# DM@CMS

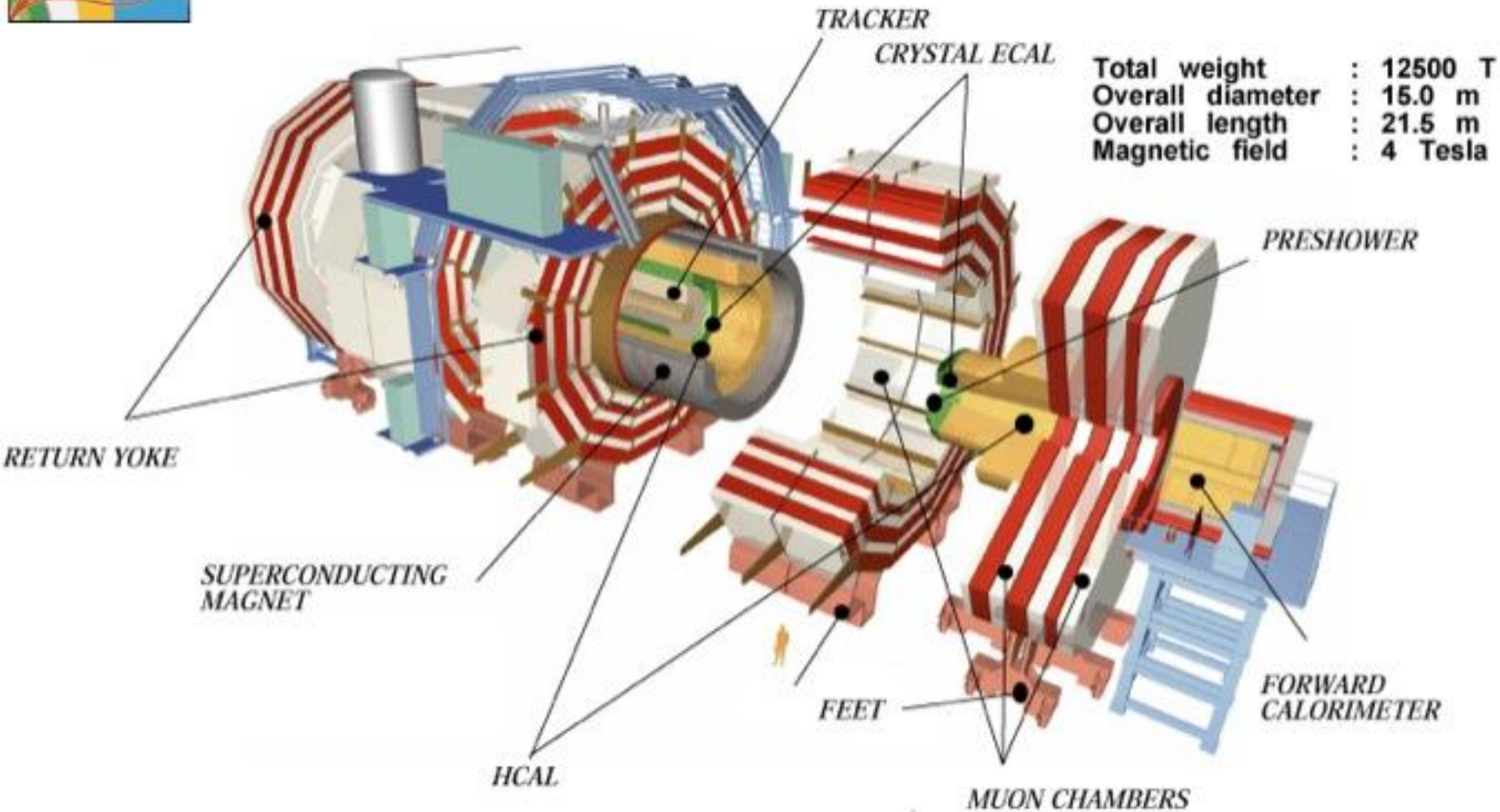
Sezen Sekmen (Florida State University)
on behalf of CMS collaboration

Galileo Galilei Institute on Dark Matter
LHC mini-workshop 10-11/06/2010, Firenze

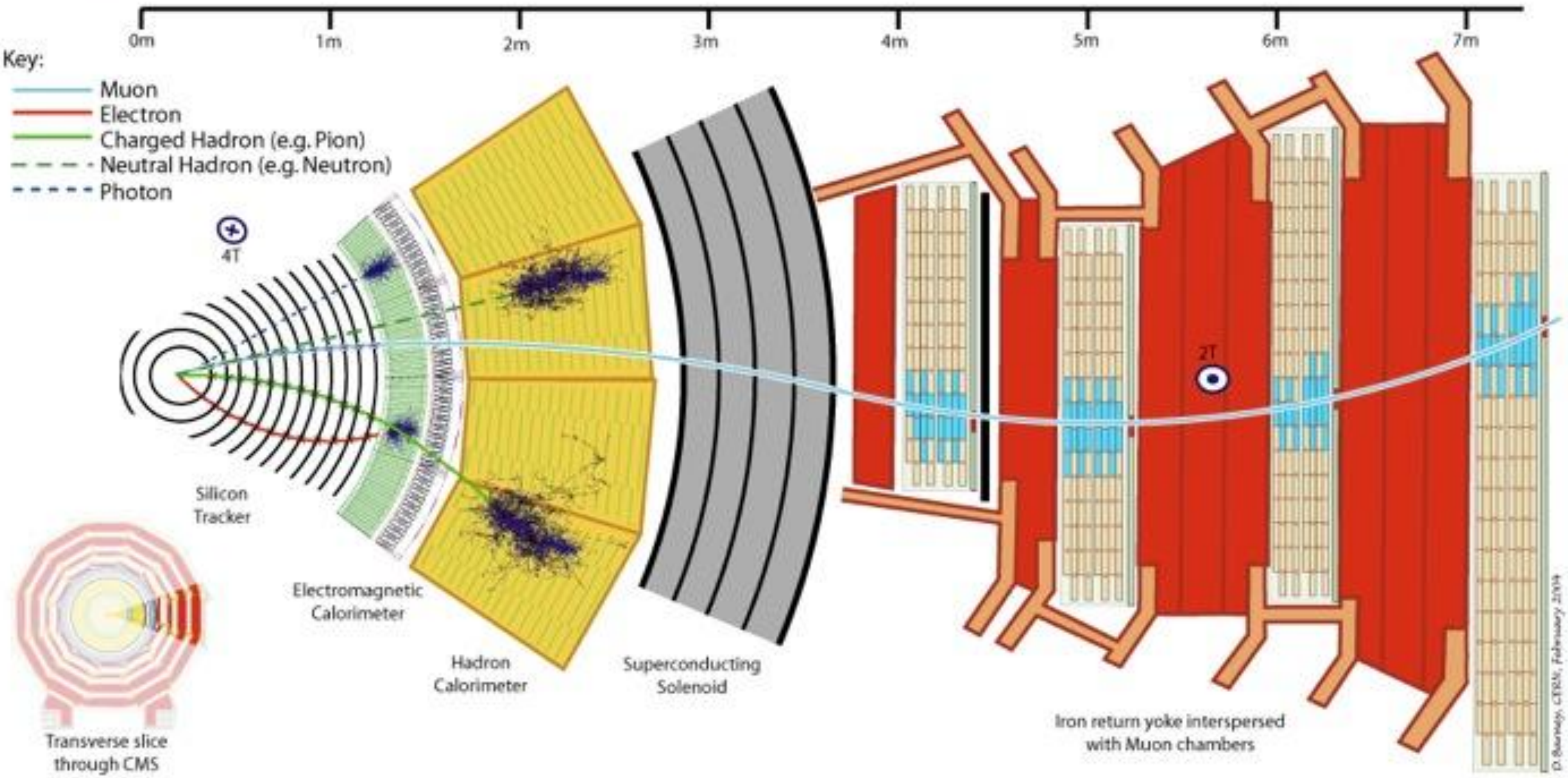
In this talk:

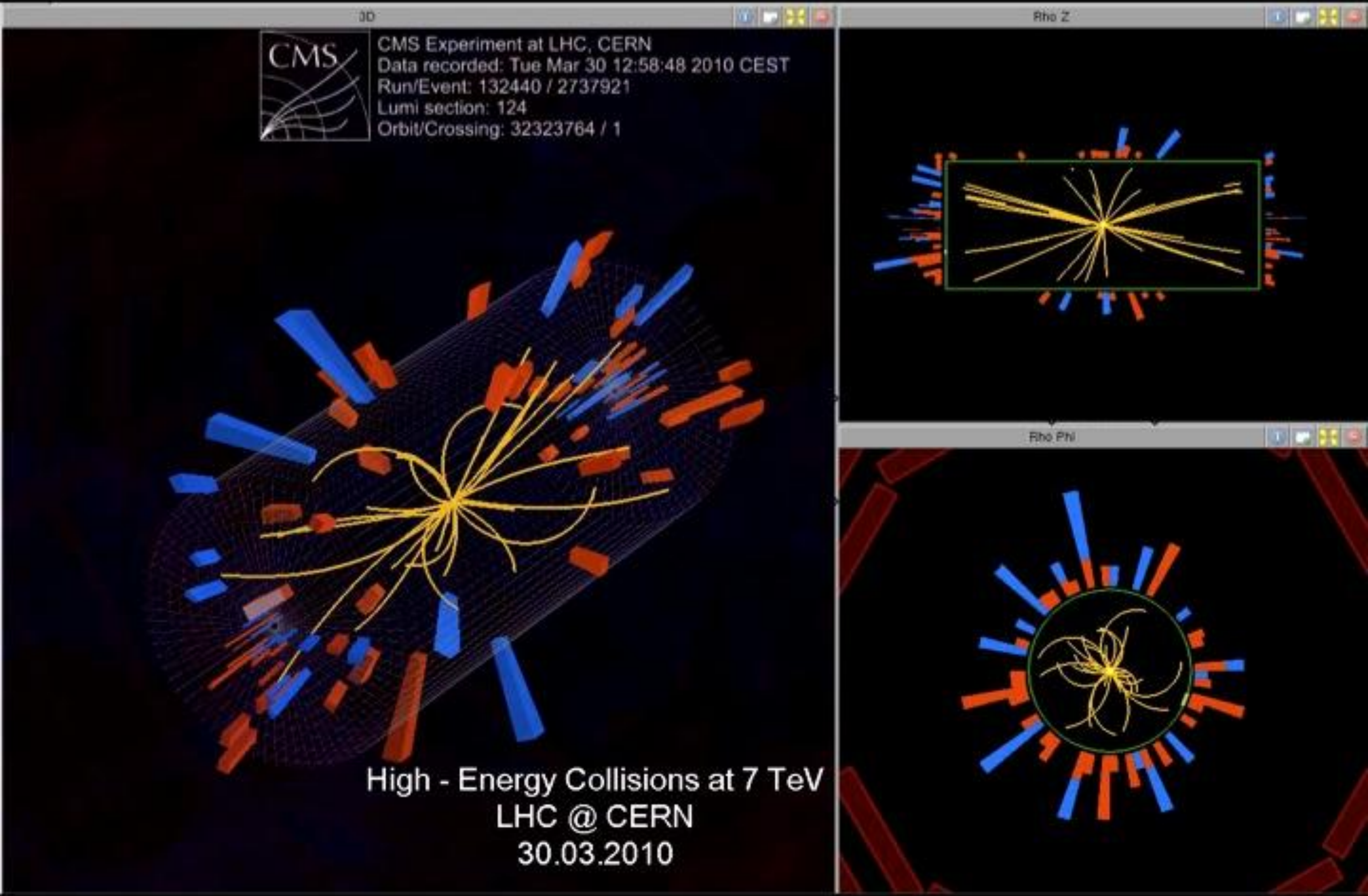
- The Detector
- The current status with data:
  - Luminosity, $j/\psi$, $\pi^0$, $\eta$, W, Z, jets, MET, heavy flavor
- Dark matter searches
  - Methods
  - Exercising edges
  - Reach studies
  - Estimating the background

# The Detector



# Particles in The Detector

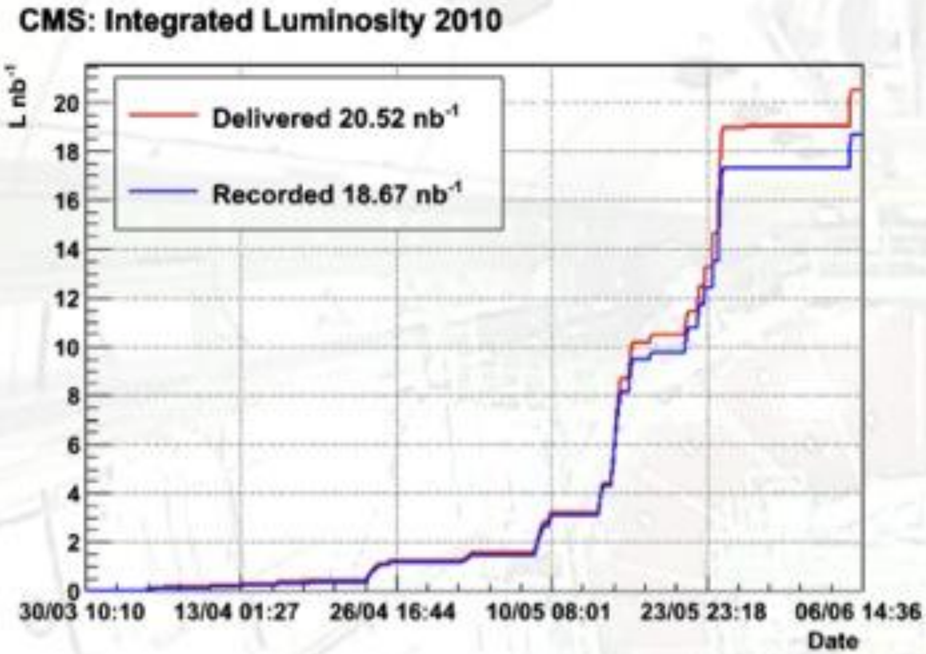



3D
Rho Z
Rho Phi
CMS
CMS Experiment at LHC, CERN
Data recorded: Tue Mar 30 12:58:48 2010 CEST
Run/Event: 132440 / 2737921
Lumi section: 124
Orbit/Crossing: 32323764 / 1
High - Energy Collisions at 7 TeV
LHC @ CERN
30.03.2010

30 March 2010 – CMS control room


cmseye07 2010-06-02 15:25:12
CMS current status

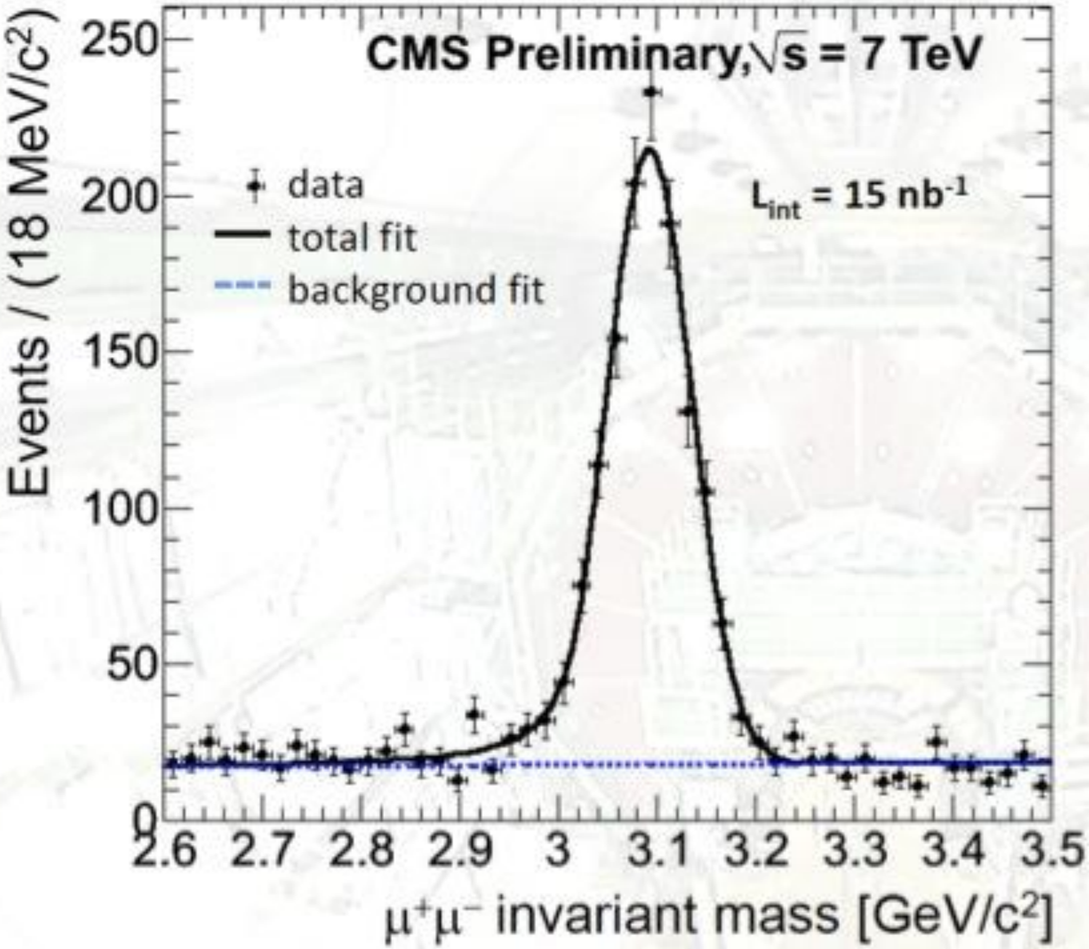
# Collecting data




| Luminosity | Physics reach |
|---|---|
| 1 mb-1 | UE, MB |
| 1 µb-1 | Jets, heavy flavor |
| 1 nb-1 | W, Z |
| 1 pb-1 | ttbar |
| 10 pb-1 | Dijets, HCSP, … |
| 100 pb-1 | W’, Z’, low mass SUSY |
| 1 fb-1 | SUSY, MSSM Higgs |

The plan is to reach 300nb$^{-1}$ - 1pb$^{-1}$ at the end of june, and 1fb$^{-1}$ in 2011.

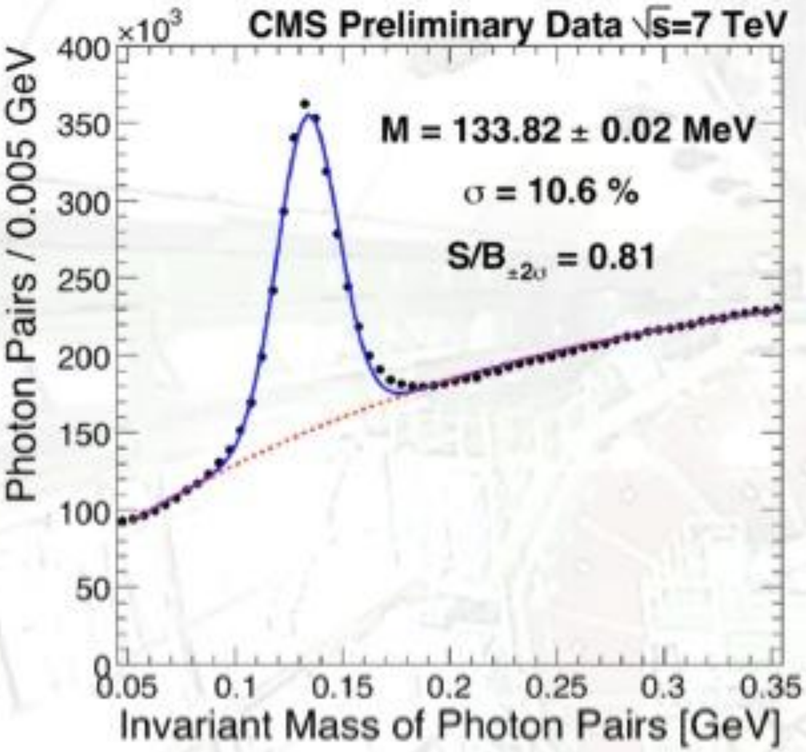
# Dimuon resonances: j/ψ

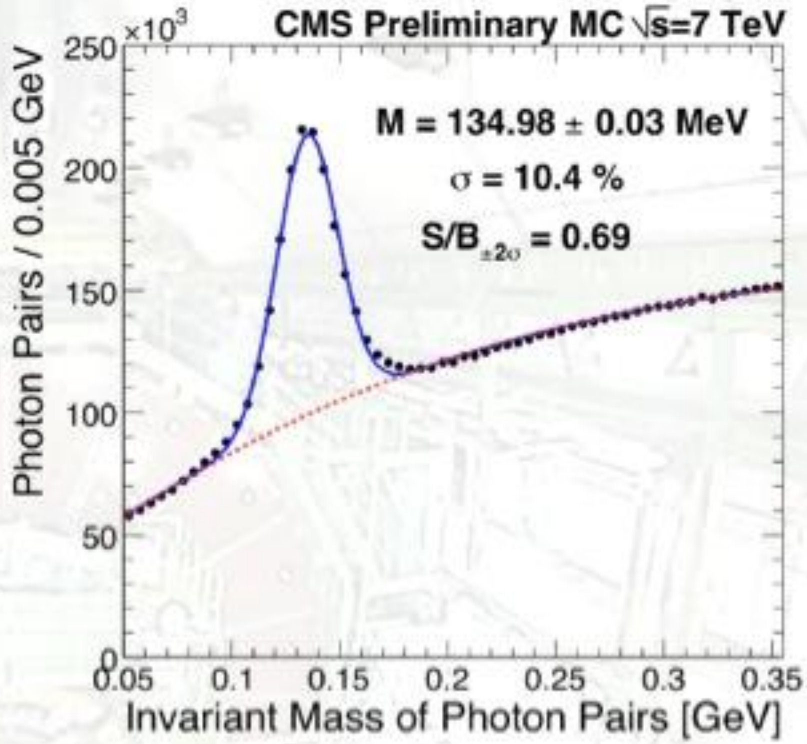



Signal events: 1230 ± 47
Sigma: (42.7 ± 1.9) MeV
$M_0$: 3.092 ± 0.001 GeV
S/B = 5.4 ($M_0$ ± 2.5σ)
$\chi^2$/ndof = 1.1

Fit: polynomial for the background and Crystal-Ball for the signal.

# Diphoton resonances: $\pi^0$



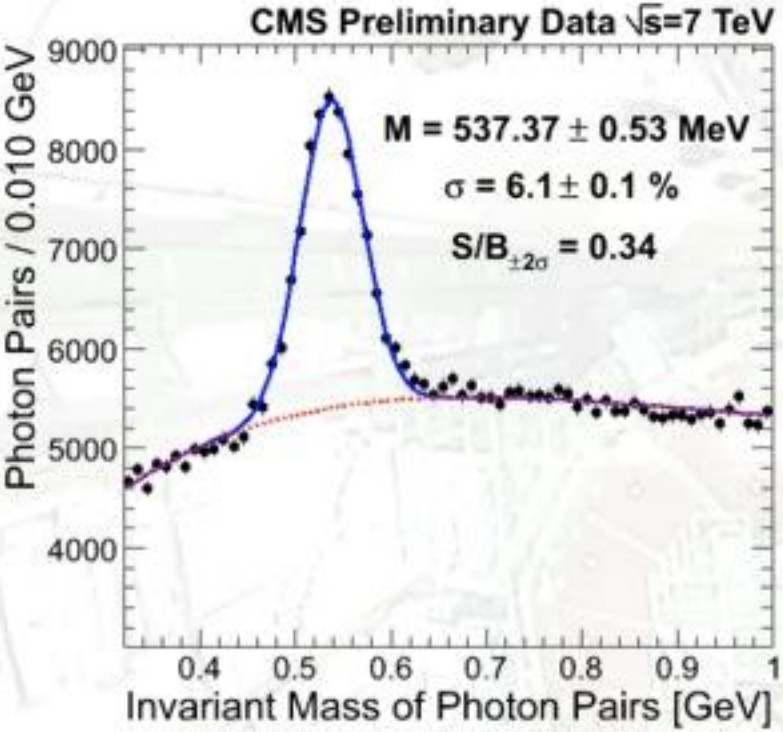



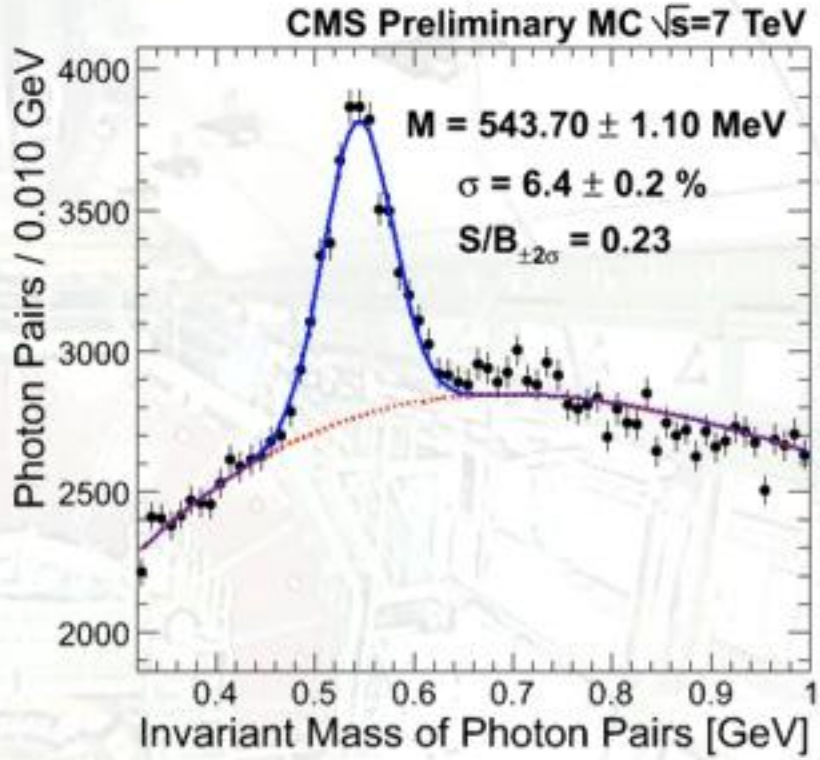

Using 0.43 $nb^{-1}$ of data.

Fit to Gaussian on top of 2nd order polynomial background.

Good agreement with MC. 1441K γγ pairs within the peak.

# Diphoton resonances: η



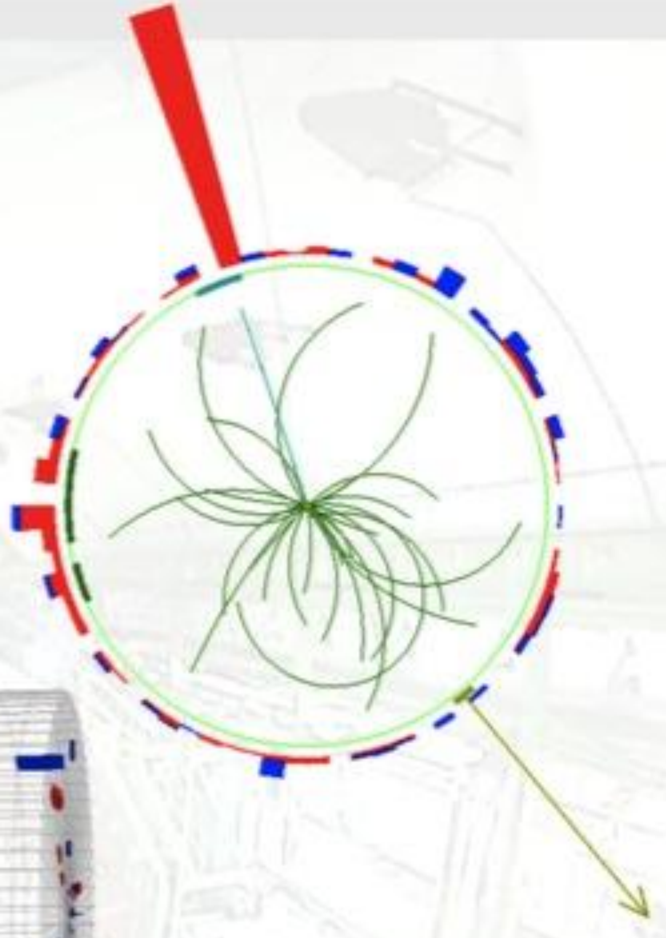

Using 0.43 $nb^{-1}$ of data.

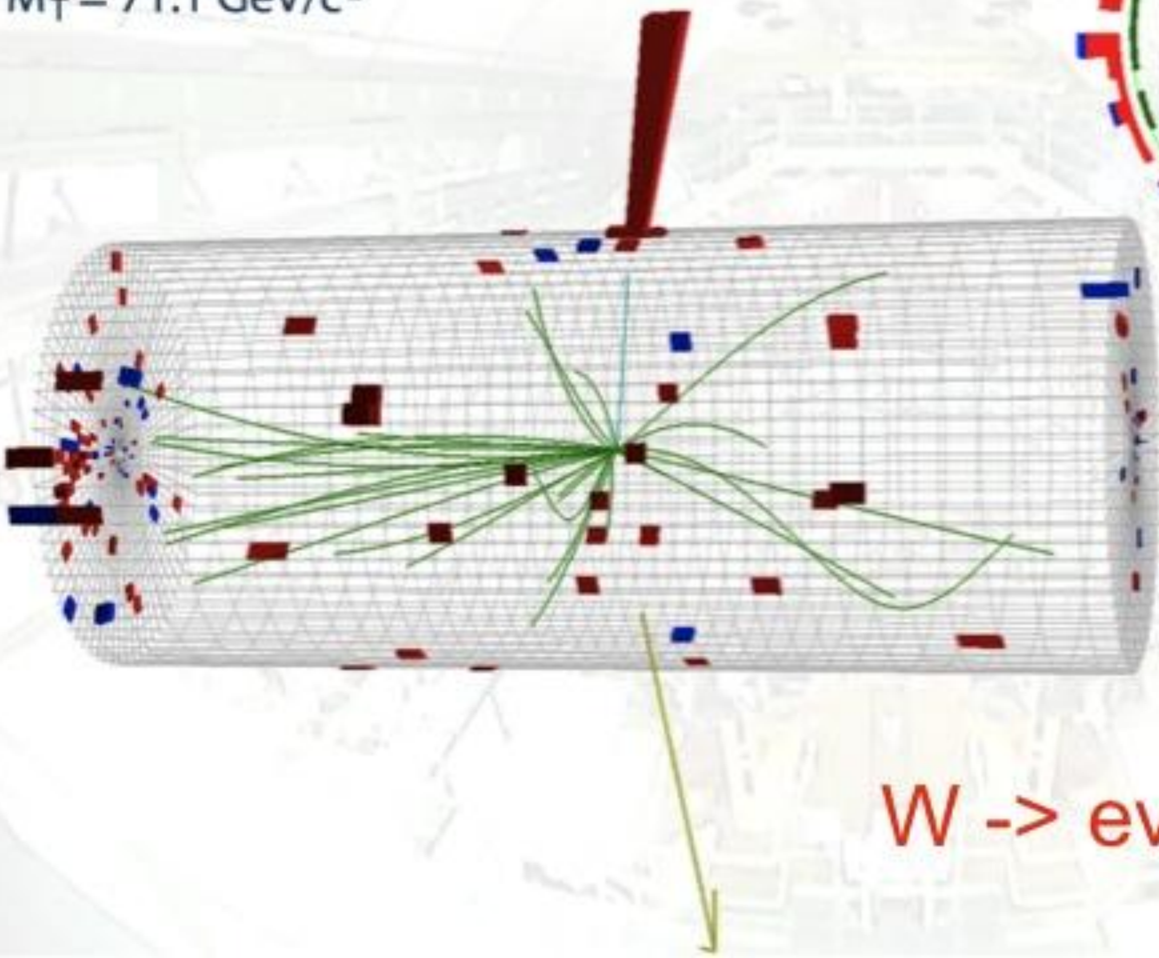
Fit to Gaussian on top of $2^{nd}$ order polynomial background.

Good agreement with MC. 25.5K γγ pairs within the peak.

CMS Experiment at LHC, CERN
Run 133874, Event 21466935
Lumi section: 301
Sat Apr 24 2010, 05:19:21 CEST

Electron $p_T = 35.6$ GeV/c
$ME_T = 36.9$ GeV
$M_T = 71.1$ GeV/$c^2$



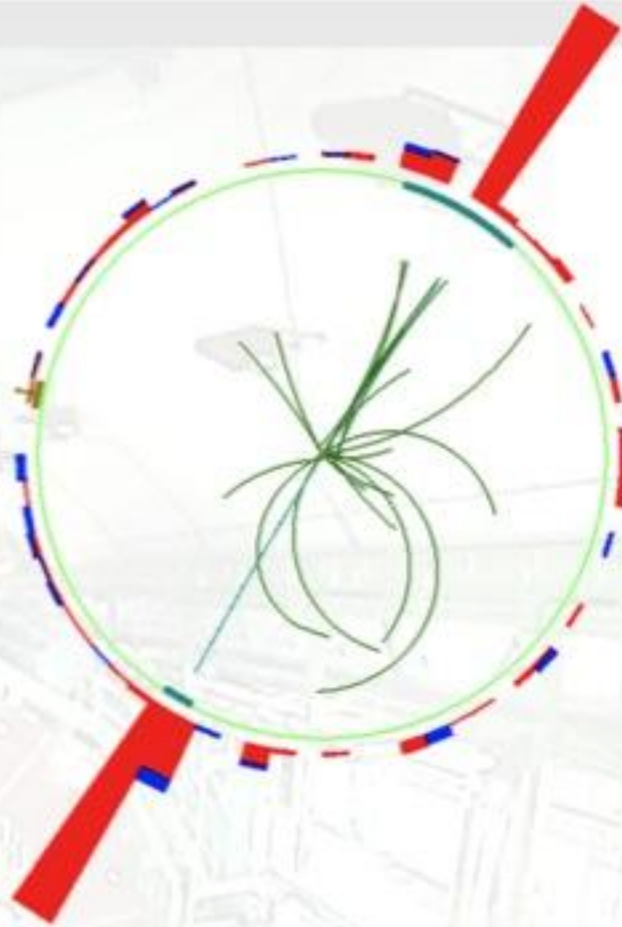


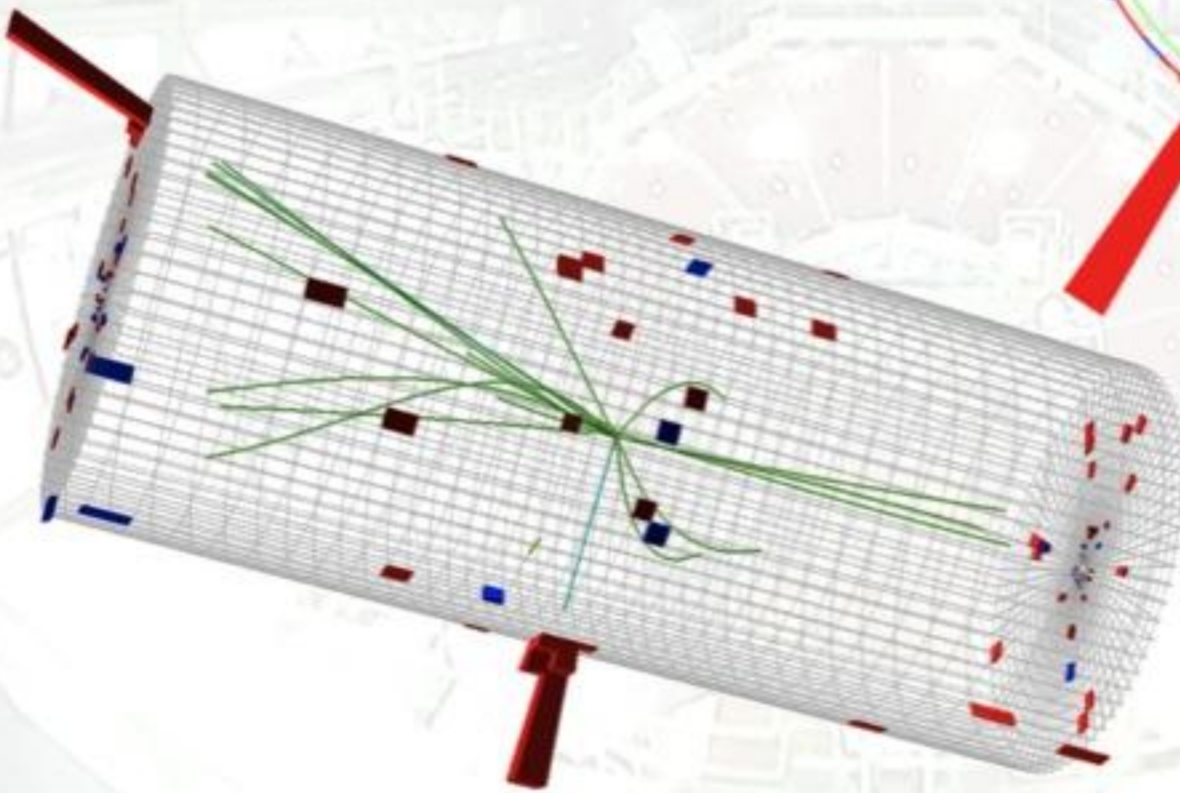
W -> ev candidate

CMS Experiment at LHC, CERN
Run 133877, Event 28405693
Lumi section: 387
Sat Apr 24 2010, 14:00:54 CEST

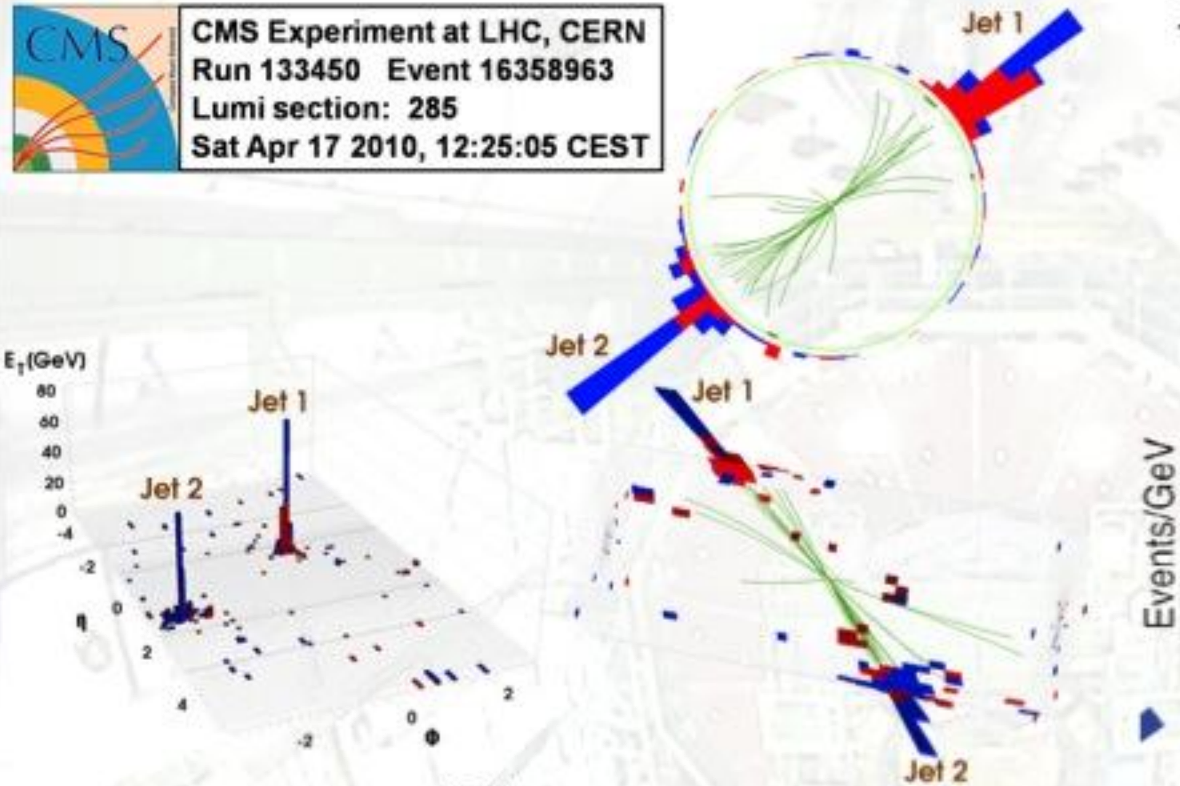
Electrons $p_T$ = 34.0, 31.9 GeV/c
Inv. mass = 91.2 GeV/$c^2$

# Z -> e+e- candidate

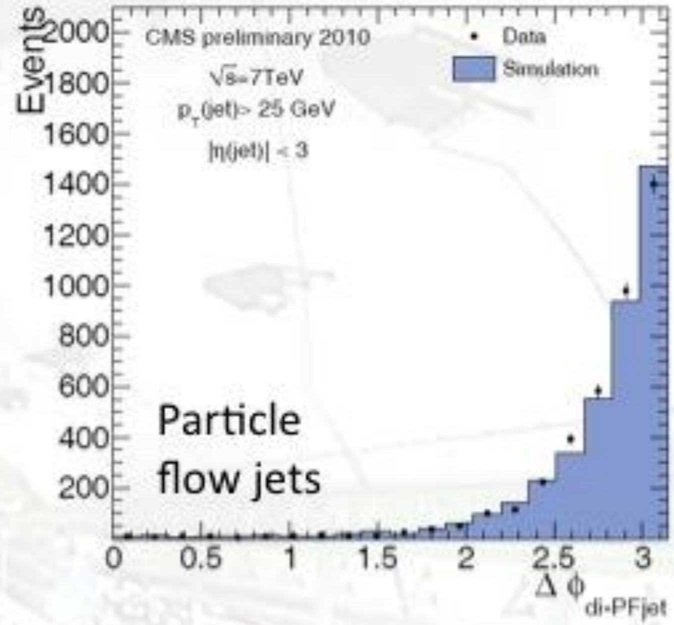


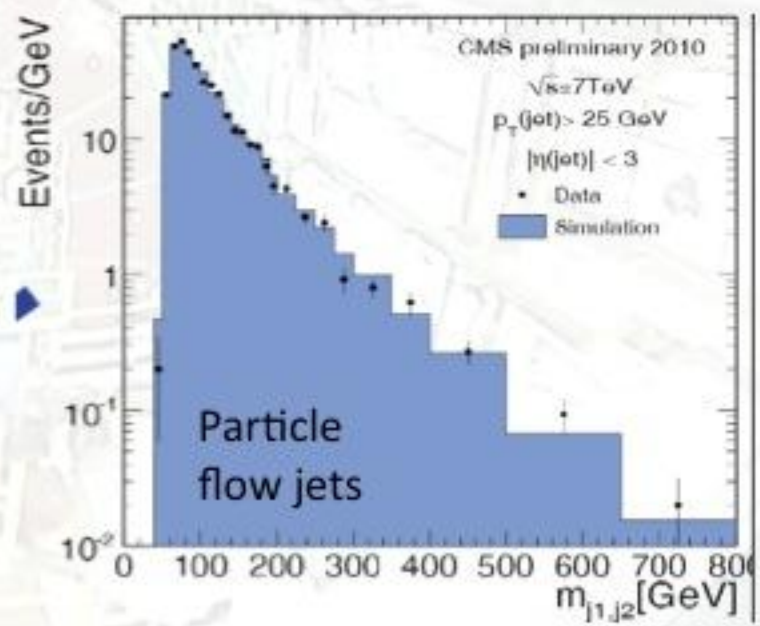


# Jets

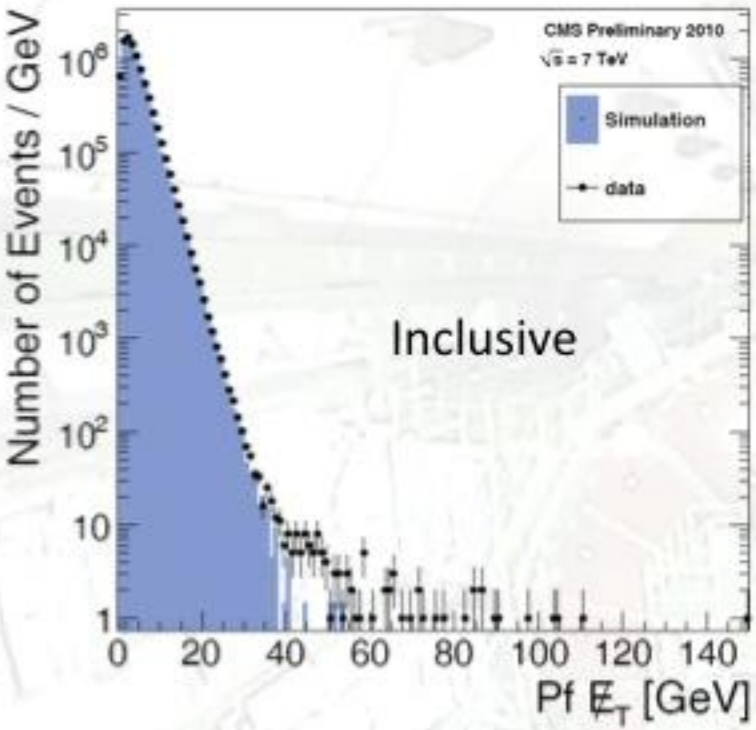



Dijet event

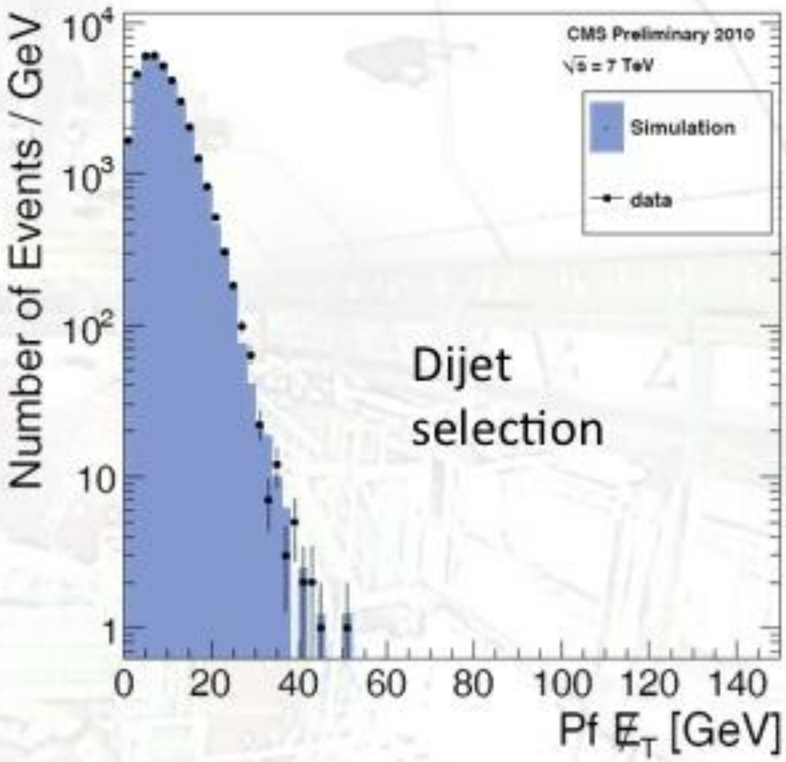


# Missing energy

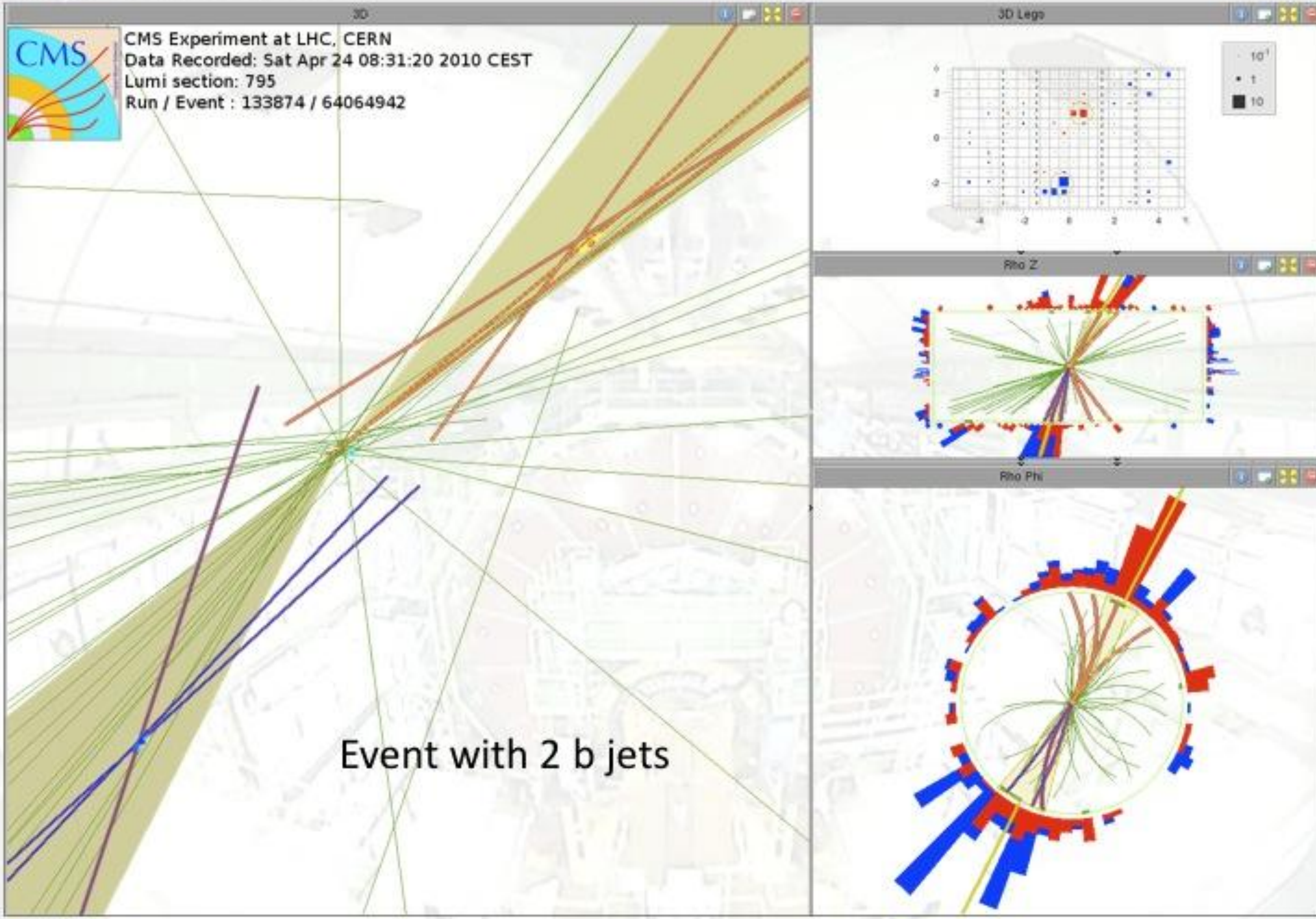



Inclusive




Dijet selection

MET overall well described. More tails in data. New methods being investigated for cleaning noise.




Event with 2 b jets


www.wallpapersite.net

# Which DM can CMS look for?

- WIMP dark matter (neutralinos, lightest KK particles, lightest T-odd parity particles…): DM that shows up as missing energy in the colliders. But all such candidates come with similar signatures – in many cases LHC is not sufficient to distinguish between them.
- Gravitinos (very indirect hints from heavy charged stable particles - HCSP)
- Axions/axinos (very indirect hints from discovery of neutralino with excess relic abundance, or discovery of HCSP)
- …

CMS and ATLAS can find valuable hints, however they cannot reveal the exact nature of dark matter alone. Need complementary results from direct/indirect detection experiments, axion searches, etc.

# Difficulty with missing energy signals

Pair production of new particles, each decaying into an invisible particle. Double-sided contribution to MET. Long, tangled chains, complicated signatures.

- No resonances over the background
- Not possible to reconstruct the complete event.
- Small kinematic sensitivity to mass of the invisible particle
- Difficult to measure absolute masses. Mass differences are easier to measure (using mass differences introduce correlations when extracting the absolute masses)
- Extra jets from QCD radiation complicate the jet signatures.

Also see J Alwall LBL RPM talk , March 4 2010

# Long way to omega…

Measure all that is possible: masses (especially in the neutralino , slepton and higgs sectors), branching ratios, cross sections.

“more” model-dependent (top-down) way (Baltz, Battaglia, Peskin, Wizansky):

- Perform a scan over the MSSM24 parameter space and compute the probability distributions (PD) for the input parameters
- Using the model PDs, get the PDs for $\Omega h^2$ and cross sections.

“less” model-dependent (bottom-up) way (Nojiri, Polesello, Tovey):

- Sector by sector constrain the SSB parameters at the EW scale
- Compute $\Omega h^2$ from the predicted SSB values

See Polesello’s talk.

# The looong shopping list…

| mass/mass splitting | LCC1 Value | | LHC | ILC 500 | ILC 1000 |
|---|---|---|---|---|---|
| $m(\tilde{\chi}_1^0)$ | 95.5 | ± | 4.8 | 0.05 | |
| $m(\tilde{\chi}_2^0) - m(\tilde{\chi}_1^0)$ | 86.1 | ± | 1.2 | 0.07 | |
| $m(\tilde{\chi}_3^0) - m(\tilde{\chi}_1^0)$ | 261.2 | ± | @[a] | 4.0 | |
| $m(\tilde{\chi}_4^0) - m(\tilde{\chi}_1^0)$ | 280.1 | ± | 2.2[a] | 2.2 | |
| $m(\tilde{\chi}_1^+)$ | 181.7 | ± | - | 0.55 | |
| $m(\tilde{\chi}_2^+)$ | 374.7 | ± | - | - | 3.0 |
| $m(\tilde{e}_R)$ | 143.1 | ± | - | 0.05 | |
| $m(\tilde{e}_R) - m(\tilde{\chi}_1^0)$ | 47.6 | ± | 1.0 | 0.2 | |
| $m(\tilde{\mu}_R) - m(\tilde{\chi}_1^0)$ | 47.5 | ± | 1.0 | 0.2 | |
| $m(\tilde{\tau}_1) - m(\tilde{\chi}_1^0)$ | 38.6 | ± | 5.0 | 0.3 | |
| $BR(\tilde{\chi}_2^0 \to \tilde{e}e)/BR(\tilde{\chi}_2^0 \to \tilde{\tau}\tau)$ | 0.077 | ± | 0.008 | | |
| $m(\tilde{e}_L) - m(\tilde{\chi}_1^0)$ | 109.1 | ± | 1.2 | 0.2 | |
| $m(\tilde{\mu}_L) - m(\tilde{\chi}_1^0)$ | 109.1 | ± | 1.2 | 1.0 | |
| $m(\tilde{\tau}_2) - m(\tilde{\chi}_1^0)$ | 112.3 | ± | - | 1.1 | |
| $m(\tilde{\nu}_e)$ | 186.2 | ± | - | 1.2 | |
| $m(h)$ | 113.68 | ± | 0.25 | 0.05 | |
| $m(A)$ | 394.4 | ± | * | (> 240) | 1.5 |
| $m(\tilde{u}_R), m(\tilde{d}_R)$ | 548. | ± | 19.0 | 16.0 | |
| $m(\tilde{s}_R), m(\tilde{c}_R)$ | 548. | ± | 19.0 | 16.0 | |
| $m(\tilde{u}_L), m(\tilde{d}_L)$ | 564., 570. | ± | 17.4 | 9.8 | |
| $m(\tilde{s}_L), m(\tilde{c}_L)$ | 570., 564. | ± | 17.4 | 9.8 | |
| $m(\tilde{b}_1)$ | 514. | ± | 7.5 | 5.7 | |
| $m(\tilde{b}_2)$ | 539. | ± | 7.9 | 6.2 | |
| $m(\tilde{t}_1)$ | 401. | ± | (> 270) | - | 2.0 |
| $m(\tilde{g})$ | 611. | ± | 8.0 | 6.5 | |

Example list for a low mass mSUGRA point.

Errors estimated based on LHC (mostly ATLAS) measurements.

From Baltz et. Al.

See Raklev's talk for more on mass measurements.

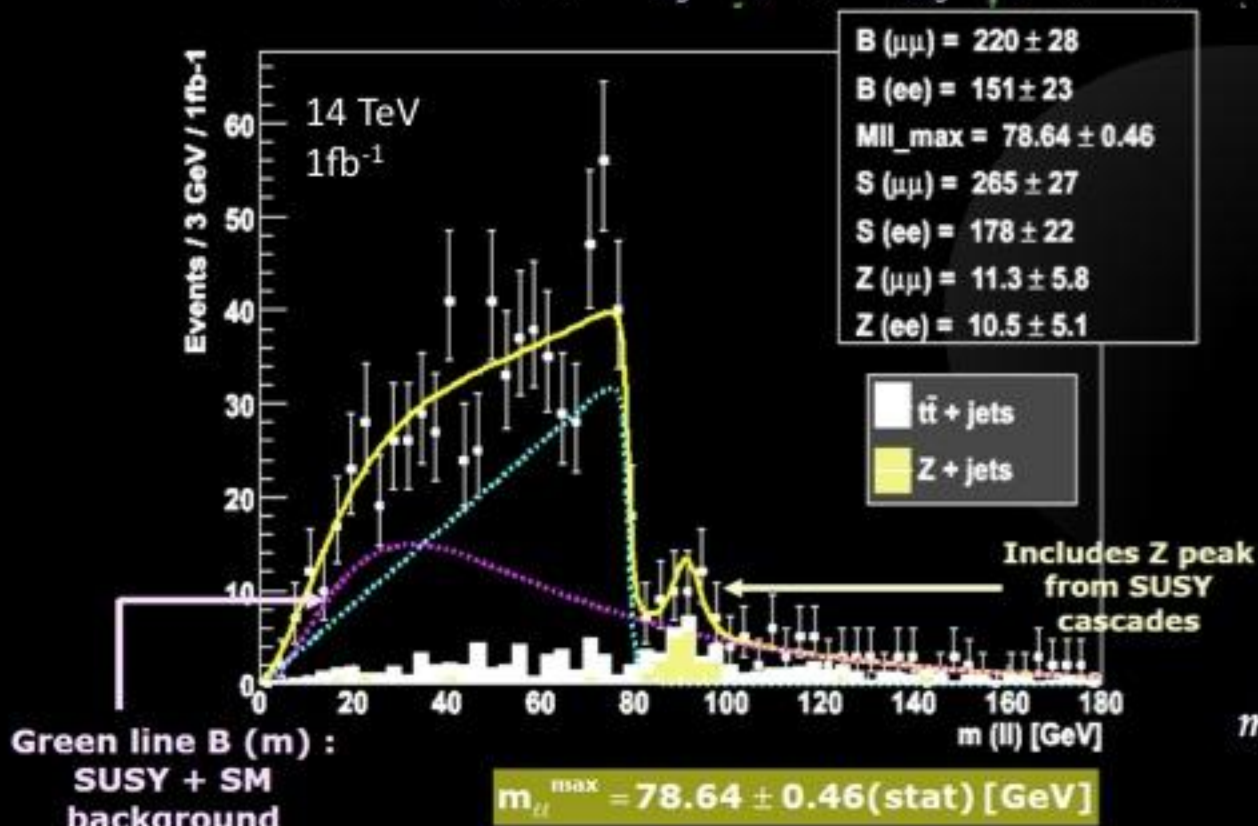
# Most common exercise: dilepton edge

Baseline dileptons + jets + MET selection:

- ≥ 2 isolated OSSF leptons with $p_T > 10$ GeV, $|\eta| < 2.4$
- ≥ 3 jets $E_T > 30$ GeV, $|\eta| < 3$
- $E_T(j1, j2) > 120, 80$ GeV
- MET > 200 GeV

Simultaneous fit to

$$F(m) = N_{sig} \cdot S(m) + N_{bkg} \cdot B(m) + N_Z \cdot Z(m)$$




$m_{ll}^{max} = 78.64 \pm 0.46(\text{stat})$ [GeV]

For 2-body decays:

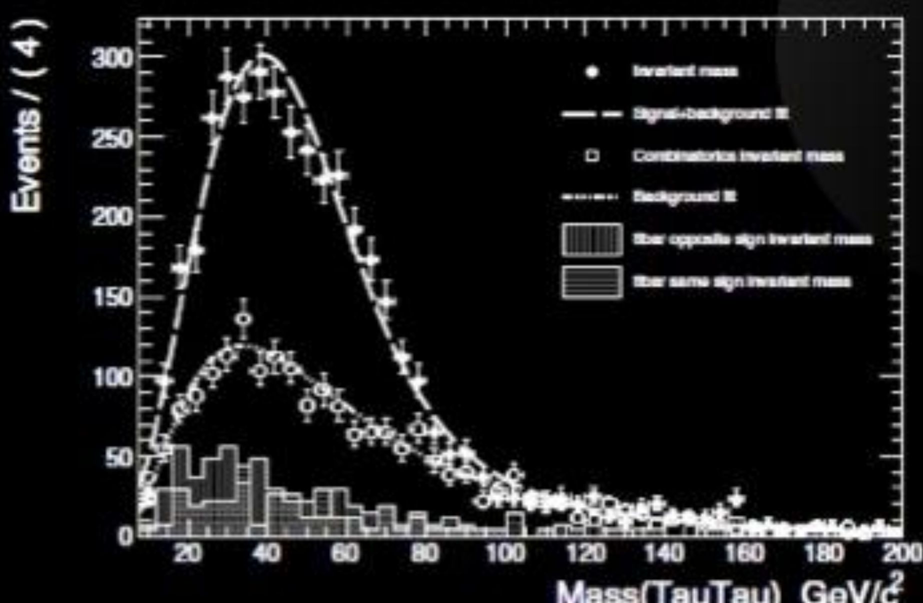
$$m_{\ell\ell}^{max} = m_{\tilde{\chi}_2^0} \sqrt{1 - \frac{m_{\tilde{\ell}_R}^2}{m_{\tilde{\chi}_2^0}^2}} \sqrt{1 - \frac{m_{\tilde{\chi}_1^0}^2}{m_{\tilde{\ell}_R}^2}}$$

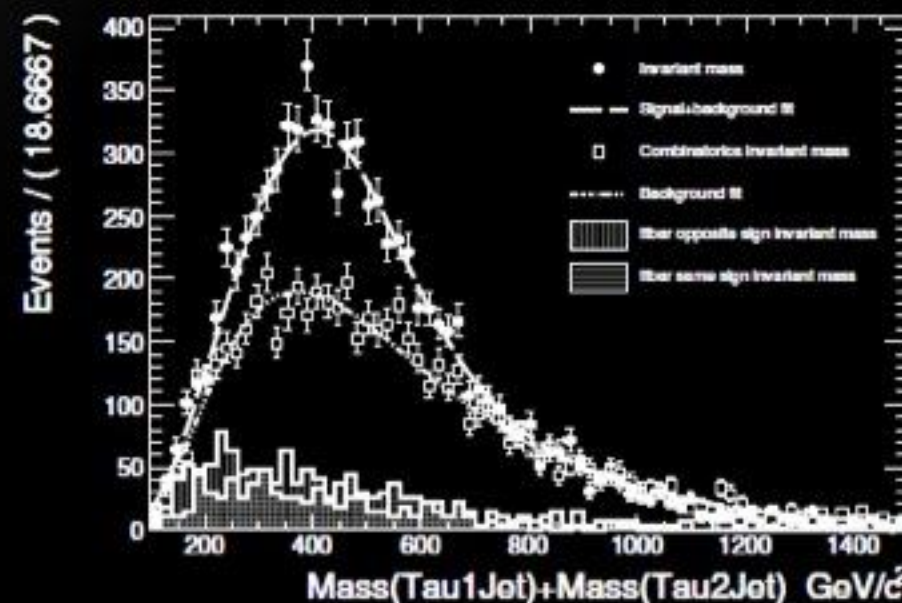
# Ditau edge

Baseline ditau + jets + MET selection (14 TeV, 40fb$^{-1}$):

- ≥ 2 itau candidates (hadronic or leptonic) with $\Delta R(\tau\tau) > 2$
- ≥ 2 jets, $E_T$(j1, j2) > 150, 150 GeV
- MET > 150 GeV

Several invariant mass distributions were fitted to composite shapes, and endpoints were extracted from the fits.



# Diltau edges: Results

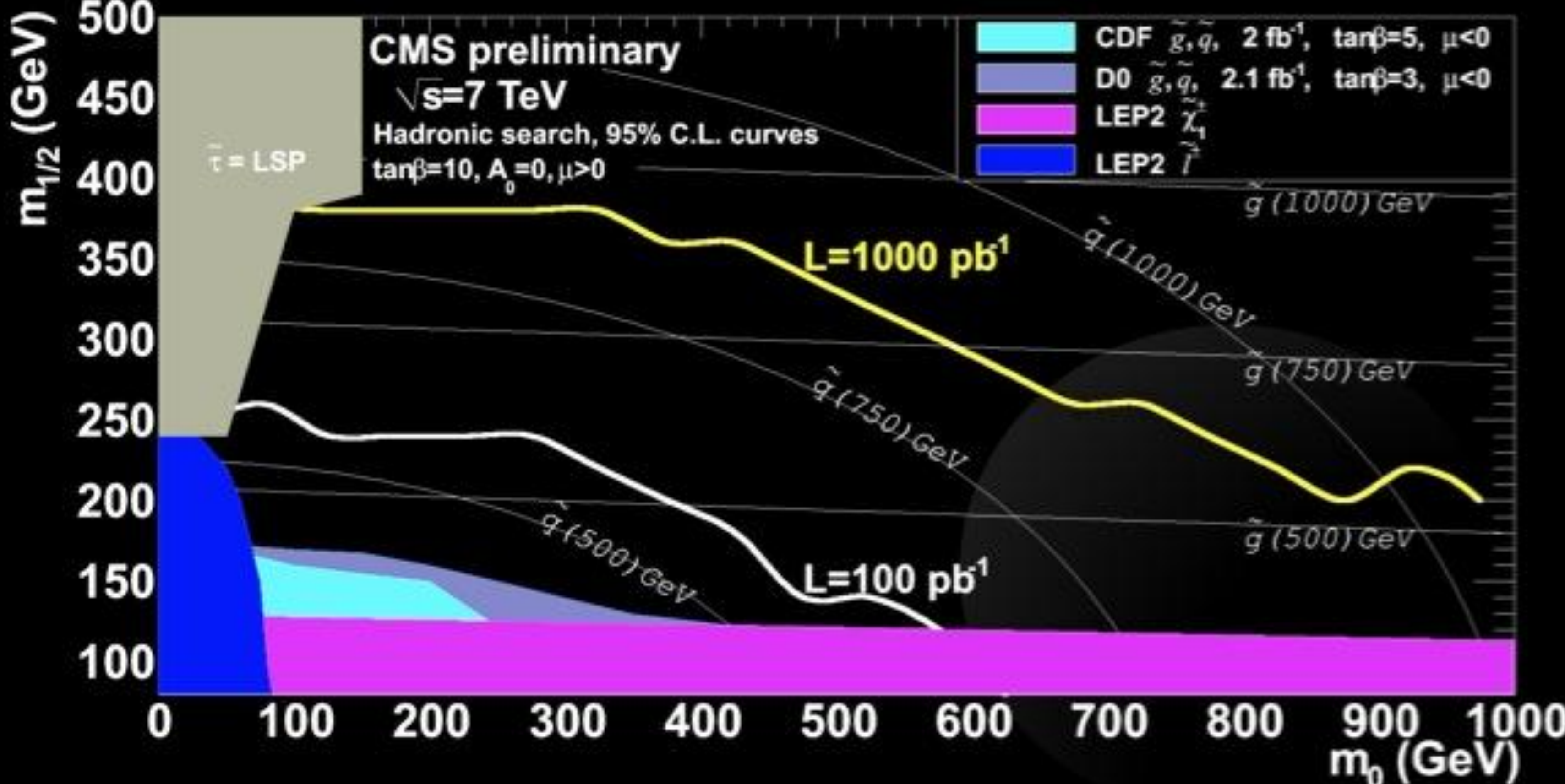
| End-points (GeV) | case 1 (GeV) | case 2 (GeV) |
|---|---|---|
| $m(\tau_1\tau_2)^{\max} = 95 \pm 3$ | $M(\tilde{\chi}_1^0) = 213 \pm 14$ | $M(\tilde{\chi}_1^0) = 147 \pm 23$ |
| $m(\tau_1 Q)^{\max} = 559 \pm 11$ | $M(\tilde{\chi}_2^0) = 337 \pm 17$ | $M(\tilde{\chi}_2^0) = 265 \pm 10$ |
| $m(\tau_2 Q)^{\max} = 298 \pm 7$ | $M(\tilde{\tau}) = 310 \pm 17$ | $M(\tilde{\tau}) = 165 \pm 10$ |
| $m(\tau_1\tau_2 Q)^{\max} = 596 \pm 12$ | $M(\tilde{q}) = 839 \pm 19$ | $M(\tilde{q}) = 763 \pm 33$ |
| $E_5^{meas} = 780 \pm 20$ | $E_5^{calc} = 815 \pm 26$ | $E_5^{calc} = 765 \pm 30$ |

Solve 4 equations giving first 4 endpoints as a function of 4 sparticle masses.
Resolve ambiguities by matching to $E_5 = m(\tau_1 Q) + m(\tau_2 Q)$.

| | LM2 benchmark point | |
|---|---|---|
| | measured | theory |
| $M(\tilde{\chi}_1^0)$ (GeV) | $147 \pm 23(\text{stat}) \pm 19(\text{sys})$ | 138.2 |
| $M(\tilde{\chi}_2^0)$ (GeV) | $265 \pm 10(\text{stat}) \pm 25(\text{sys})$ | 265.5 |
| $M(\tilde{\tau})$ (GeV) | $165 \pm 10(\text{stat}) \pm 20(\text{sys})$ | 153.9 |
| $M(\tilde{q})$ (GeV) | $763 \pm 33(\text{stat}) \pm 58(\text{sys})$ | 753-783 (light $\tilde{q}$) |

# mSUGRA reach @ 7TeV: jets+MET inclusive (+ lepton veto)

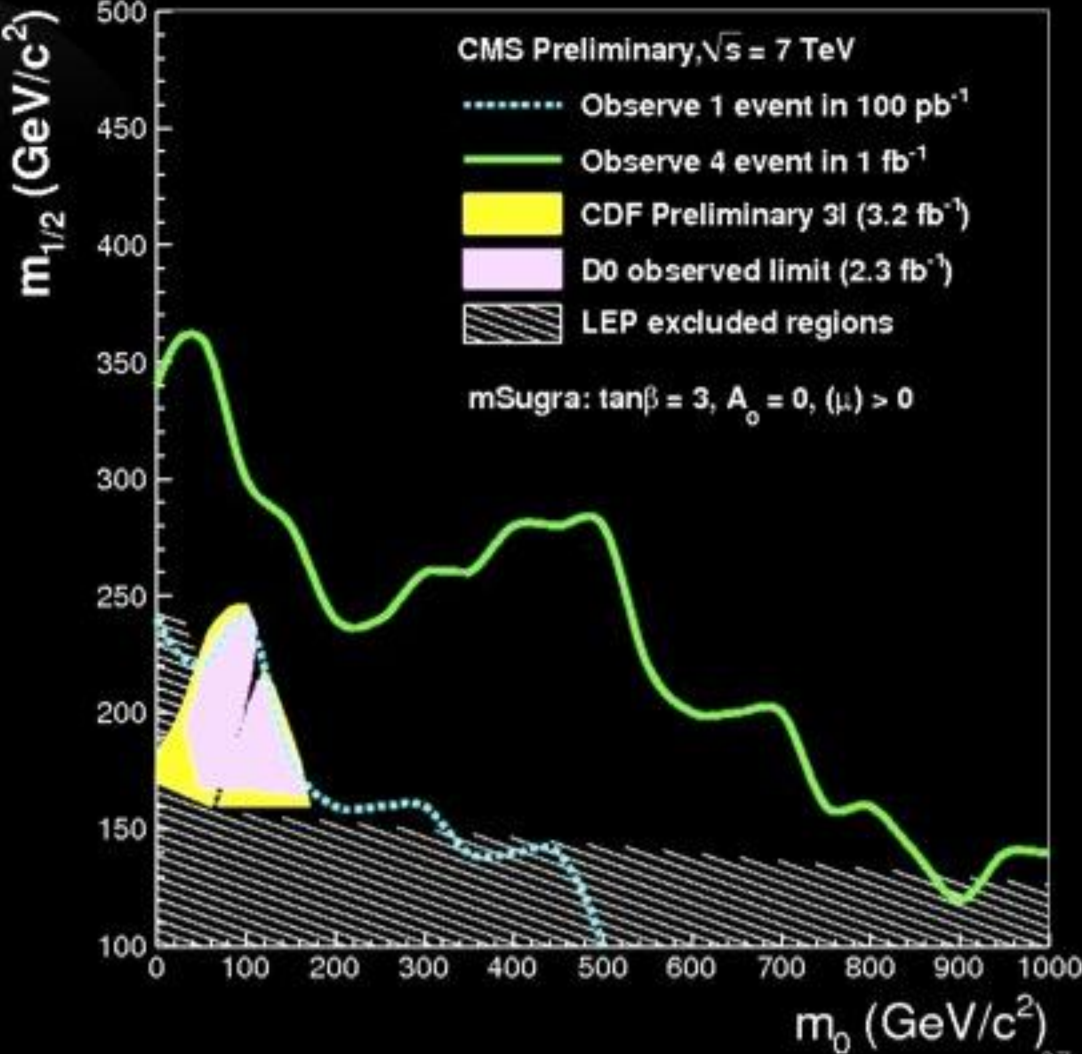
High signal efficiency, but significant background contamination.



# mSUGRA reach @ 7TeV: Same sign dileptons (ee, μμ, eμ)

Very low background (mainly ttbar+jets), but very low signal, too.

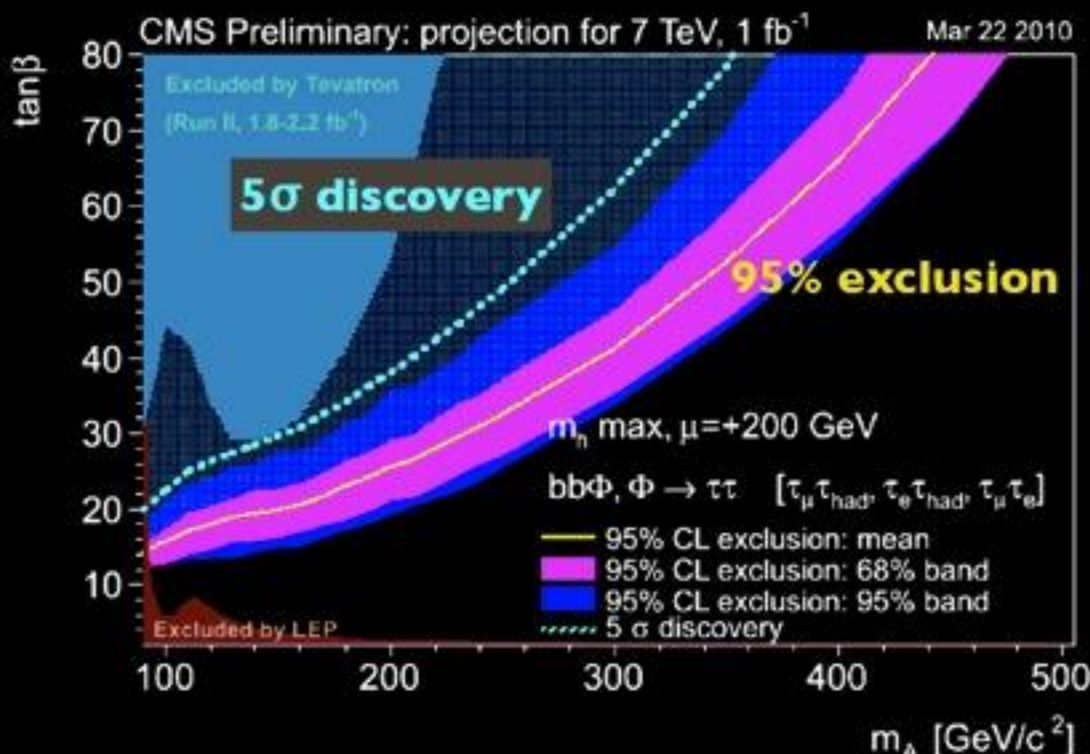
Plot shows exclusion limits at 95% CL.



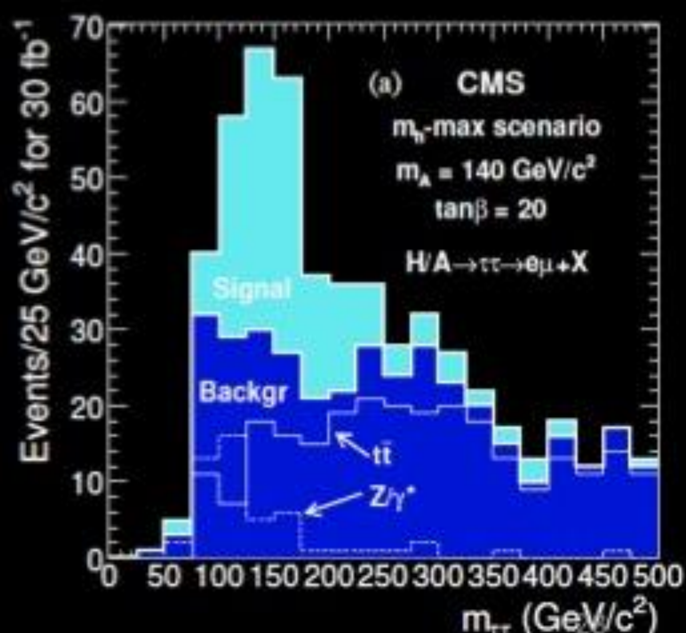
# MSSM Higgs: ττ channel

Associated production with b jets: pp -> bbΦ

Now: Higgs discovery reach for 7 TeV)
Cross sections scaled from 14 TeV to 7 TeV.

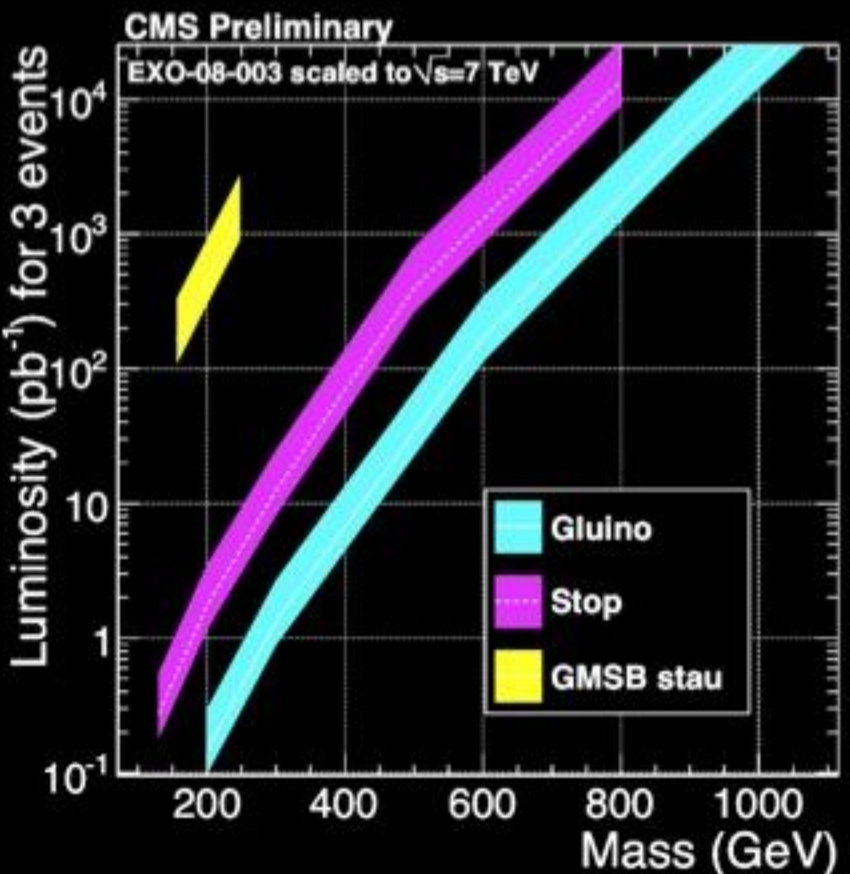



Future: The pseudoscalar Higgs ($m_A$) peak:
14 TeV, 30fb$^{-1}$.
$m_A$ = 140 GeV, tanβ = 20.
(Can check possibility of neutralino annihilation via $m_A$ if $m_A$ is light)



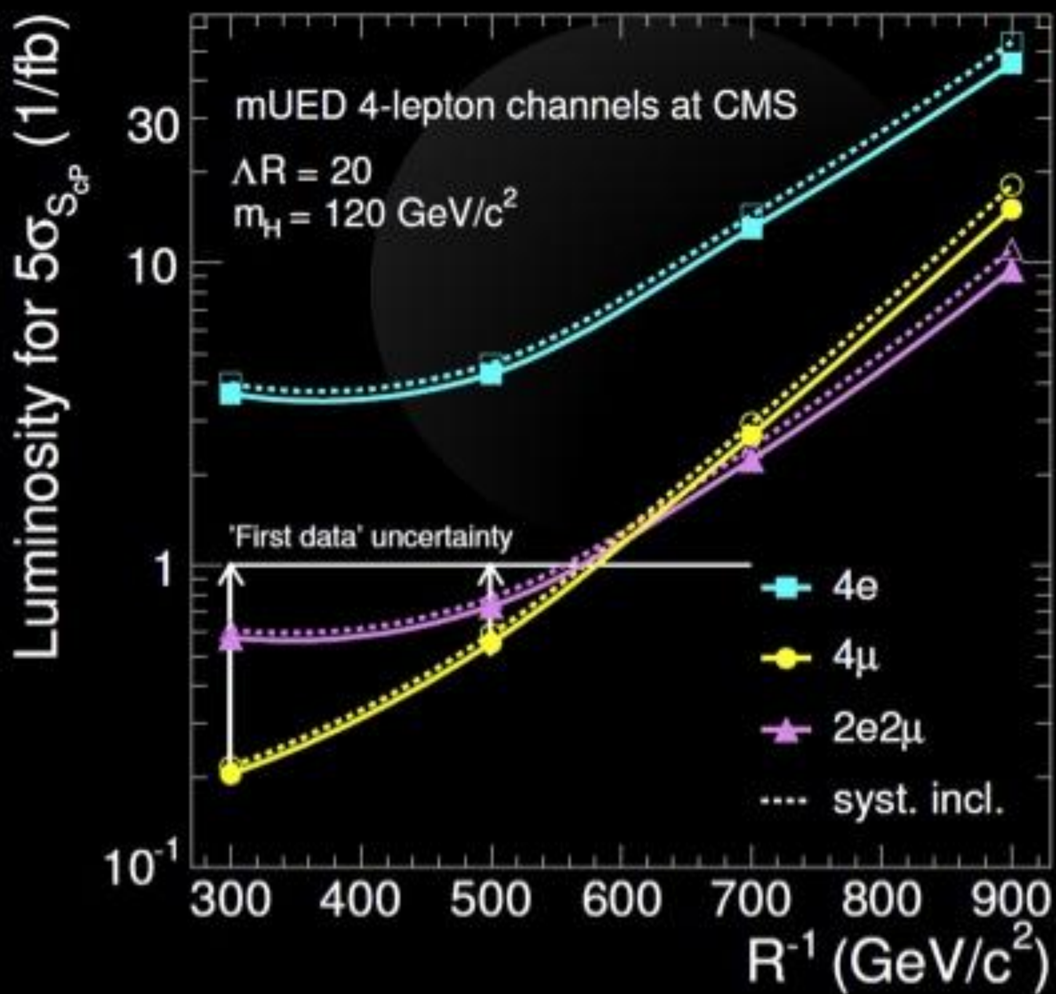
# HCSP (enter non-WIMP)

- Heavy, charged particles with long lifetimes hint non-WIMP dark matter such as gravitinos or axinos.
- Heavy charged "stable" particles (HCSP) have muon like signature – but they have low velocity (non-relativistic).
- Measure β using tracker dE/dx or muon time of flight (check delayed hits), then calculate the mass.
- Negligible backgrounds.



# mUED in 4leptons

- Reach for 14TeV
- Very compressed spectra: mass difference between heaviest and lightest mode is O(100GeV) -> soft SM decay products.
- Selection
    - 2 pairs of soft, isolated OSSF leptons
    - b jet and Z veto
    - MET > 60



# Note: Dark photons

There is also current CMS investigation for dark photons, which are carriers of the hidden U(1) sector dark matter (but no approved results).

Analysis is based on search for leptons to which the dark photons decay.

There is one prerequisite to all this:

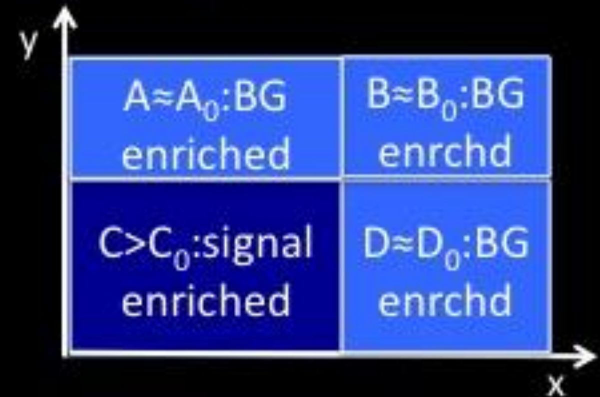
Estimate the background right!

# Background estimation

Dominantly used idea: Estimate BG shape and amount at a signal-free control region, then extrapolate to the signal region. Various methods for different processes.

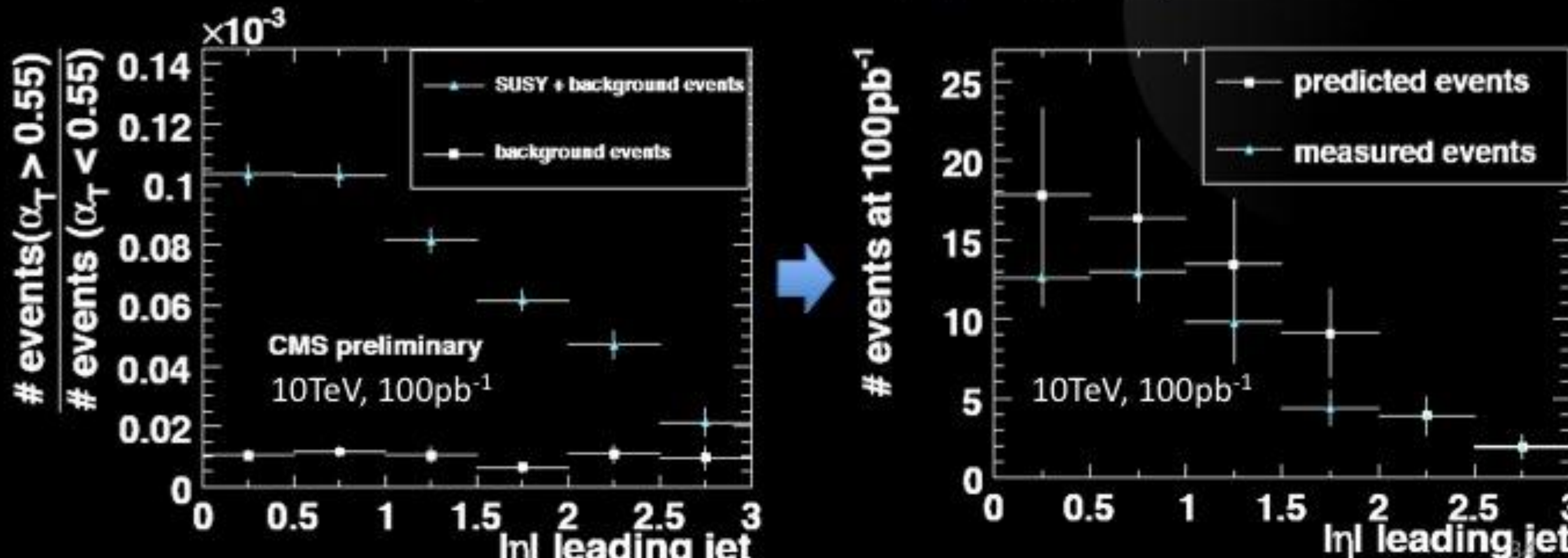
- QCD: Matrix method, MET templates from Z(->ll)+jets events, jet-Z balance, jet resolution, lepton fake rates, …
- Top: Matrix, tau smearing, lost lepton, sPlots, topbox, …
- W+jets: MET templates from Z+jets, tau smearing, lost lepton, sPlots, …
- Z+jets: Z -> invisible from Z->ll or from W->μν+jets and γ+jets samples, …

# Simple example: Matrix method




- Choose 2 selection variables x, y for which background is uncorrelated.
- A,B,C,D: Total events; $A_0$, $B_0$, $C_0$, $D_0$: BG events
- When there is no signal: $A_0/B_0 = C_0/D_0$
- When there is signal: $A/B \approx C_0/D \rightarrow C_0 \approx (A/B)D$

Tried for an inclusive jets+MET analysis, for $|\eta(\text{jet }1)|$ vs $\alpha_T$:



# $\alpha_T$: The QCD terminator

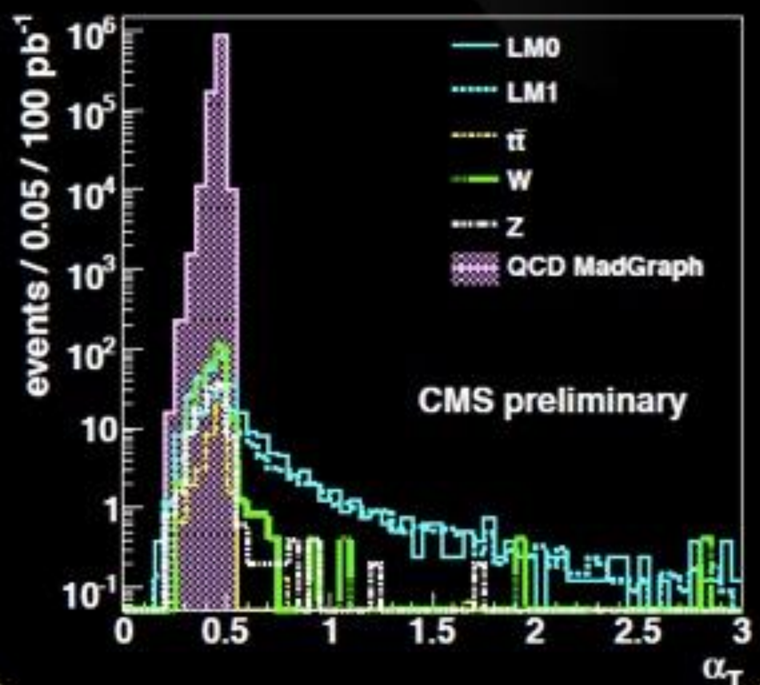
Randall, Tucker-Smith

Principles: QCD dijets back-to-back, with equal $p_T$;
MET in QCD is mostly fake, due to detector effects.

## Dijet:

$$\alpha_T = E_T^{j2} / M_T$$

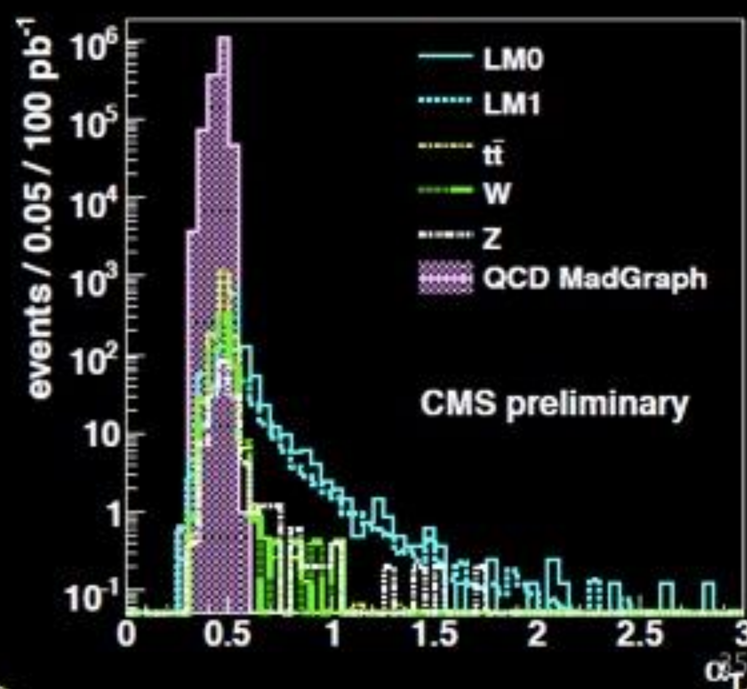
$$\alpha_T = \frac{E_T^{j2}}{\sqrt{2E_T^{j1}E_T^{j2}(1-\cos\Delta\phi)}} = \frac{\sqrt{E_T^{j2}/E_T^{j1}}}{\sqrt{2(1-\cos\Delta\phi)}}$$




## n jet generalization:

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

Make 2 pseudojets from the n jets.
2 jets should minimize ΔHT



## Summary

- LHC reached $18 nb^{-1}$, and aims about a $pb^{-1}$ in June.
- CMS happily running, performing well, generally remarkable data-Monte Carlo agreement.
- CMS and ATLAS alone cannot reveal the nature of DM, need help from direct/indirect detection experiments.
- First we must find an "excess" – then we will try all possible mass, BR, cross section measurements, from which DM properties could be extracted.
- 1fb-1 of 7 TeV will be sufficient to explore low mass regions of several BSM parameter spaces.