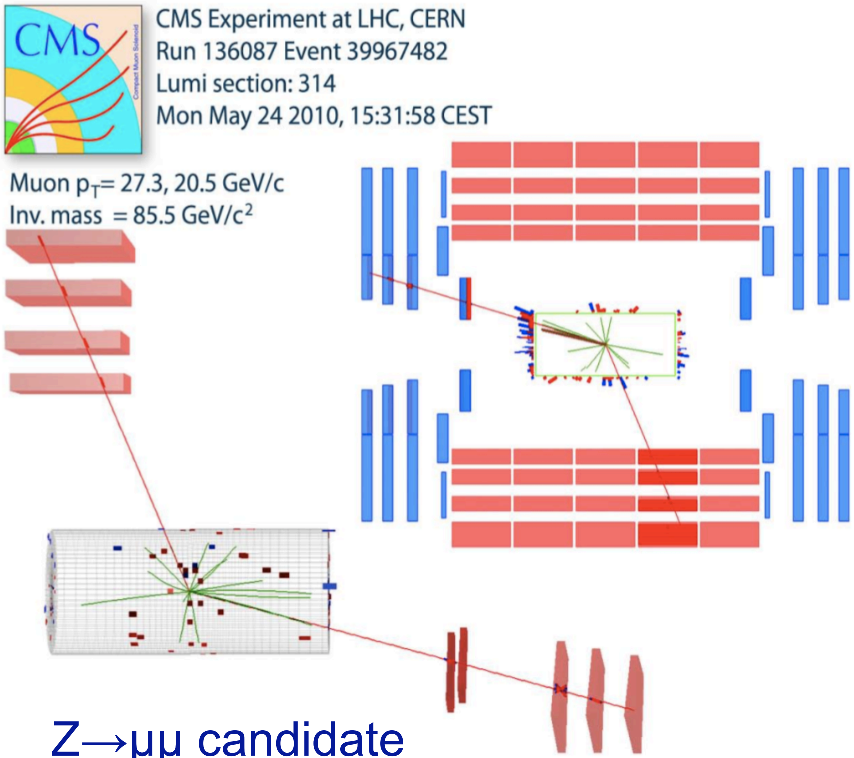


#of candidate = 18
#of expected signal = 19
#of expected background = 0.8

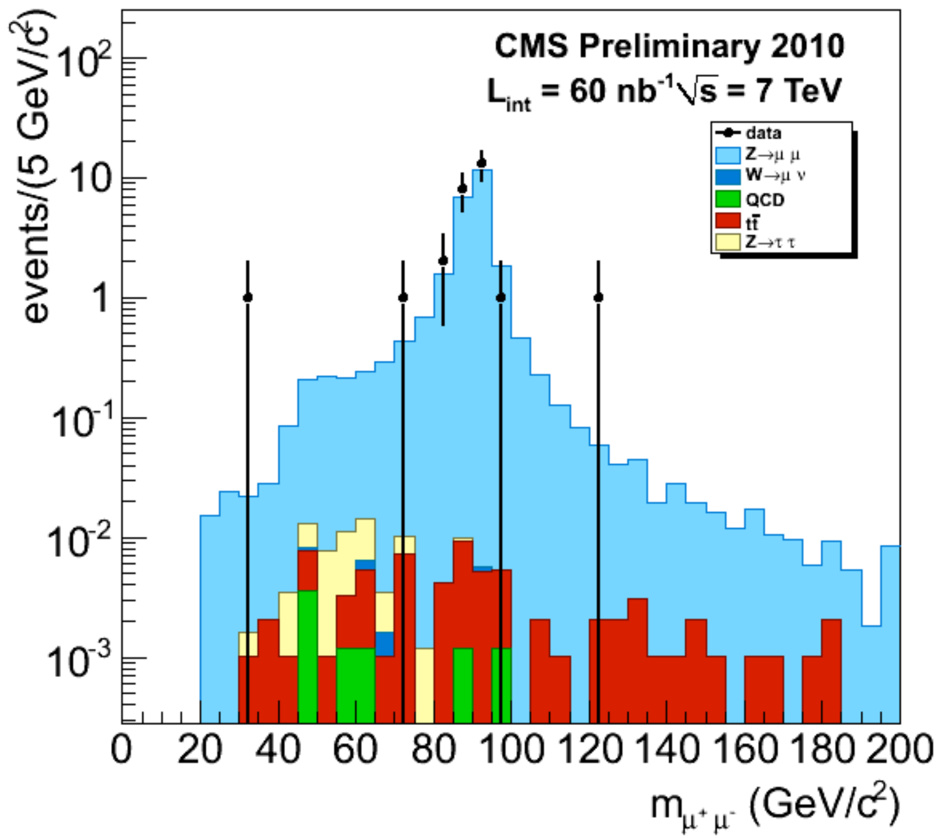
$Z \rightarrow \mu^+\mu^-$ observation

- Event selection:
  - ➢ Muon id cuts
  - ➢ Loose isolation, p_T cuts
- Monte Carlo: Event count normalized to integrated luminosity

60 nb^{-1}



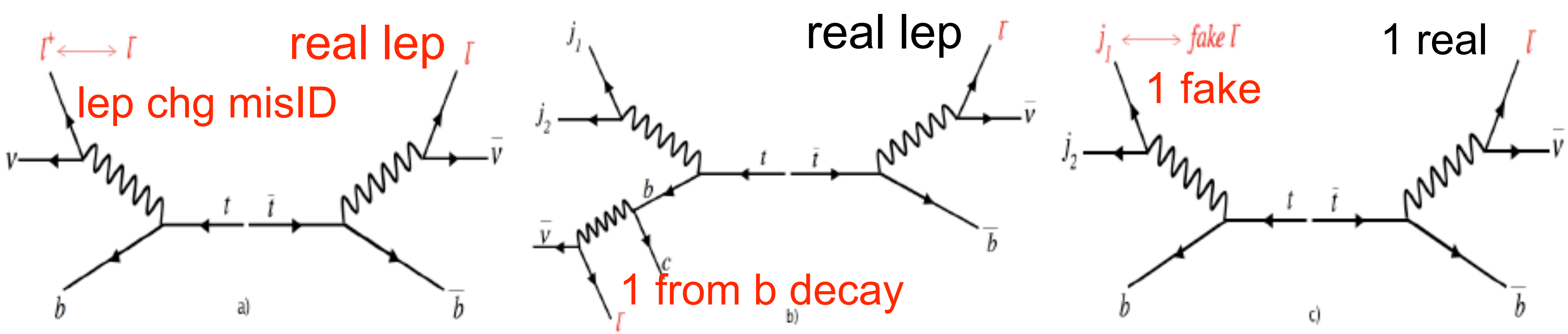
Z→μμ candidate



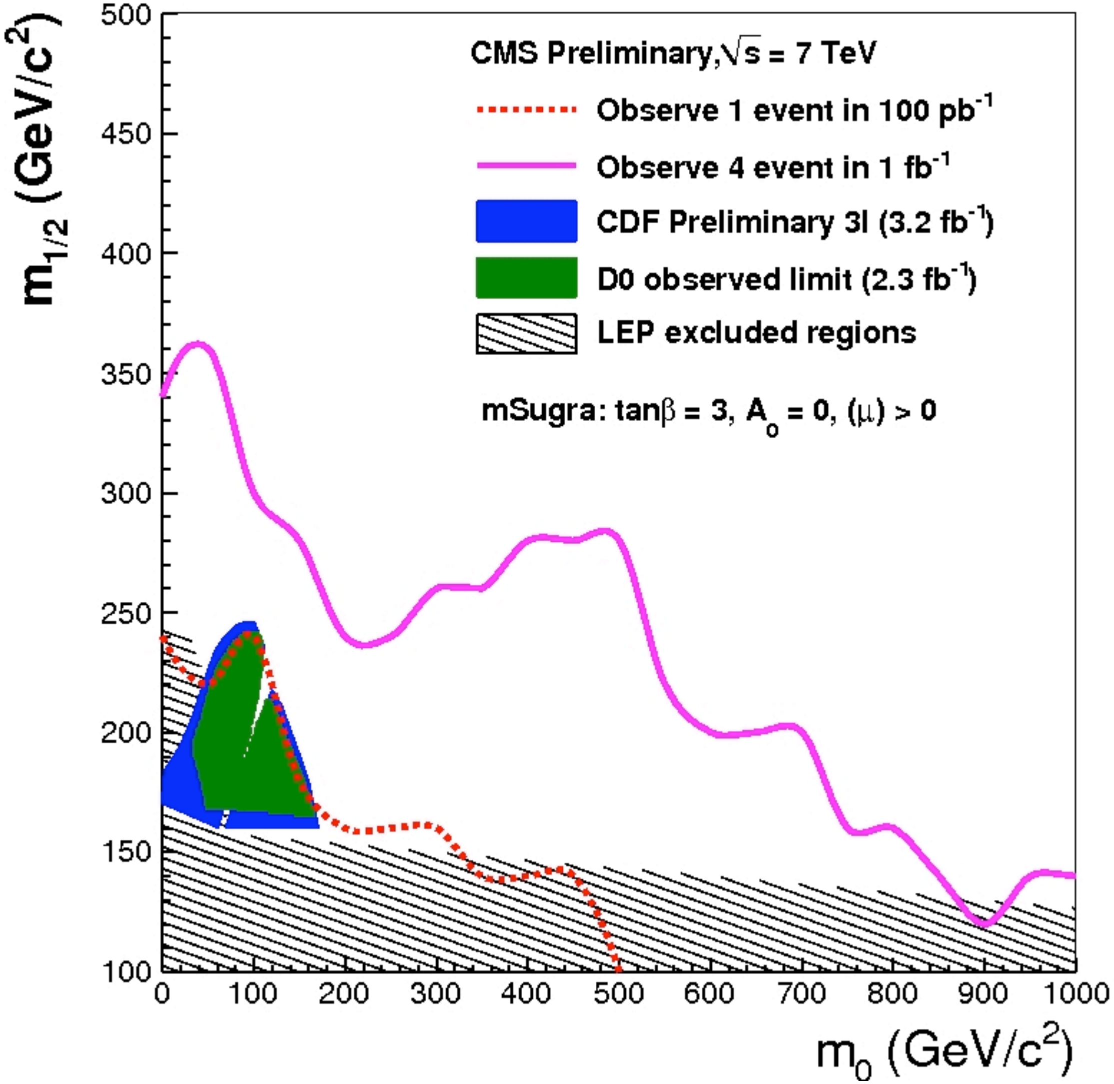
#of candidate = 25
#of expected signal = 24.7
#of expected background = 0.08

SS dileptons

Classic SUSY signature; very low SM background.
Reliable data-driven background estimate is critical.
Basic cuts: ee/eμ/μμ with pT>10, pT>20 GeV
≥3 jets ET>30; SumET(jets)>200 GeV
MET>80 GeV
Key issues: fake leptons & electron charge misID
Largest background: ttbar



SS dileptons



DM properties @ LHC

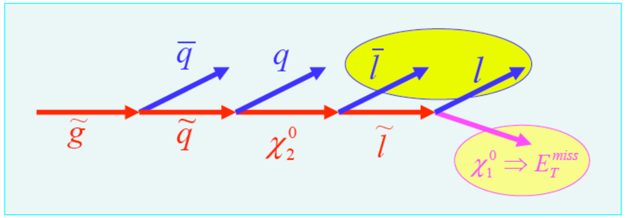
Courtesy of K. Matchev

Missing momenta reconstruction?	Mass measurements: Inclusive	Mass measurements: 2 symmetric chains	Spin measurements
None	Inv. mass endpoints and boundary lines		Inv. mass shapes
	M_{eff}, M_{est}, H_T	Wedgebox	
Approximate	S_{min}, M_{Tgen}	$M_{T2}, M_{2C}, M_{3C}, M_{CT}, M_{T2}(n,p,c)$	As usual (MAOS)
Exact	?	Polynomial method	As usual

pessimism → optimism (down the rows)

pessimism → optimism (across the columns)

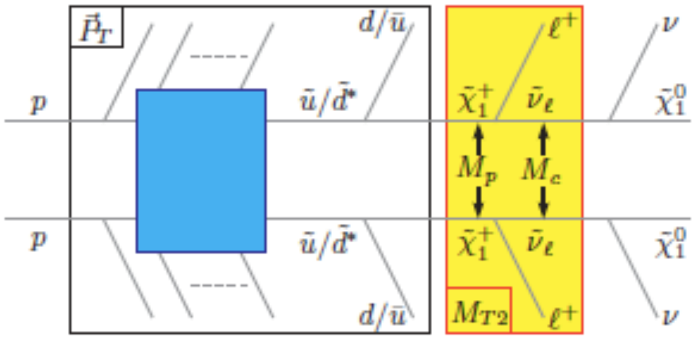
Mass reconstruction



- Kinematic endpoint technique (classic)
- More recent: polynomial method (2003), wedgebox (2003), kink in MT2 distribution (2008)

Example of new method for sparticle reconstruction @ the LHC:

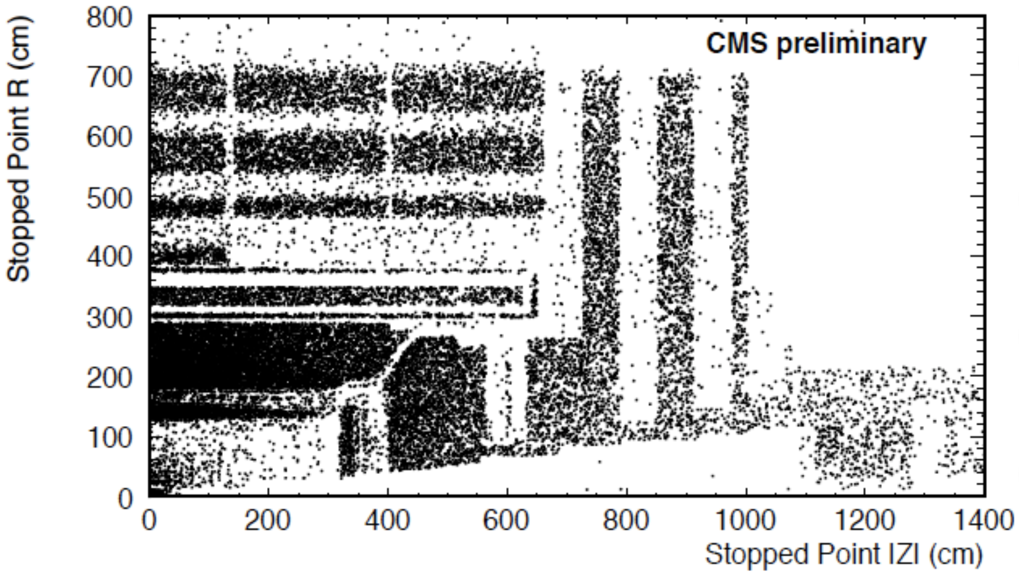
- *Precision sparticle spectroscopy in the inclusive same-sign dilepton channel at LHC,* K. Matchev, F. M., L. Pape, M. Park, hep-ph 0909.4300



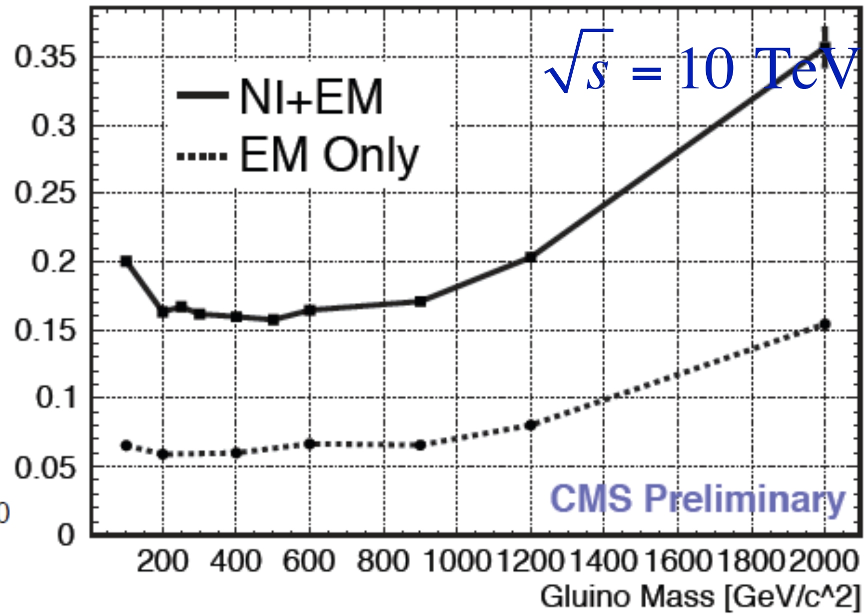
Stopped gluinos

CMS PAS EXO-09-001

Where do R-hadrons stop?



R-hadron stopping efficiency

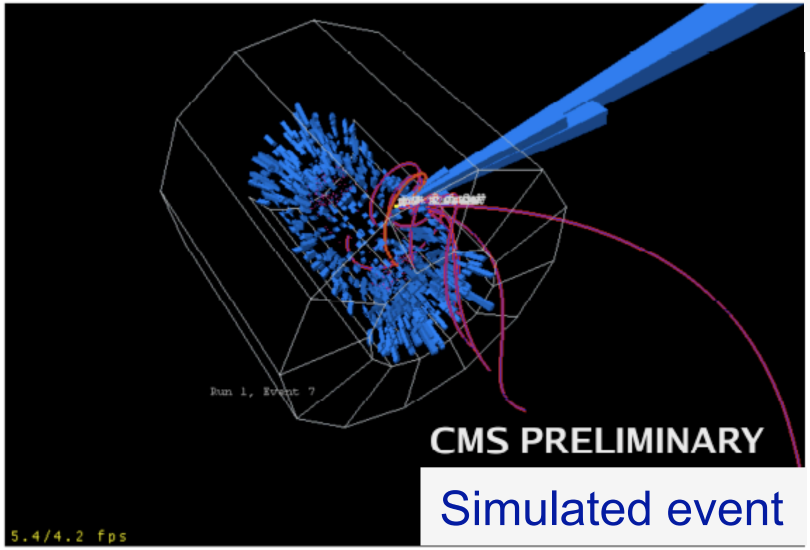


- Offline analysis based on hadronic calorimeter (HCAL) energy deposit, shower shape, and pulse shape.
- Trigger efficiency: 31.8%. Efficiency after all cuts: 16.4% of stopped gluinos.

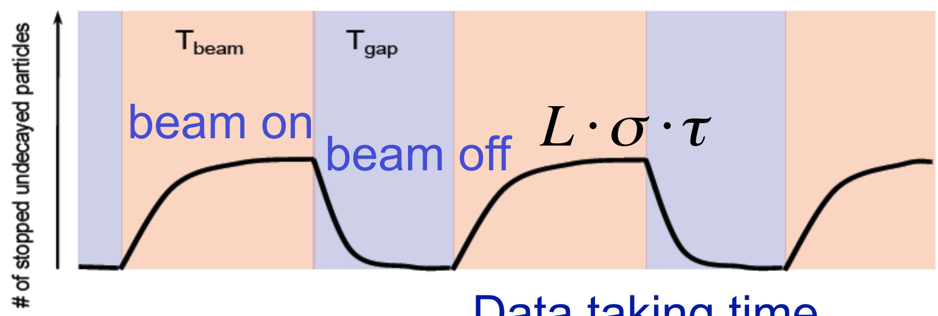
$$\sqrt{s} = 10\ \text{TeV}, m(\tilde{g}) = 300\ \text{GeV}, m(\chi_1^0) = 50\ \text{GeV}$$

Stopped gluinos (2)

CMS PAS EXO-09-001



Num stopped undecayed particles



$$\frac{S}{\sqrt{B}} \propto \frac{L \cdot t}{\sqrt{t}} \propto L\sqrt{t} \qquad t_{5\sigma} \propto L^2$$

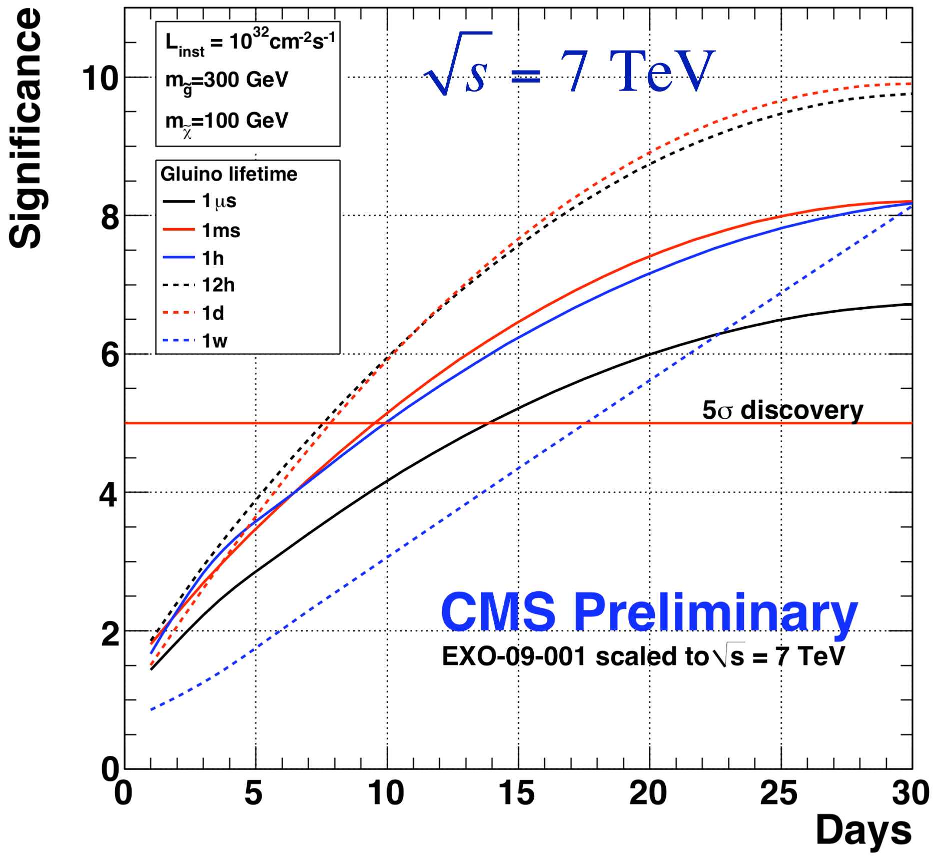
- Trigger: calorimeter (HCAL) energy + out of LHC collision times (beam gaps+interfill periods). Use coincidence of beam pick-up monitors upstream of CMS to veto pp.
- Dominant background: cosmic rays+instrumental noise (both studied during extensive CMS cosmic ray running in 2008-2009). $R_{background} \approx 4 \times 10^{-4}$ Hz.

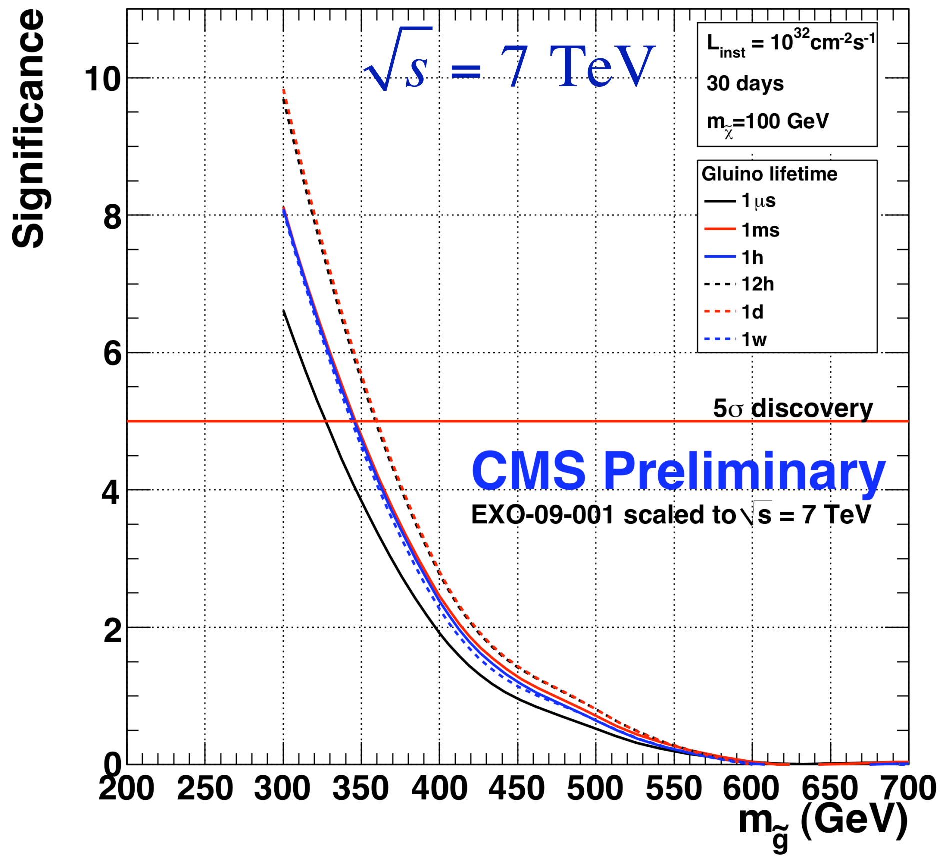
Stopped gluinos (3)

Significance vs. running time
for various gluino lifetimes

CMS PAS EXO-09-001 scaled from 10 TeV →7 TeV

Significance vs. gluino mass

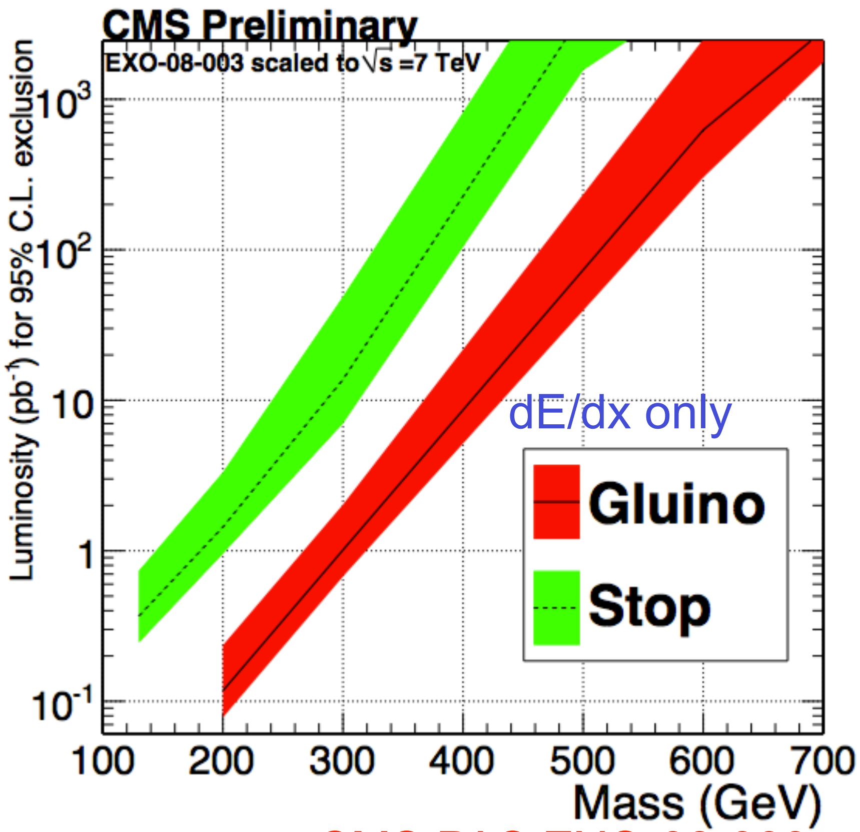


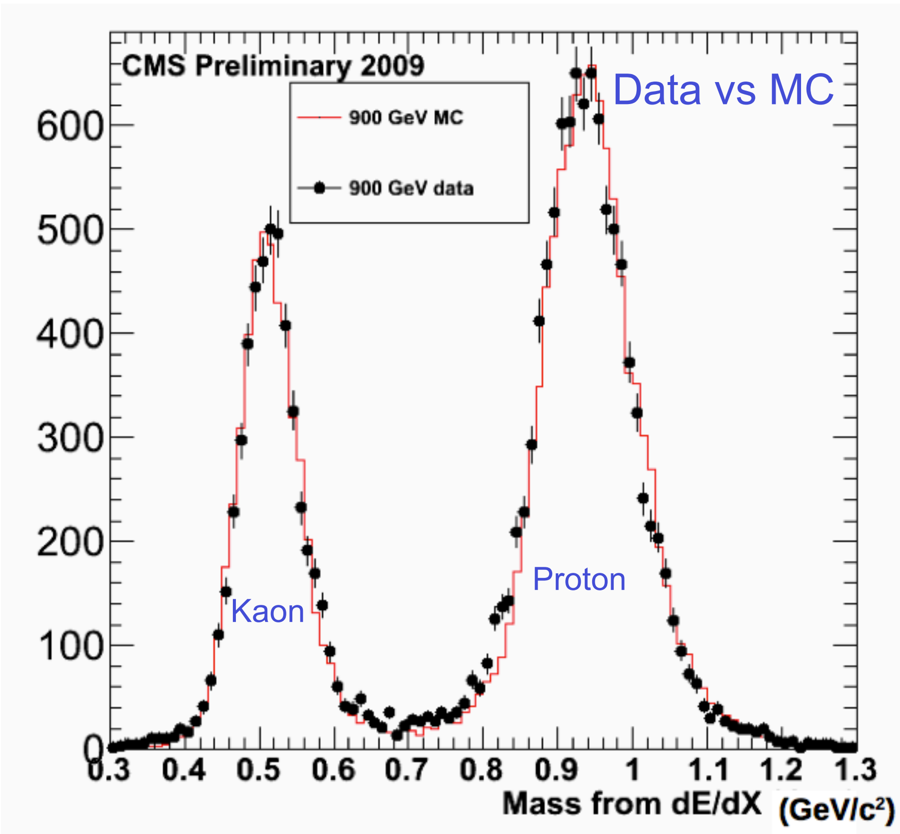


Beamgap exp't: τ≈1μs→hours; interfill exp't: τ≈hours→weeks

HSCP

- A very early analysis: dE/dx and possibly TOF based
- dE/dx part is well understood from cosmics running
- Sensitivity beyond the Tevatron with as little as 1 pb^{-1} of data





CMS PAS EXO-08-003, scaled to 7 TeV

Conclusion

- After many years of preparations, the LHC has started producing collisions at 7 TeV
- ATLAS and CMS detectors in excellent shape, first physics results appearing
- We've covered Particle Physics up to the '80s (W/Z) – soon entering the '90s (top)
- Expect to extend Tevatron searches for SUSY starting end of the year
- Stopped gluino and HSCP results earlier