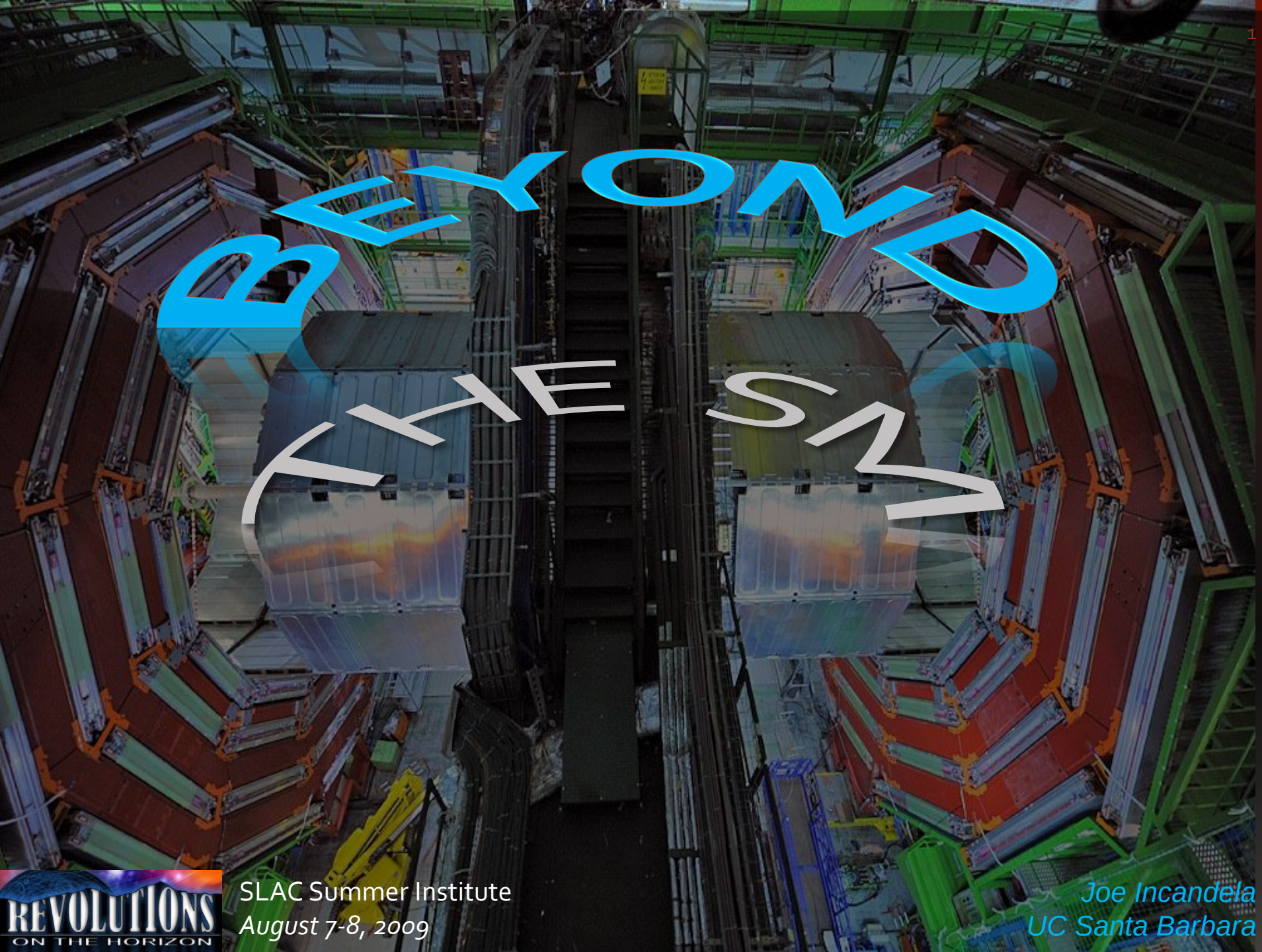
# BEYOND THE SM



REVOLUTIONS ON THE HORIZON

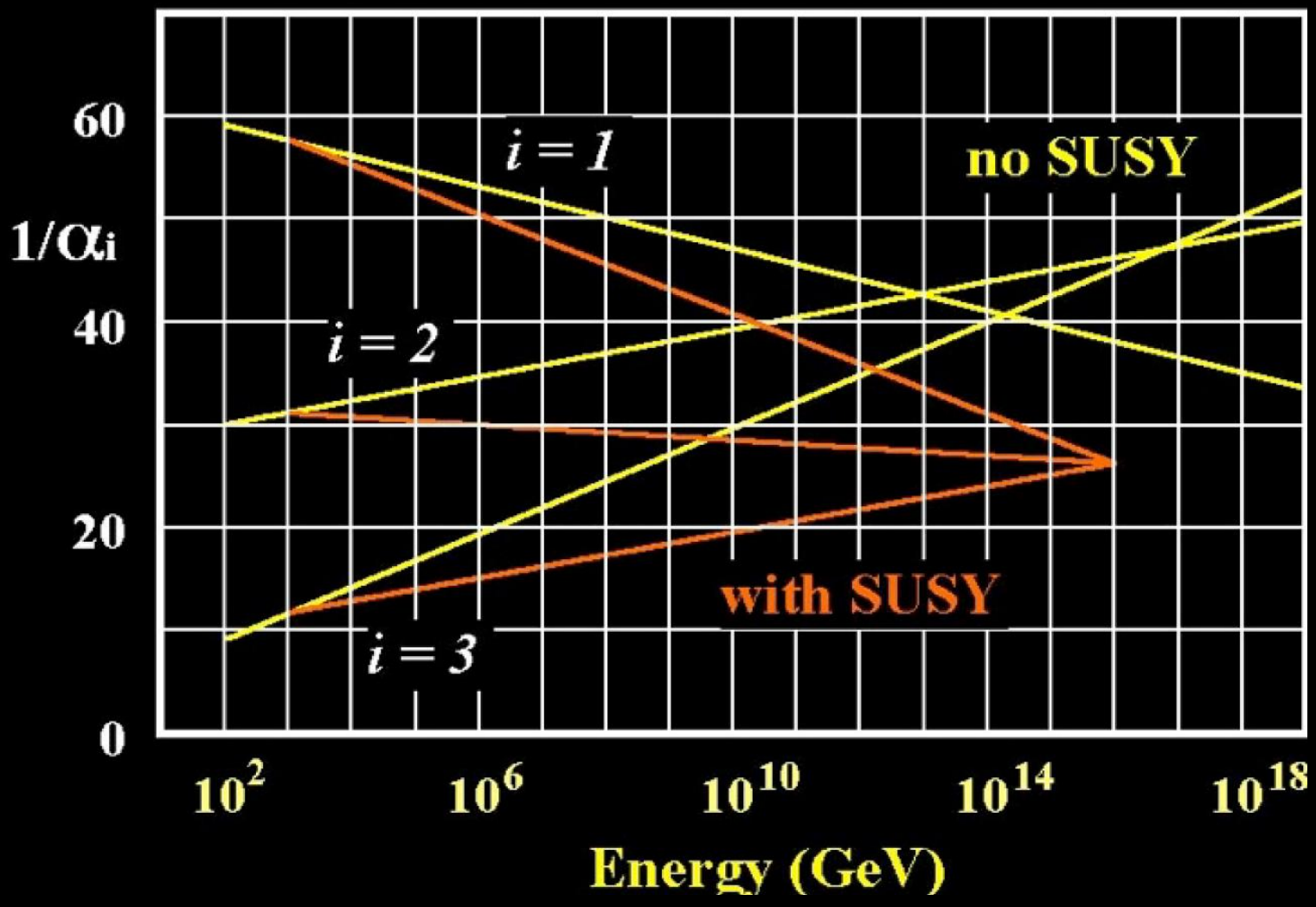
SLAC Summer Institute
*August 7-8, 2009*

*Joe Incandela*
*UC Santa Barbara*

# Current Situation

- Particle Physics
  - Many precise measurements consistent with the Standard Model (SM)
- Astrophysics and Cosmology
  - Abundant evidence for physics beyond the SM
- Experiments at the TeV scale could potentially help to bridge the gap
- Dark Matter
  - Relic Density for non-baryonic dark matter:
    - $0.094 < \Omega_{DM} h^2 < 0.129$ (95%CL)
      - h = 0.71 (km/s)/Mpc (Hubble)
- Weak scale SUSY with R-Parity conservation
  - Appealing characteristics including a dark matter candidate with the right relic density

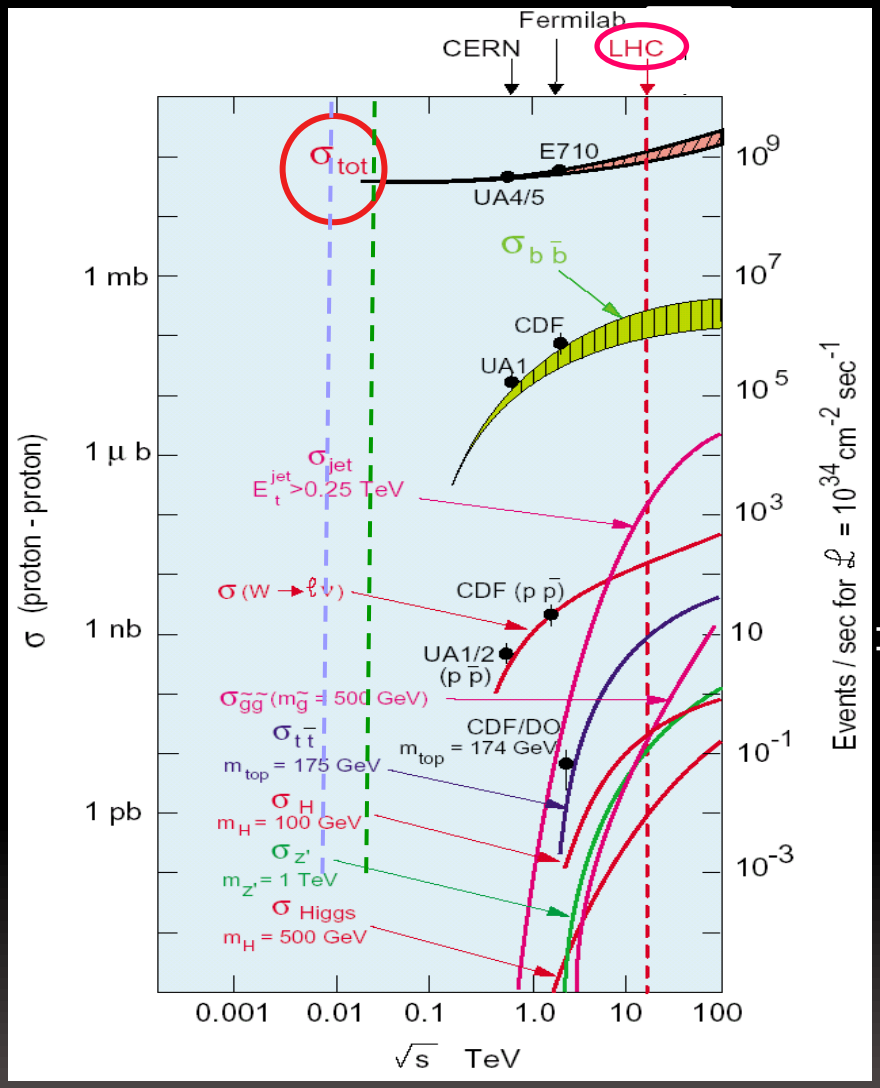
# The temptation unification



# Or maybe not

- The absence of SUSY at LEP and the Tevatron, coupled with the complicated array of results from cosmology and astrophysics experiments, has motivated many alternative models
  - Little Higgs (with T Parity)
  - Universal extra dimensions (with KK parity)
  - Strong dynamics
  - Extra dimensions (Large and warped)
  - Hidden Valleys
  - Split SUSY
  - …
- If you don't exactly know what you're looking for, a hadron collider is a great tool to be using.

# Hadron Colliders

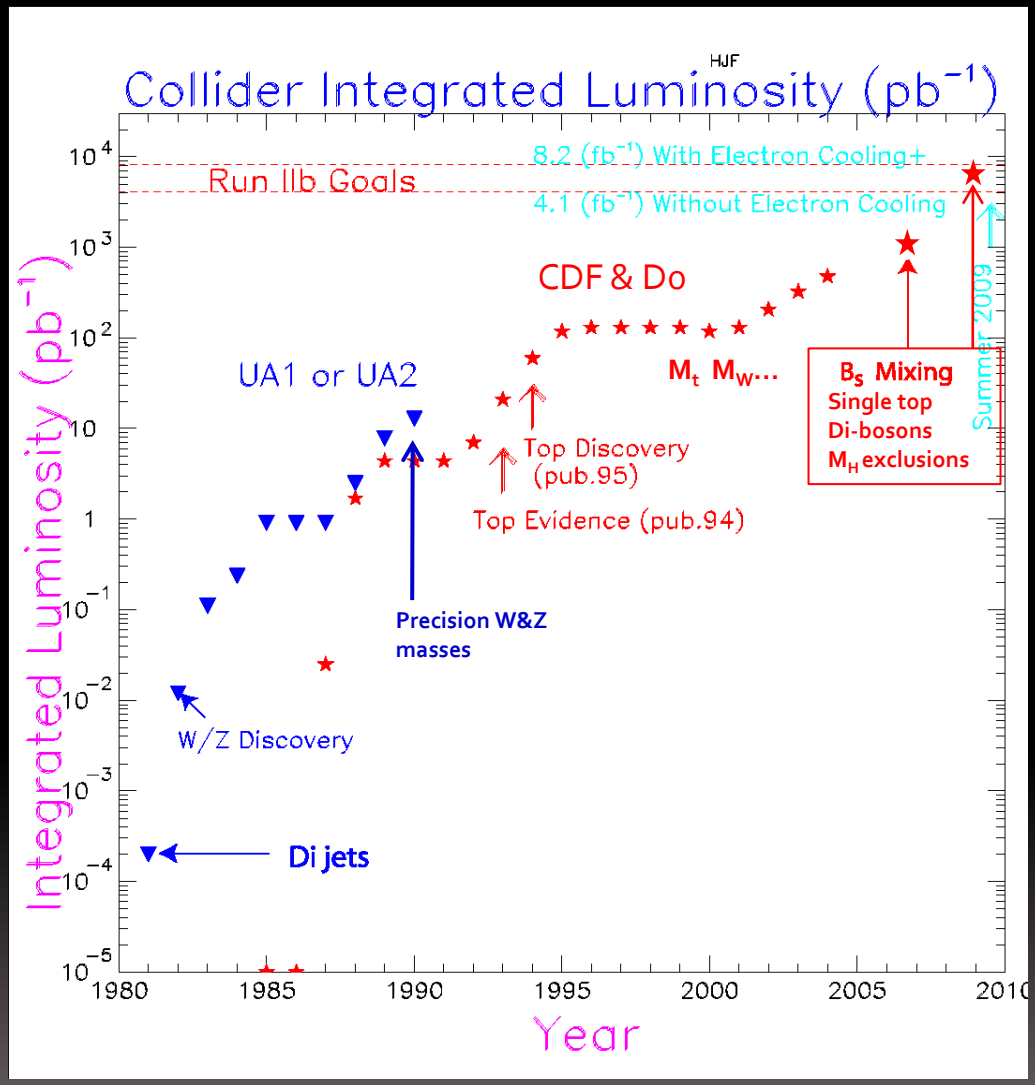



- Broad range of energies
- High mass scales and energies
- Large physics cross-section

⇒ Discovery machines …

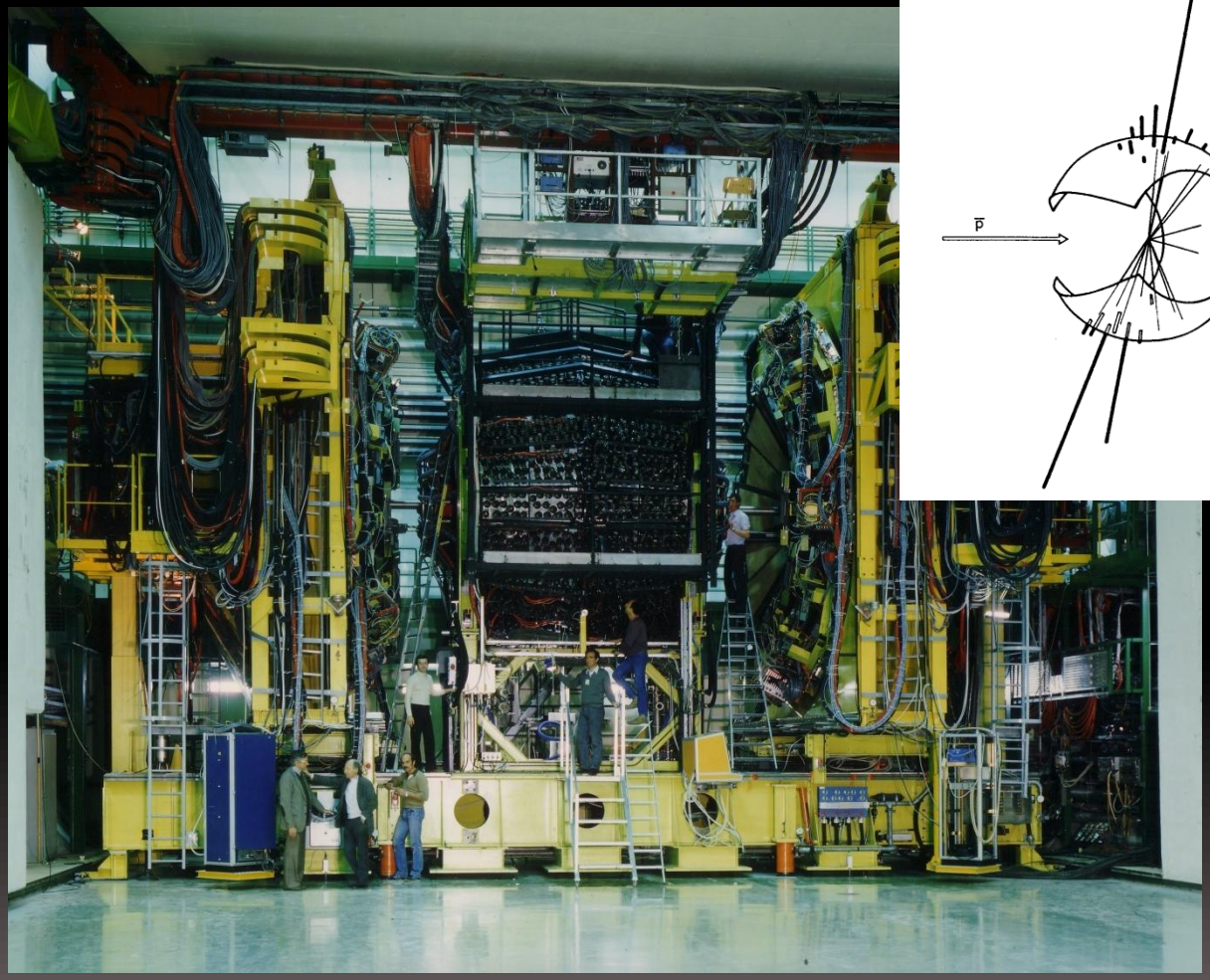
- But, interesting things are rare:
  - It takes great experiments (and sometimes a bit of luck…)

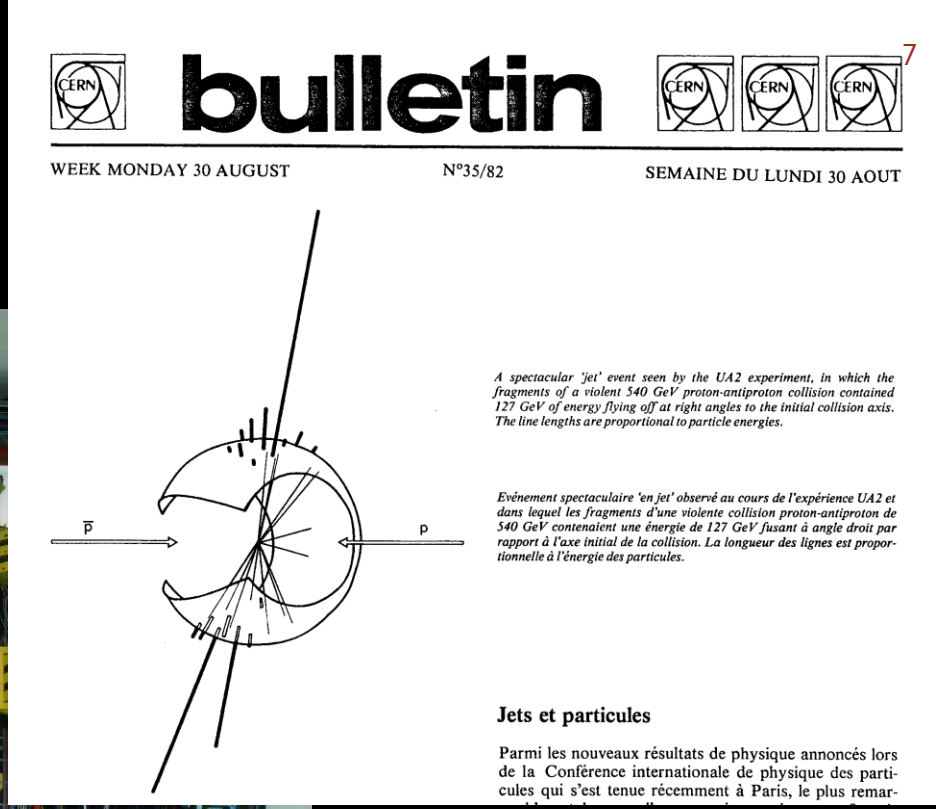
# Big things come early…and late.




- SPS & Tevatron Discoveries
  - SPS turn-on led to quick major discoveries by UA1 and UA2
  - Not true at the Tevatron
- SPS had a lot of data
  - Already probed a lot higher than the mean constituent com energy of ~100 GeV
- Tevatron needed to ~match SPS integrated luminosity
  - in order to probe a "new" energy domain and then discovered top!
- Early discoveries have been followed by other important results at hadron colliders
  - but these generally come late

# UA2





bulletin

WEEK MONDAY 30 AUGUST N°35/82 SEMAINE DU LUNDI 30 AOUT

*A spectacular 'jet' event seen by the UA2 experiment, in which the fragments of a violent 540 GeV proton-antiproton collision contained 127 GeV of energy flying off at right angles to the initial collision axis. The line lengths are proportional to particle energies.*

*Evénement spectaculaire 'en jet' observé au cours de l'expérience UA2 et dans lequel les fragments d'une violente collision proton-antiproton de 540 GeV contenaient une énergie de 127 GeV fusant à angle droit par rapport à l'axe initial de la collision. La longueur des lignes est proportionnelle à l'énergie des particules.*

**Jets et particules**

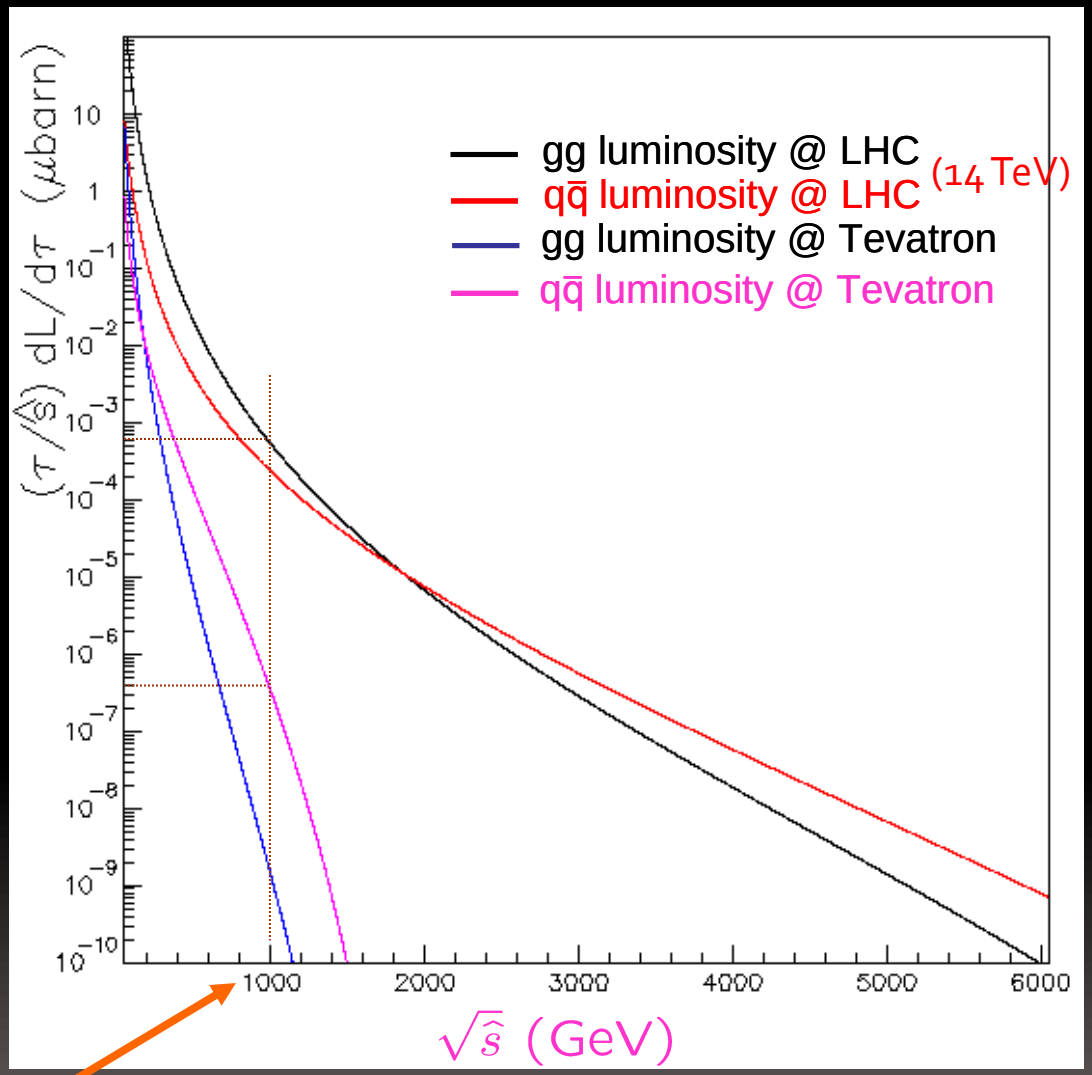
Parmi les nouveaux résultats de physique annoncés lors de la Conférence internationale de physique des particules qui s'est tenue récemment à Paris, le plus remar-

September 1981: first (small) run for UA2

↓

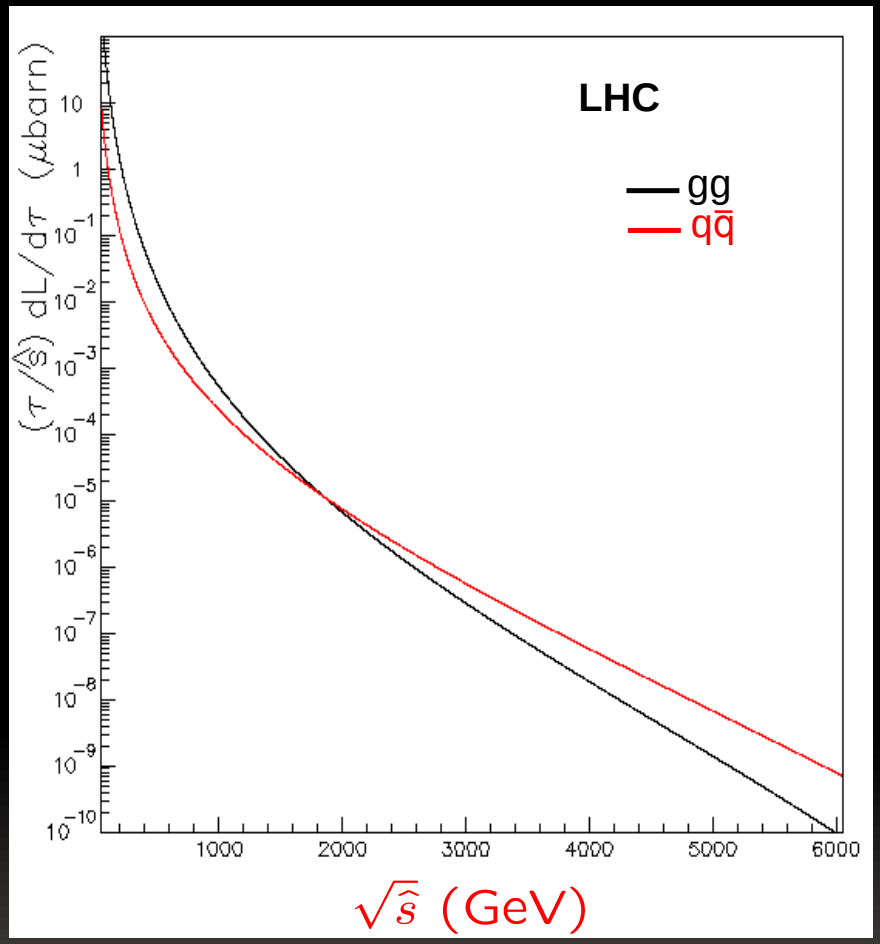
First observation of jets in hadronic collisions

# LHC will explore very new territory




- At 1 TeV constituent c.o.m. energy
  - 1 $fb^{-1}$ $q\bar{q}$ at Tevatron is like 1 $pb^{-1}$ gg at 14 TeV LHC

# Parton Luminosity falls steeply




Improving sensitivity is tough....
but you can turn evidence into an observation

- At the LHC it falls x10 every 600 GeV in multi-TeV region:
  - If you have a limit M > 1 TeV for a pair-produced particle, your sensitivity improves by ~ (600/2)=300 GeV = 30% for 10 times more integrated luminosity
- New states always produced near threshold
  - If nothing new is found relatively early, one may have to wait a long time

# Past versus future discoveries

Past

- W & Z
  - Masses and production rates were predicted
  - Signals stood out “like being hit on the head with a hammer”
  - Interpretation was unambiguous
- Top
  - Signal was a bit harder to dig out (initially a counting experiment) and less straightforward to interpret but…
  - We knew it had to be “somewhere”
  - Production and decay properties were predicted

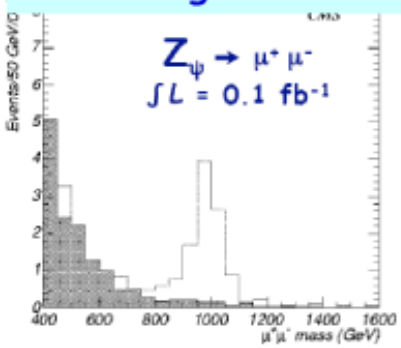
Future

- Higgs
  - Somewhat like top – for a given mass, we know its production and decay properties in the SM and alternative BSMs. For some masses, counting experiments may be the first sign.
  - Somewhat like W & Z –the signal could appear as a striking mass peak
- New Physics
  - Don’t know what to expect. Theory provides examples, some are compelling, none are guaranteed ...

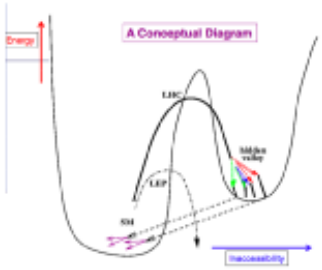
# BSM Billboard

## BSM Physics at the LHC: pp @ 14 TeV

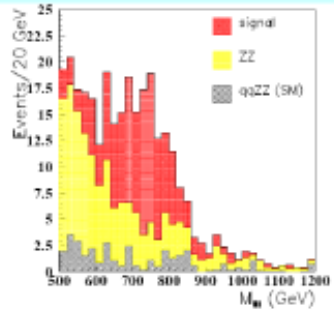
### New Gauge Bosons?



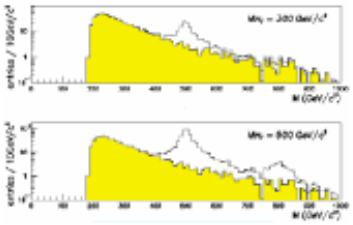

### Hidden Valleys?



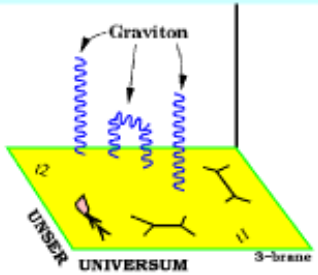

### ZZ/WW resonances?



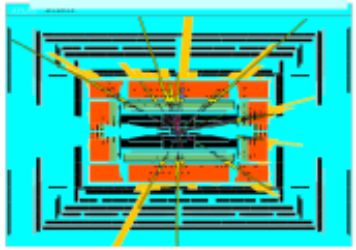

### Technicolor?



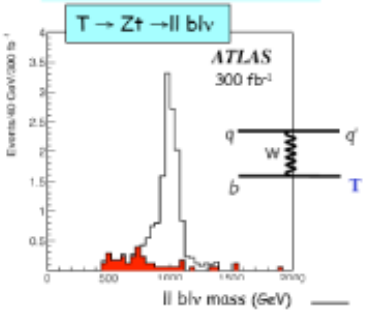
### Extra Dimensions?




### Black Holes???



### Little Higgs?




### Split Susy?


Starts to look like we have more models than theorists..

We do not know what is out there for us...

# BSM Signatures

- A few thoughts …
  - Models provide ideas for unexpected signatures
    - Very uncertain that any of these models will be seen, but there is an important benefit
      - We prepare more broadly and look at generic things from a different perspective
        - e.g. very boosted top quarks, very high $E_T$ leptons, triggering on jets when there's no beam!
  - The number and variety of theories are indicative of the fact that what's really needed is data!

## New Physics Signatures

Many channels in New Physics : Typical signals

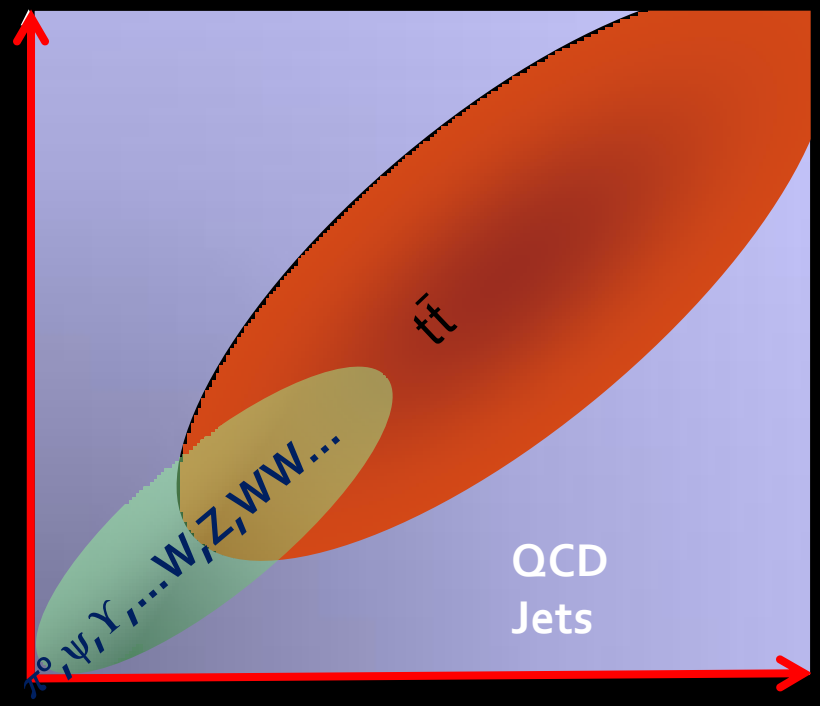
- Di-leptons (like sign/same sign)
- Leptons + MET
- Photons + MET
- Multi-jets (2 → ~10)
- Multi-jets +MET (few 10 → few 100 GeV)
- Multi jets + leptons + MET…
- B/τ final states…

Also: new unusual signatures

- Large displaced vertices
- Heavy ionizing particles (heavy stable charged particles)
- Non-pointing photons
- Special showers in the calorimeters
- Unexpected jet structures
- Very short tracks (stubs)…

*Albert De Roeck*

# The Standard Model at $\lesssim$ 10 TeV




A new window on Nature

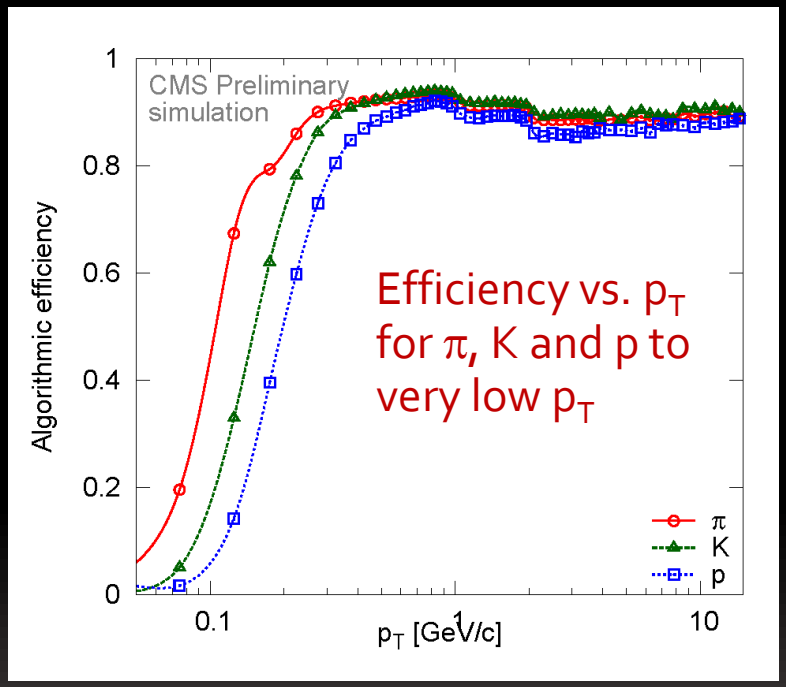
Parts of SM we have not seen.

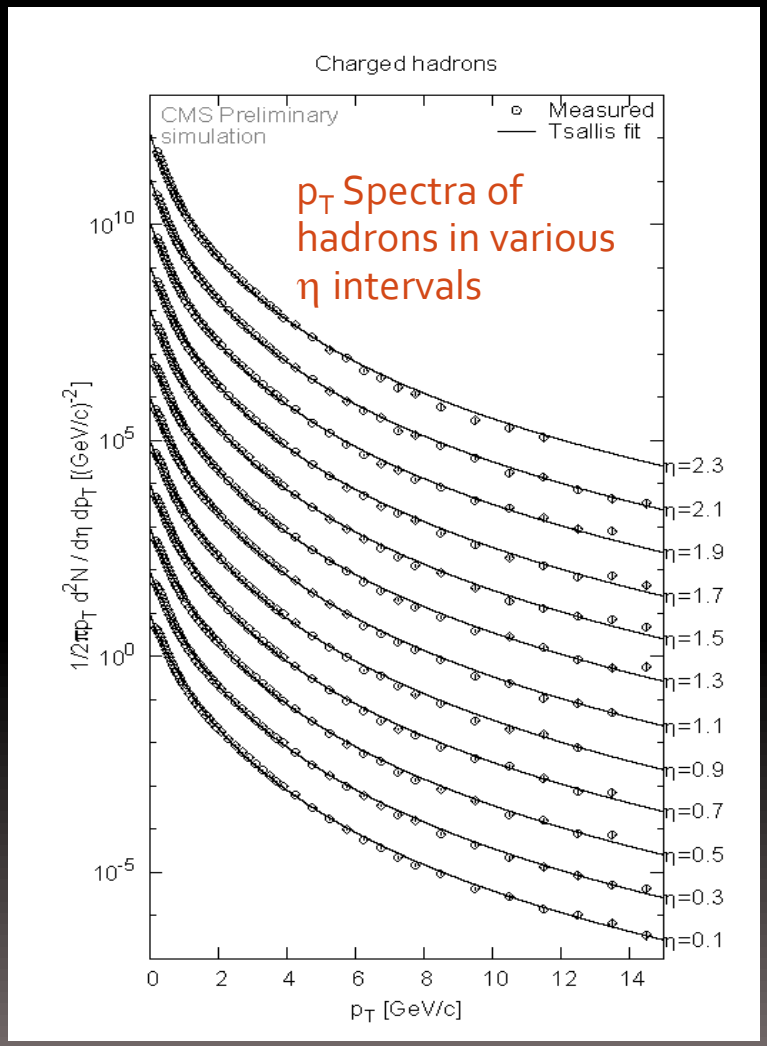
Somewhat familiar but more jets

- Low initial luminosity
  - Study Min Bias, $dN^{\pm}/d\eta$ etc
    - Refine triggers
    - Constrain Underlying Event, PDFs
      - Tune MC's
  - Jets
    - Optimize algorithms for resolution & scale
    - Study lepton fakes, b tagging, photons.
  - Then more complex final states
- Also calibrate with known objects
  - Study "candles" for leptons and photons
    - $\pi^0, \psi, \Upsilon$ initially to understand detector, tracking, leptons & other objects
    - Extend to W or Z $\rightarrow$leptons
- Compare to MC V+Jets (V=W,Z,$\gamma$)
- Extend into $t\bar{t}$ core region and then
- Deal with tails…

# Charged Hadrons

- Inclusive charged hadron production*
  - "first-paper" analysis…



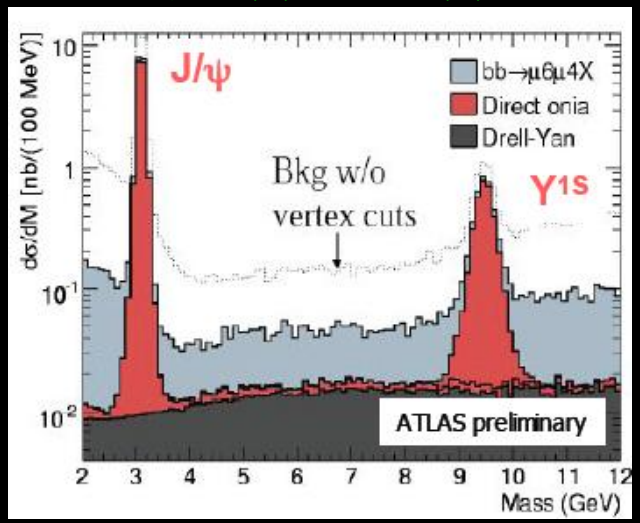




- constrain QCD models of hadron production

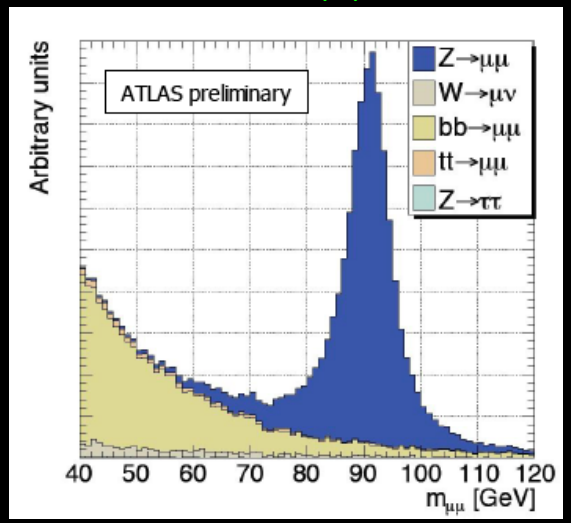
*14 TeV shown
recently repeated at 900 GeV and 10 TeV

# Explore the SM at 7-14 TeV

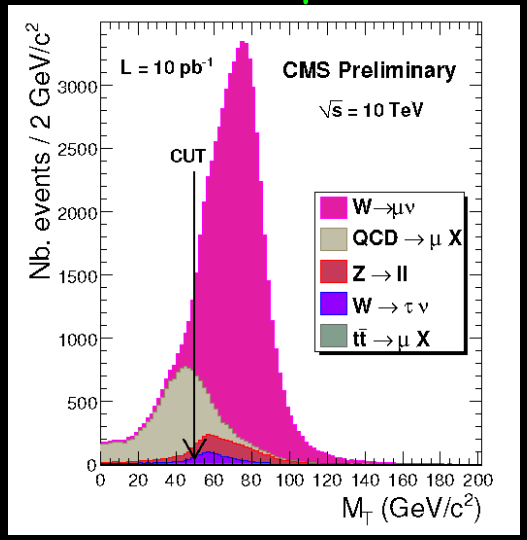
$J/\psi \to \mu\mu$ $\Upsilon \to \mu\mu$

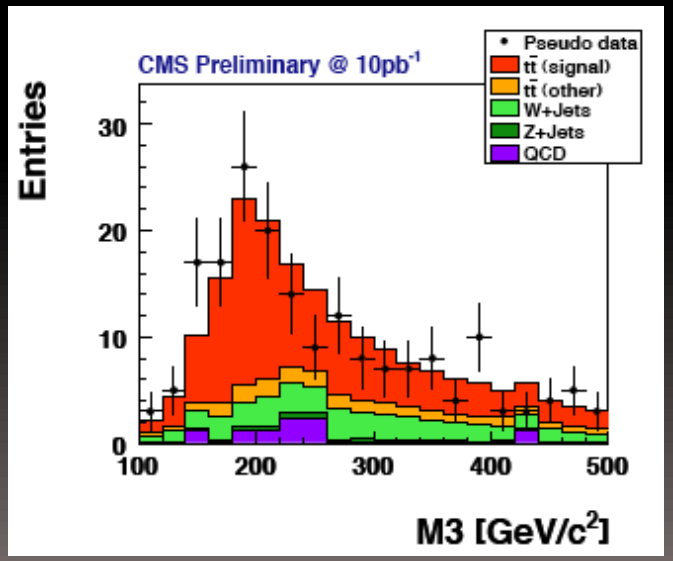



$Z \to \mu\mu$




$W \to \mu\nu$




$t\bar{t} \to q_1 q_2 \bar{b} b \mu\nu$

# Life at low x in a pp collider

- LHC ≠ Tevatron
  - Small momentum fractions x for many key searches:
- Large phase space for gluon emission
  - For $p_T^{jet} \gtrsim 20$ GeV, all $t\bar{t}$ events have additional jets
  - Ratio of LHC to Tevatron production cross sections for W/Z + n jets grows fast as n increases

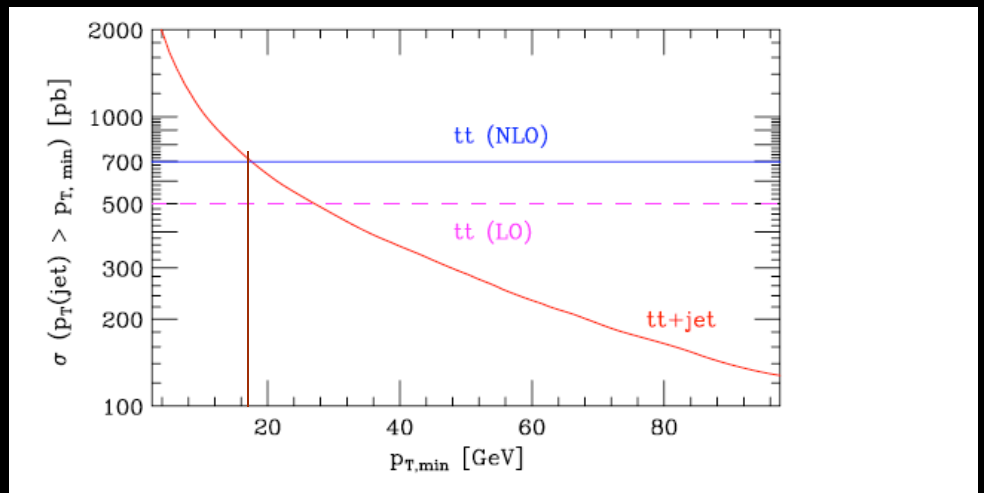
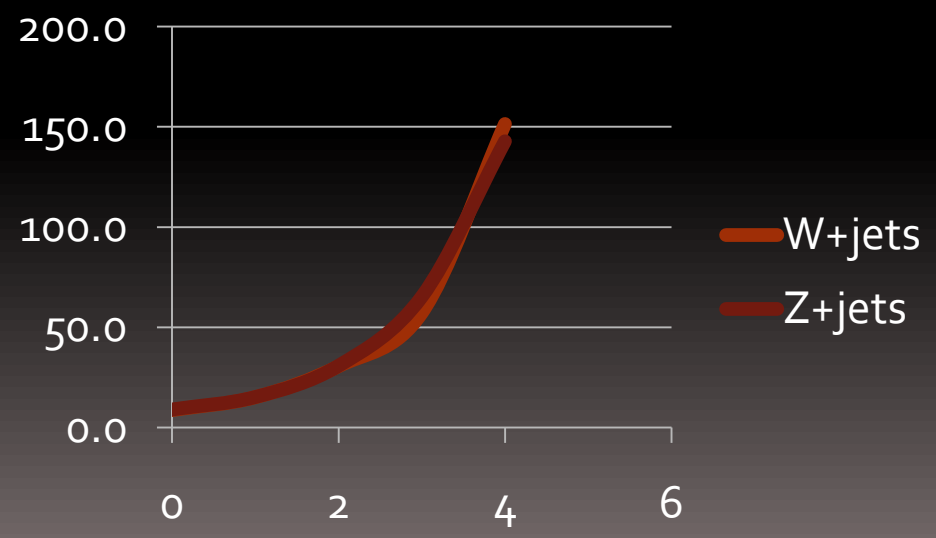


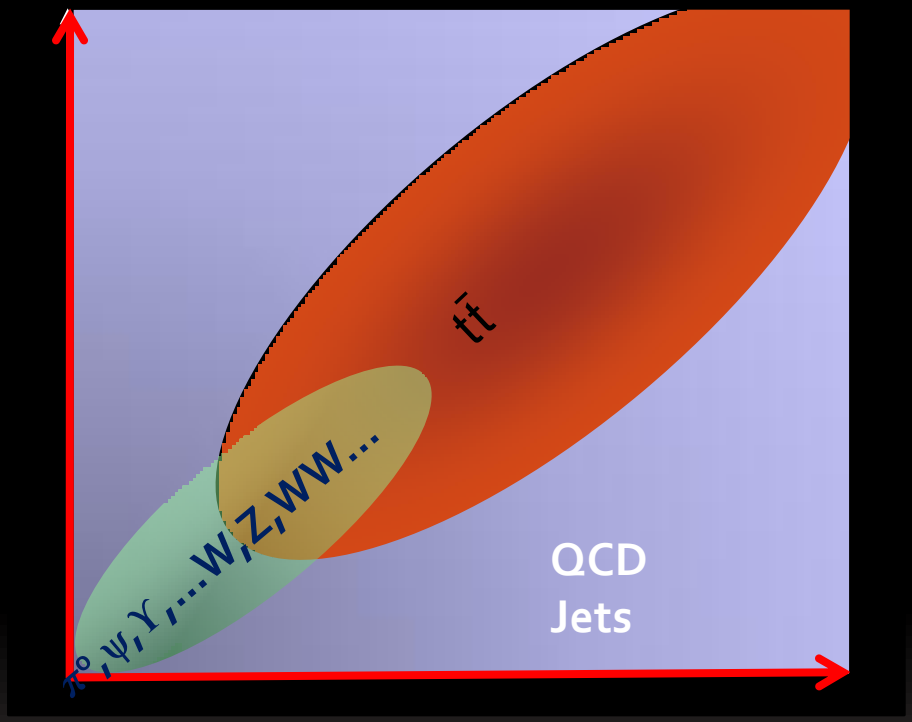

**Figure 95.** The dependence of the LO $t\bar{t}$+jet cross section on the jet-defining parameter $p_{T,\min}$, together with the top pair production cross sections at LO and NLO.

*Huston*




*M.L.Mangano*

# $t\bar{t}$




- Additional jets complicate reconstruction of $t\bar{t}$
  - First we need to understand the control regions:
    - W,Z,$\gamma$ + n jets for low n, and QCD jets faking e, $\mu$
  - Then we can begin to tackle the core regions of $t\bar{t}$.
- But the devil is in de tails

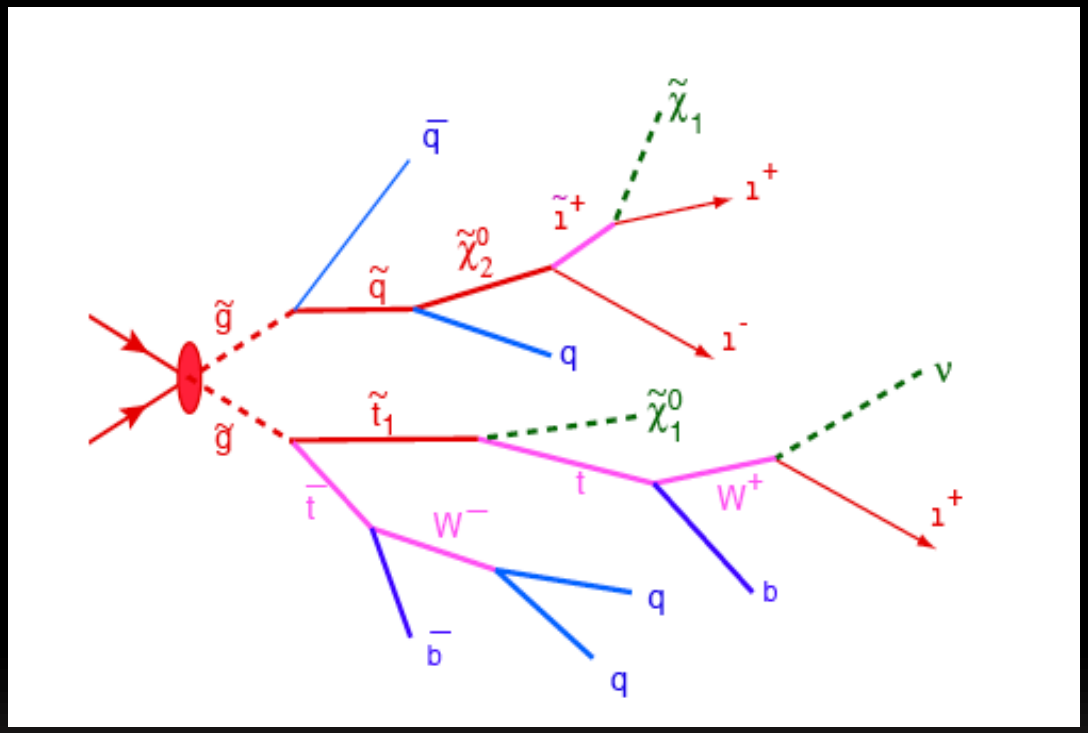
# SEARCHING FOR SOMETHING NEW

# Early Searches for New Physics

- Following the data
  - There is a lot of indirect evidence for the Higgs, direct evidence for Dark Matter (DM), and a good chance we can make one or both at the LHC
- Higgs (lecture 1)
  - Either a rare process or difficult to discriminate from background so…it will take a lot of data.
    - Not likely we can say that much about it in the upcoming run.
- Dark Matter
  - We don't know what it is
  - We can think of early SUSY searches as effectively looking for Dark Matter
    - The topologies, methods, backgrounds relevant to SUSY apply to broad class of Dark Matter theories

# "SUSY search"

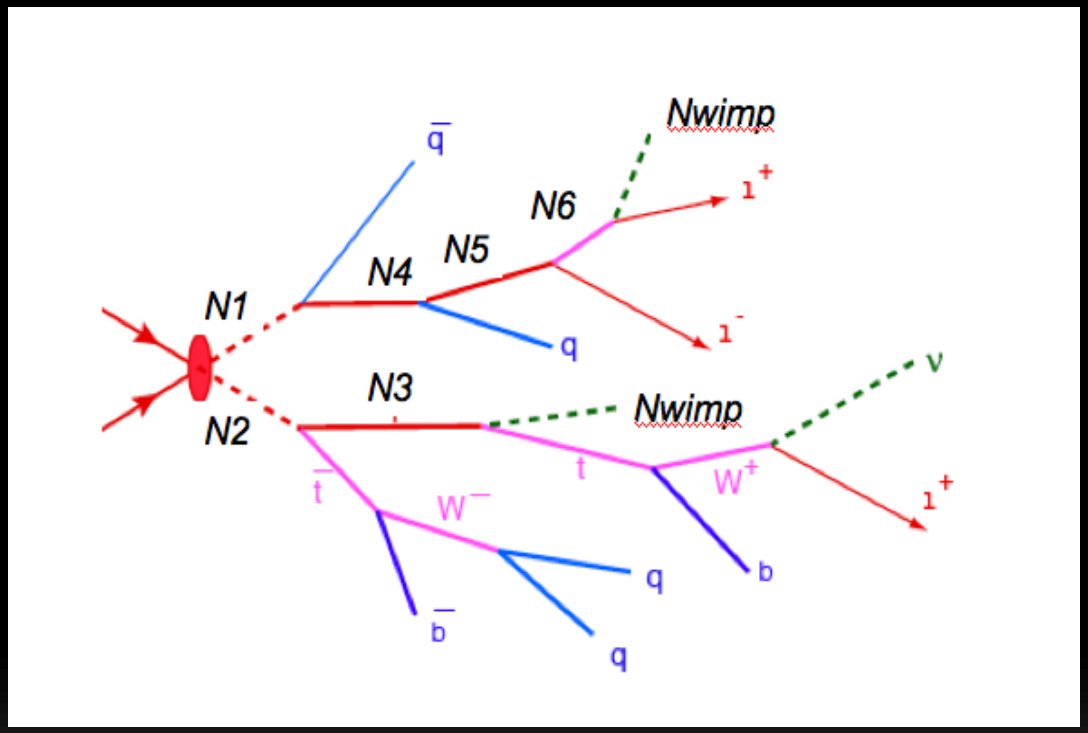





R-Parity-Conserving SUSY

- Missing Energy:
  - from LSP
  - 
- Multi-Jets:
  - from cascade decay (gaugino)
  - particles like top, W, Z)
- Multi-Leptons:
  - from decay of the Nj

# "SUSY search"




Extra dimensions, Little Higgs, Technicolor, etc

- Missing Energy:
  - Neutral Weakly Interacting Massive Particle (NWIMP)
  - NWIMP appears at the end of the cascade (which could be shorter or longer…)
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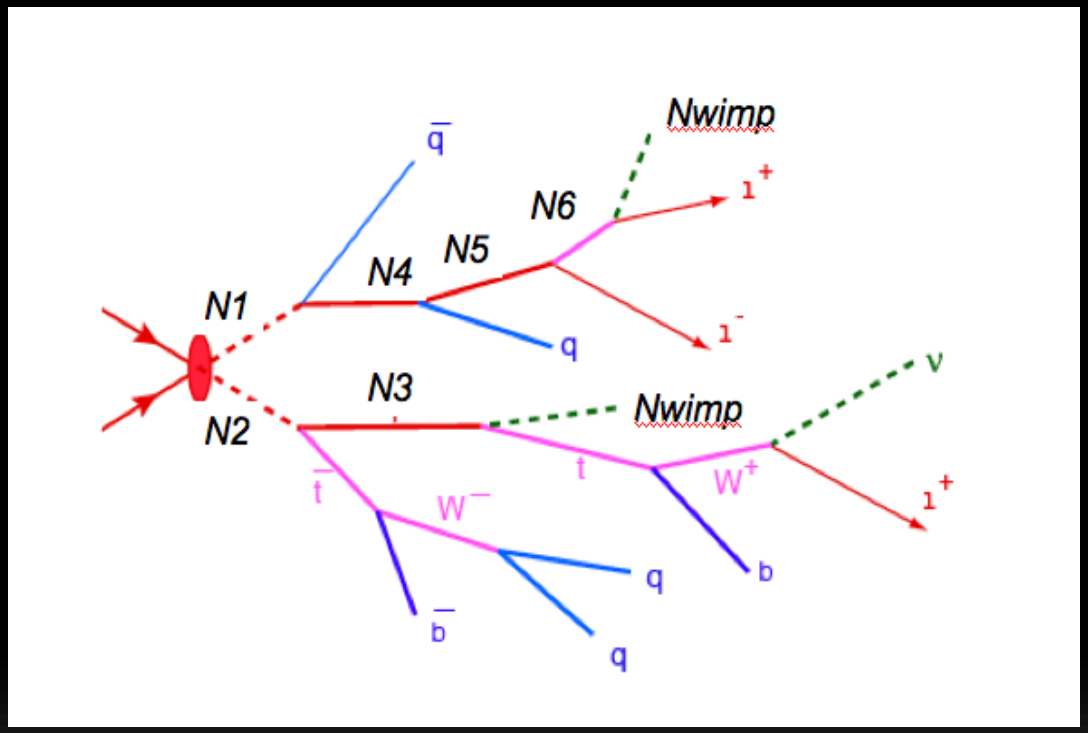


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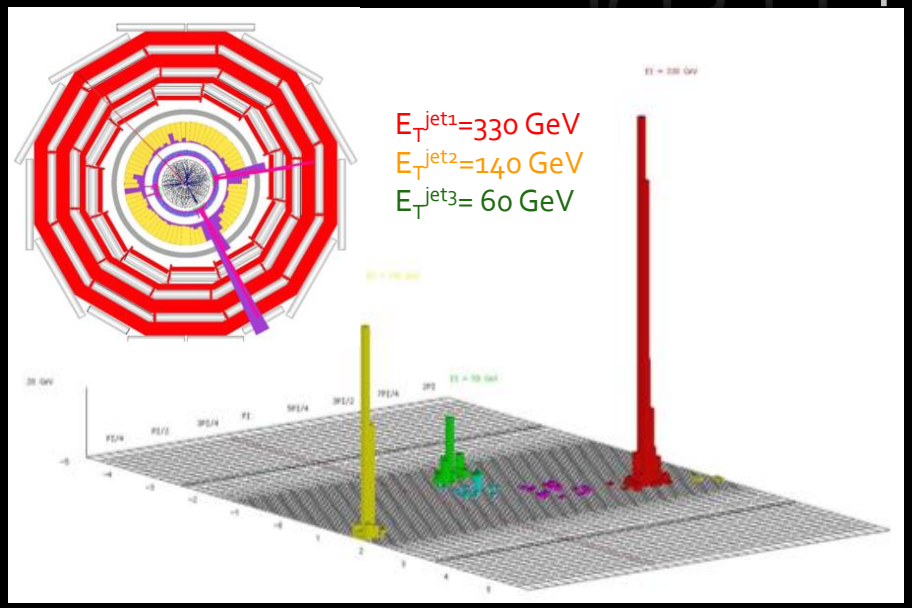
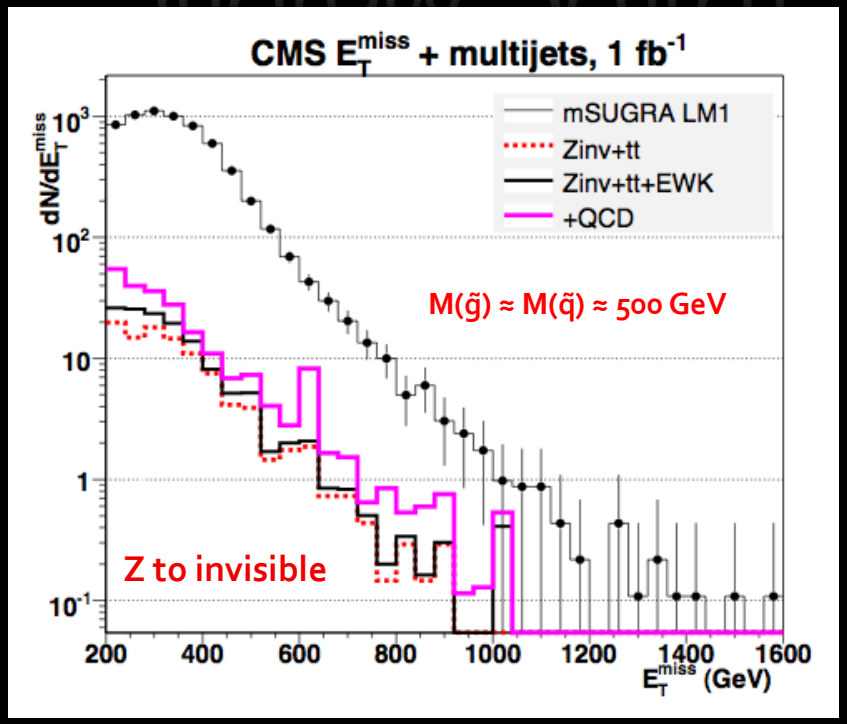
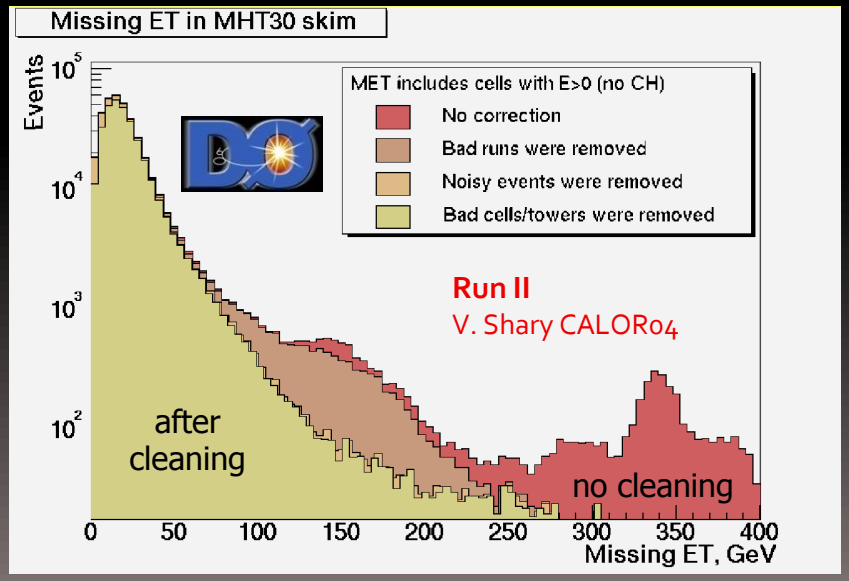
Extra dimensions, Little Higgs, Technicolor, etc

For SUSY we use mSUGRA at about ~10 points x in parameter space (LMx and HMx, in CMS and SUx in ATLAS x=1,2,3….). This is not because we believe only in mSUGRA but because we focus on different event signatures. We are now doing this more systematically

# Jets + $E_T^{miss}$ - Inclusive Search




The simplest topology and the greatest potential

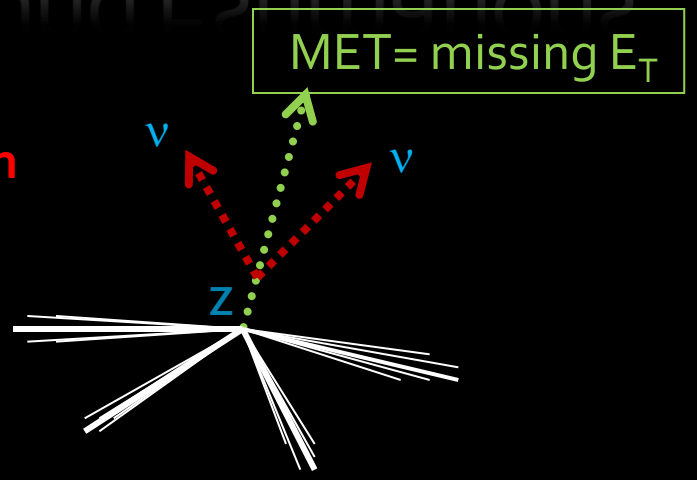
Analysis Strategy: be brave!

- Fight background and noise
- Use data control samples
- Estimate background from data

# Data Driven Background Estimations

**An illustrative example: Z→νν+jets**
**An irreducible background for Jets + MET search**

**Define control samples and understand their strength and weaknesses:**



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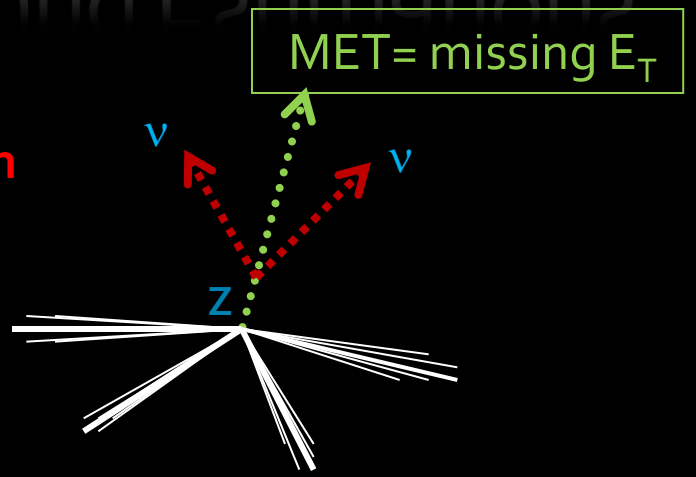


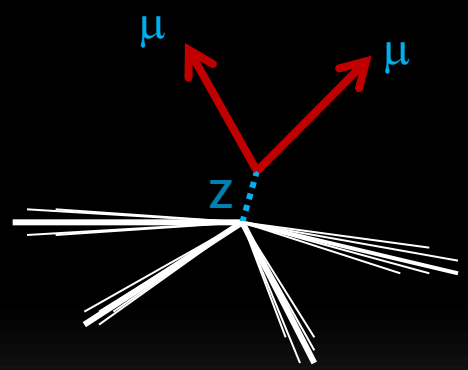


$Z \rightarrow \mu\mu$+jets

Ignore the 2 μ's and you have a good stand in for $Z \rightarrow \nu\nu$

very clean but low statistics: factor 6 suppressed compared with $Z \rightarrow \nu\nu$

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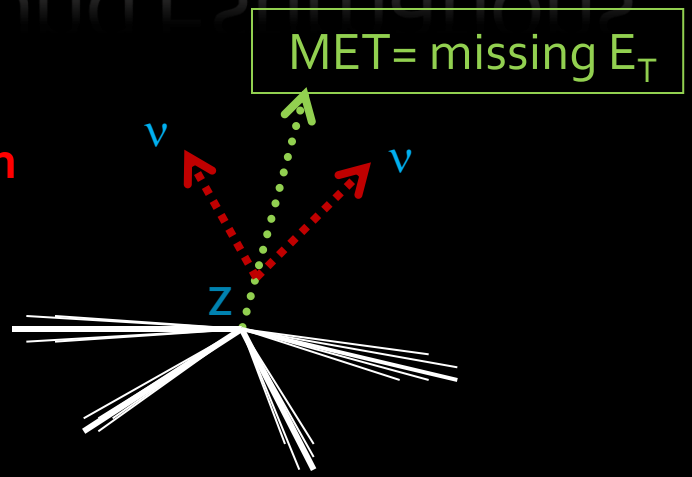


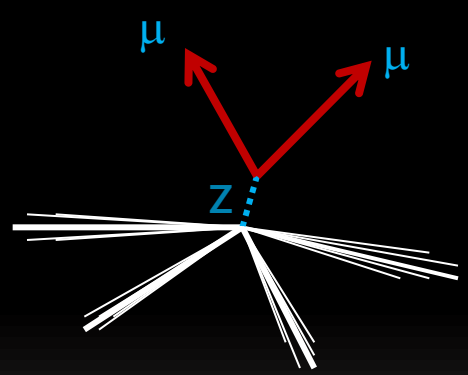


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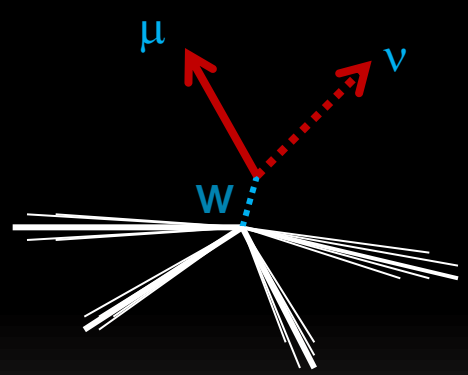


$W \rightarrow \mu\nu$+jets

Ignore the μ …

Larger statistics but not so clean, SM tt and signal contamination

# Data Driven Background Estimations

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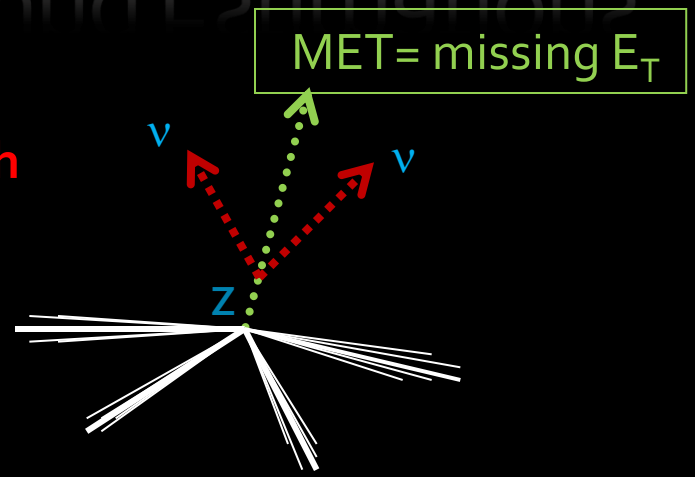
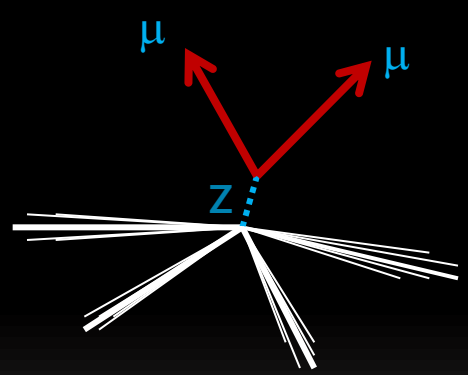
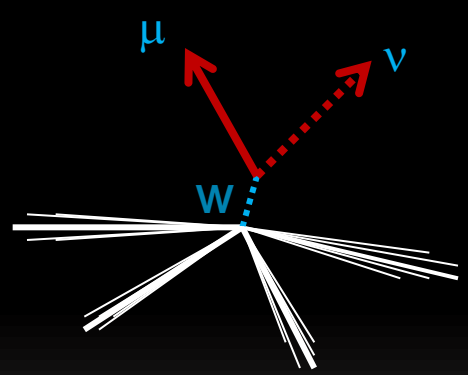
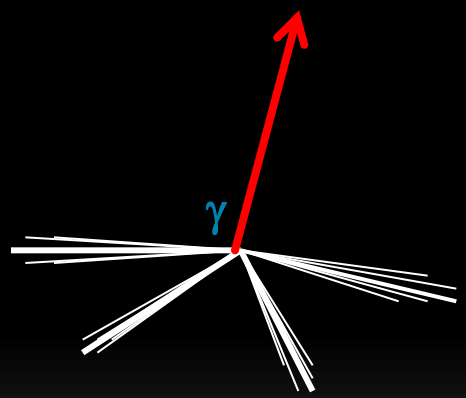
**Define control samples and understand their strength and weaknesses:**




$Z \to \mu\mu$+jets

Ignore the 2 μ's and you have a good stand in for $Z \to \nu\nu$

very clean but low statistics: factor 6 suppressed compared with $Z \to \nu\nu$

$W \to \mu\nu$+jets

Ignore the μ …

Larger statistics but not so clean, SM tt and signal contamination

γ+jets

Ignore the γ …

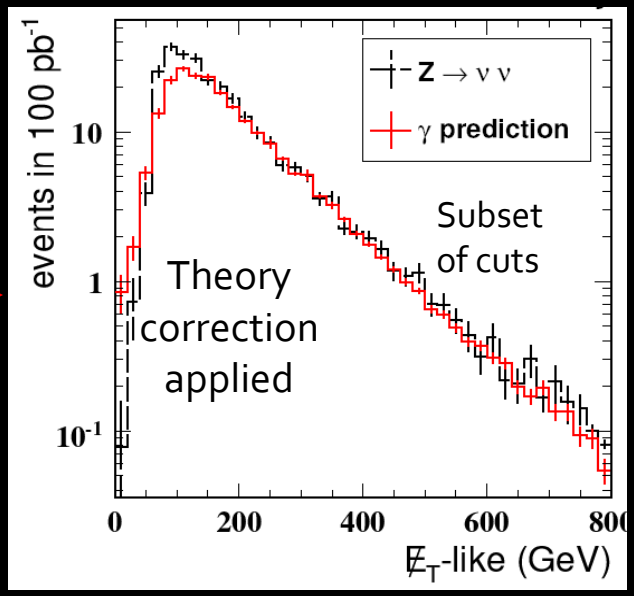
Large statistics, clean for $E_\gamma > 200$ GeV

# Predicting $Z \rightarrow \nu\bar{\nu}$ 100 pb$^{-1}$

Search region (MET> 200GeV)

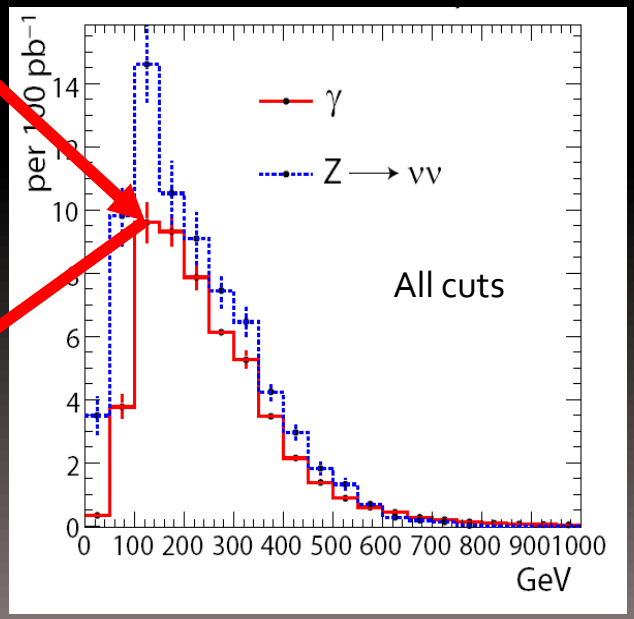
$\gamma$ + jets: 124 Events per 100 pb$^{-1}$ (14 TeV)

- Photon backgrounds estimated from data
  - QCD, electrons
  - QFT correction to reproduce Z spectrum
  - NB: Out-of-box agreement is already good without QFT corrections




W + jets: 24 events with $W \rightarrow \mu\nu$

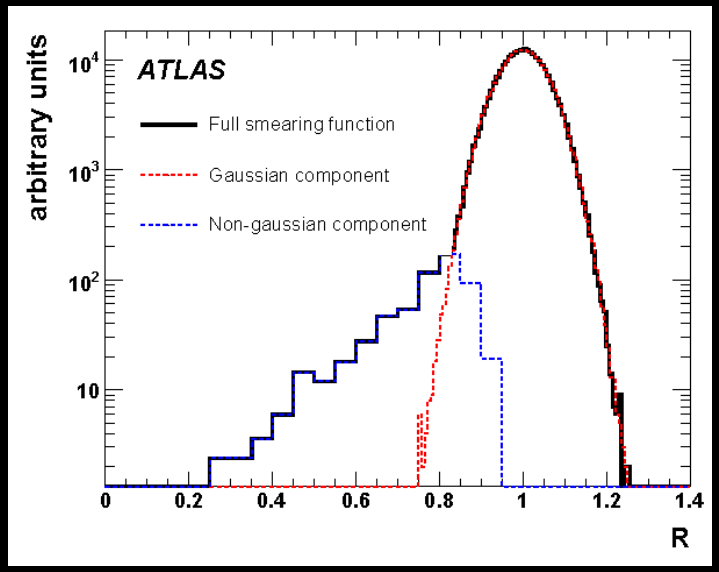
- Backgrounds estimated from data
  - QCD, $t\bar{t}$, Z
- Well known correspondence to Z+jets

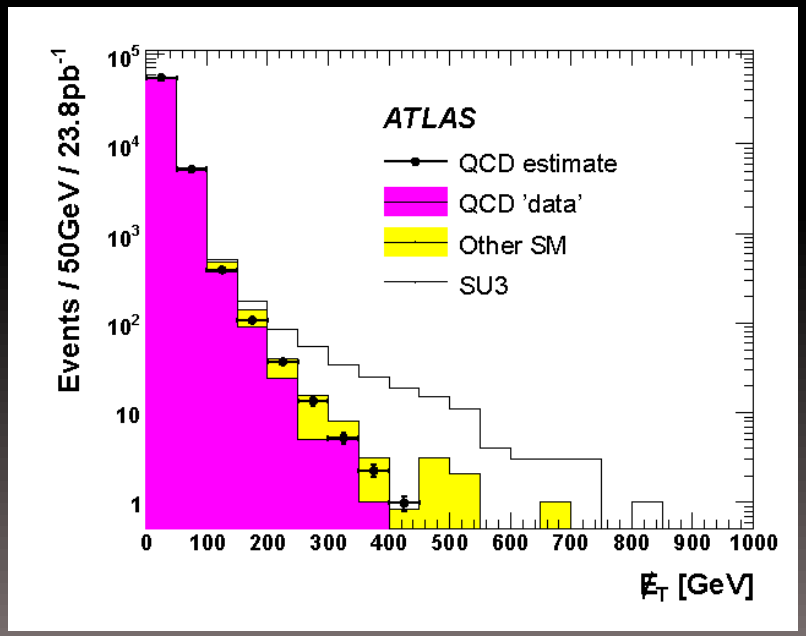



| $Z \rightarrow \nu\nu$ background estimate (100 pb$^{-1}$) | |
|---|---|
| MC-truth | 35 |
| From $\gamma$+jets | $29 \pm 3$ (stat) $\pm 5$ (sys) uncorrected |
| From W+jets | $35 \pm 10$ (stat) $\pm 8$ (sys) $\pm 3$ (theory) |

$Z \rightarrow \mu\mu$ + jets: only 4 events pass the search cuts

# QCD is harder…



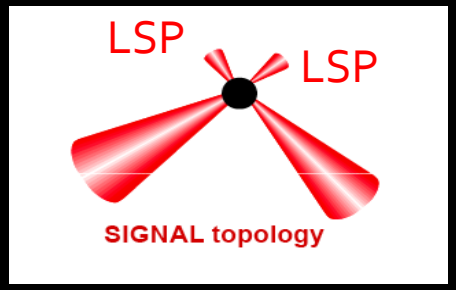

- Need to predict MET in multijet events without using MC
  - Jet response functions
    - Gaussian piece from jet+photon events, using transverse energy of photon to determine "true" jet $E_T$
    - Non-Gaussian piece from multijet events in which MET is aligned with a jet
  - Apply to data
    - Use jet response to smear $E_T$ of jets in multi-jet events that have no significant MET associated with the jets

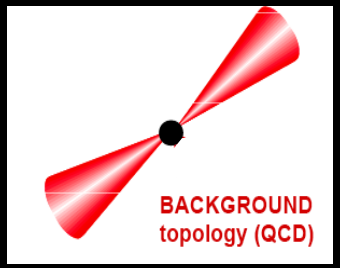
# SUSY search with dijet events using $\alpha_T$

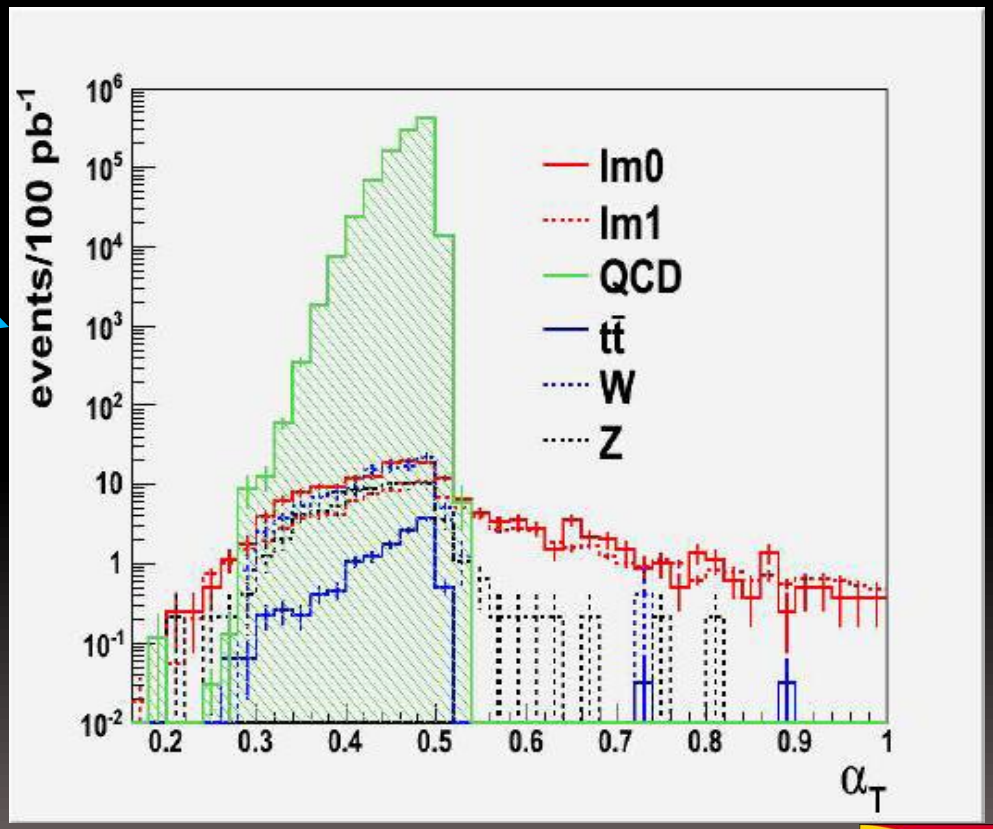
- Case of a short cascade
  - $\tilde{q}\tilde{q}$ production with $\tilde{q} \rightarrow q$+LSP
- Signature:
  - 2 jets + MET
- Kinematic cuts:
  - $\Delta\Phi < 2/3\pi$
  - $\alpha_T > 0.55$

$$\alpha_T = \frac{E_{Tj2}}{M_{Tj1j2}} = \frac{\sqrt{E_{Tj2}/E_{Tj1}}}{\sqrt{2(1-\cos\Delta\varphi)}}$$

  - (inspired by arXiv0806.1049)
- Use kinematics of dijets:
  - No direct calorimetric MET dependence
- Has been extended to n-jet systems
  - http://cms-physics.web.cern.ch/cms-physics/public/SUS-09-001-pas.pdf



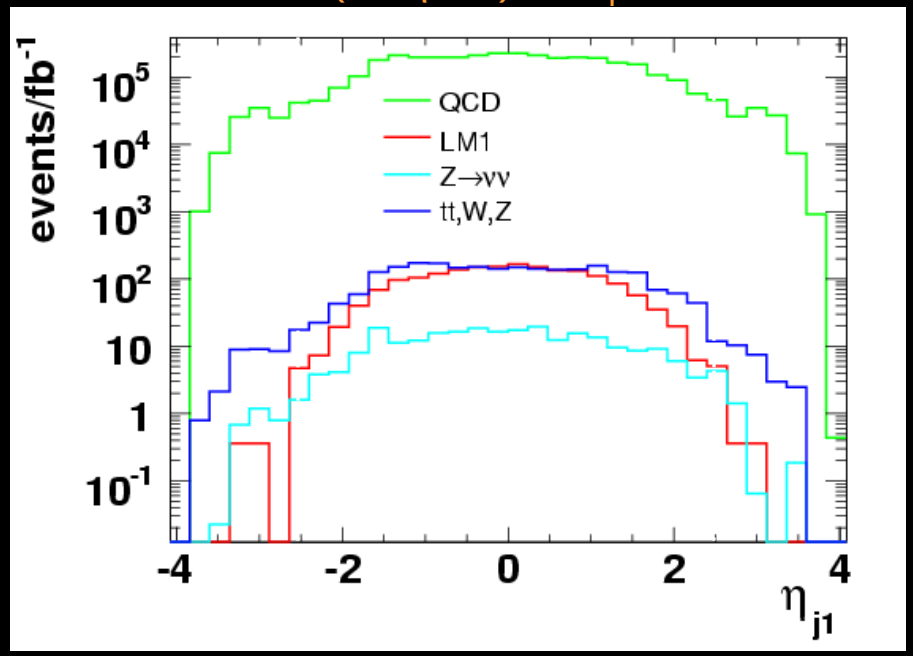
# Background Estimate from data

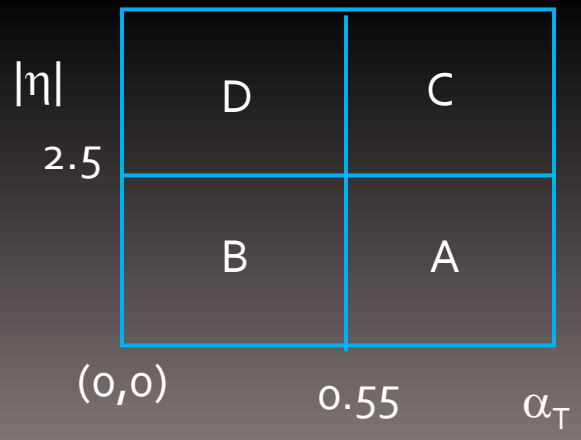


- Signal enriched/depleted regions
  - Split sample via:
    - Leading jet central
    - Leading jet forward
  - SUSY is central ⇒ use following ratio of event counts in forward regions ($|\eta| \geq 2.5$) to predict central background ($|\eta| < 2.5$).

$R_\alpha \equiv N(\alpha_T > 0.55)/N(\alpha_T < 0.55)$

Pre-selection (no $\eta$ cut) + $H_T > 500$ GeV



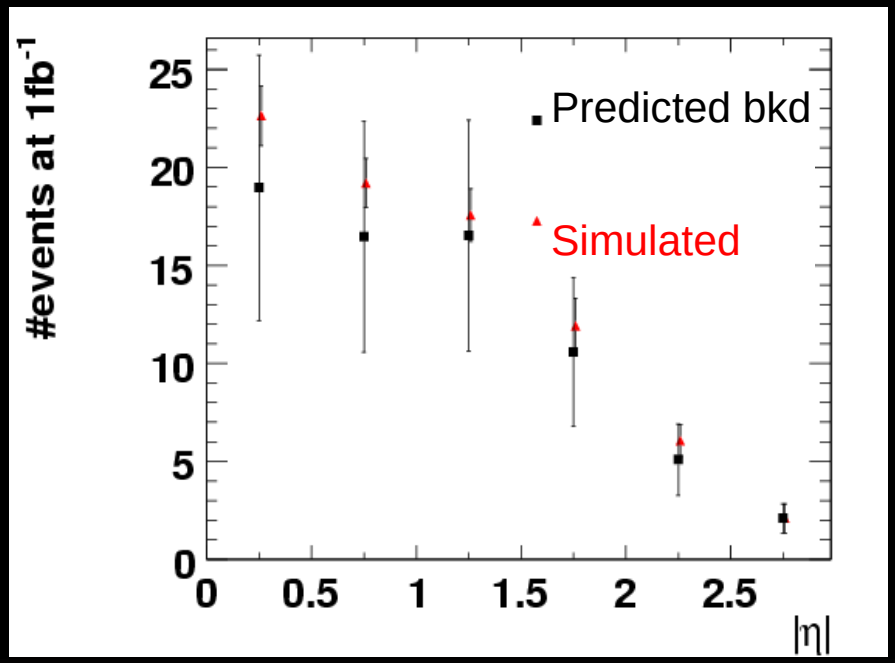

$R_\alpha = N_C/N_D$: assumed to be constant over $\eta$ and ~ signal free

Background in signal region A:

$N_A = N_B * R_\alpha$

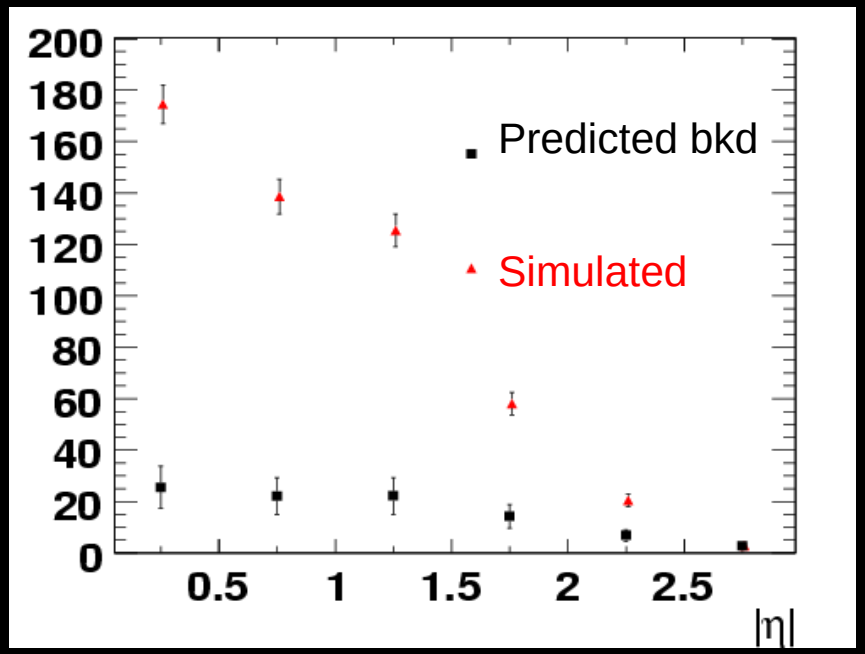
# Without and with SUSY

**Without SUSY (closure test)**




simulated: 77 ± 3
predicted: 68 ±12

**With SUSY LM1**



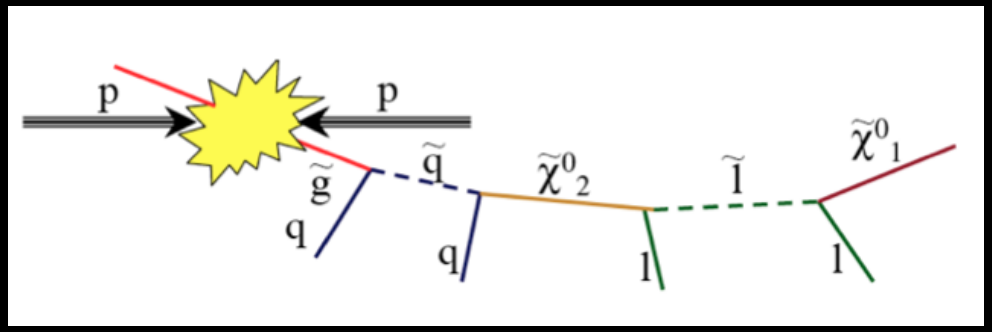

simulated: 517 ± 13
predicted: 91 ± 14

# MET + Jets + n leptons

- Lower rates and backgrounds
- Similar approach as for MET + Jets
  - Expected yields & backgrounds smaller
- N=1 Lepton: Backgrounds
  - W+jets, tt involving single leptonic W decay
  - Z+jets, tt with 2 leptonic W decays
    - In both cases, a lepton is lost (outside acceptance) or not identified (overlaps a jet, or involves significant Bremstrahlung etc.)
  - QCD Multijets
    - A jet fakes a lepton and there's large MET from jet mismeasurement
- N=2 Leptons: Background
  - W+jets, tt involving single leptonic W decay
    - Now a jet fakes the second lepton
    - Z+jets, tt with 2 leptonic W decays
- Small contributions from single top, dibosons etc.

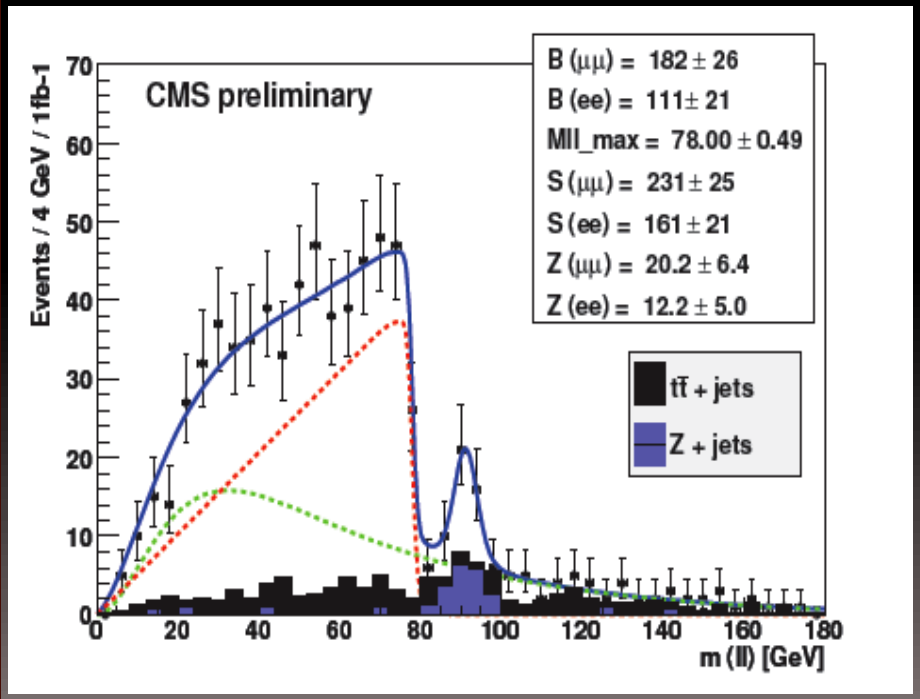
# First Kinematic Measurements

…With a bit of luck we might see this




- Two undetected particles of unknown mass in the final state so cannot reconstruct mass peaks
- Edges, endpoints give 1st detailed info on underlying spectrum

Jets + MET+ 2 Leptons of Same Flavor and Opposite Signs (SFOS )




$$M_{\ell\ell}^{max} = M(\tilde{\chi}_2^0)\sqrt{1-\frac{M^2(\tilde{\ell}_R)}{M^2(\tilde{\chi}_2^0)}}\sqrt{1-\frac{M^2(\tilde{\chi}_1^0)}{M^2(\tilde{\ell}_R)}}$$

- Estimate SF $t\bar{t}$ and WW bkgd from $e\mu$ events
- Relatively precise extraction of $M_{ll}^{max}$ early

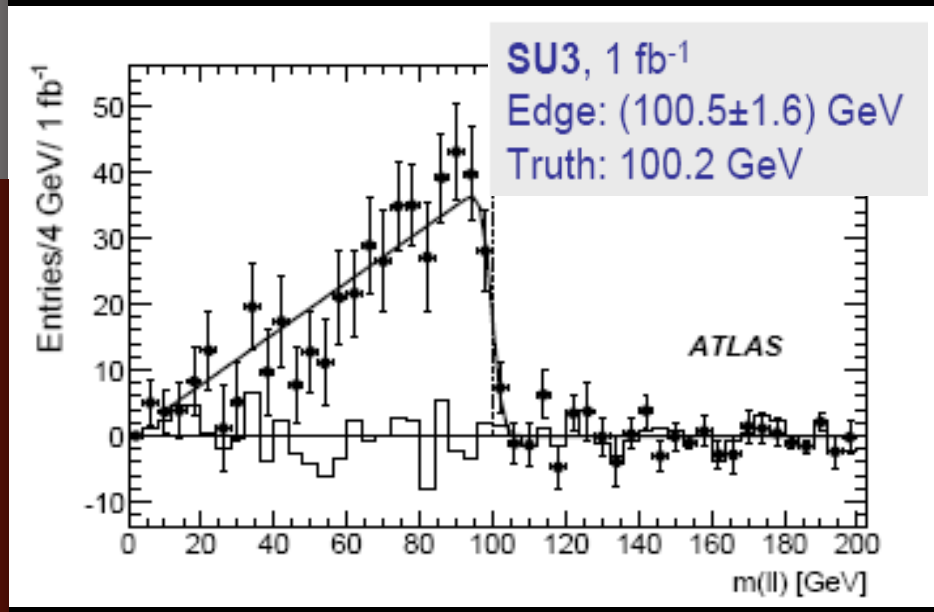
$\Delta M_{ee}^{max}=1.07_{stat}\pm0.36_{sys}$ GeV for 1 $fb^{-1}$

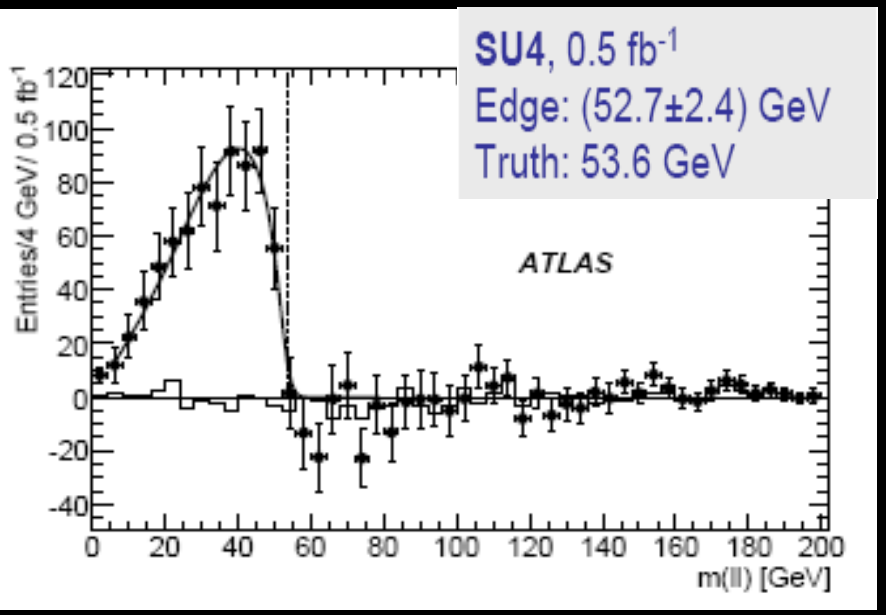
$\Delta M_{\mu\mu}^{max}=0.75_{stat}\pm0.18_{sys}$ GeV for 1 $fb^{-1}$

# Dilepton edge

$\tilde{\chi}^0_2 \rightarrow \tilde{l}\, l \rightarrow \tilde{\chi}^0_1 \; l^+ l^-$

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




SU3 (bulk point), two body decays
Fitting function: triangle smeared with a gaussian

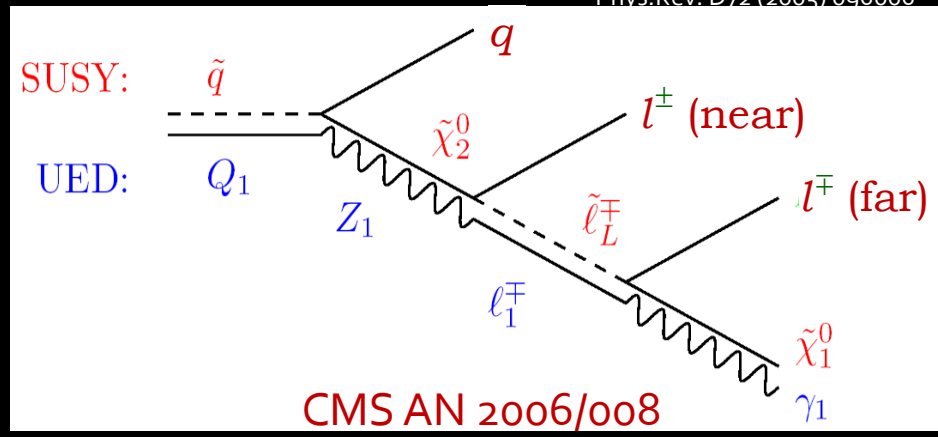
SU4 (low-mass point near Tevatron limits), three body decay.
Fitting function: theoretical three-body decay shape with Gaussian smearing

More luminosity is needed to discriminate 2-body and 3-body decays.
With 1 $fb^{-1}$ both fitting functions give reasonable $c^2$.

# What we see may be difficult to interpret

- Minimal Universal Extra Dimensions
  - 1 Extra compact dimension: R
  - Everything propagates in Bulk
  - KK tower of "SM-like" states

Datta, Matchev, Kong
Phys.Rev. D72 (2005) 096006



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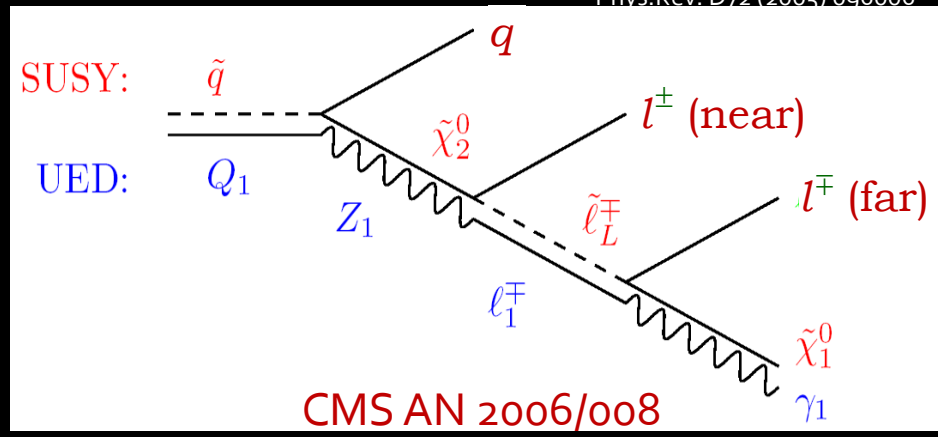
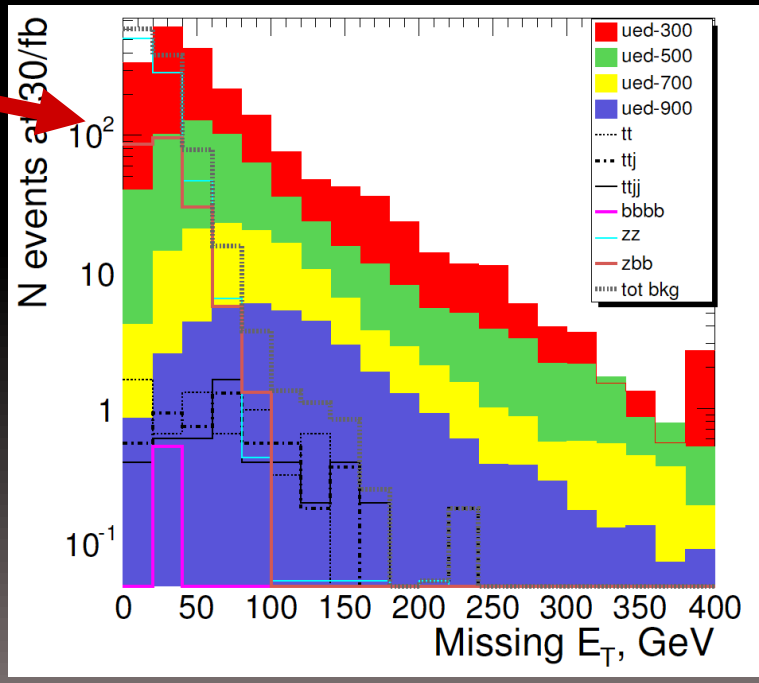



CMS AN 2006/008

Signatures like low mass SUSY!
  - Many Jets
  - Large MET (KK parity → stable LKP)
  - Leptons
    - With OS dilepton mass edges
  - High cross-section
    - Early Physics Potential
- Current constraints:
  - $R^{-1}$ > 600 Gev (for $m_H$ >115 GeV)



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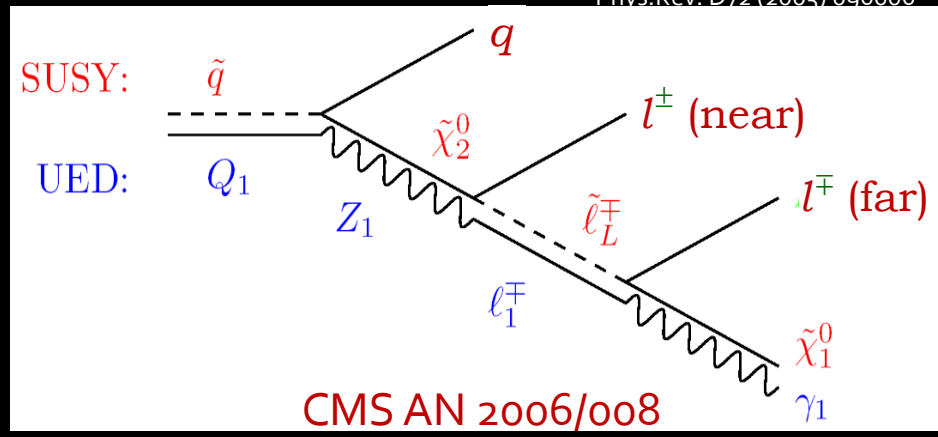


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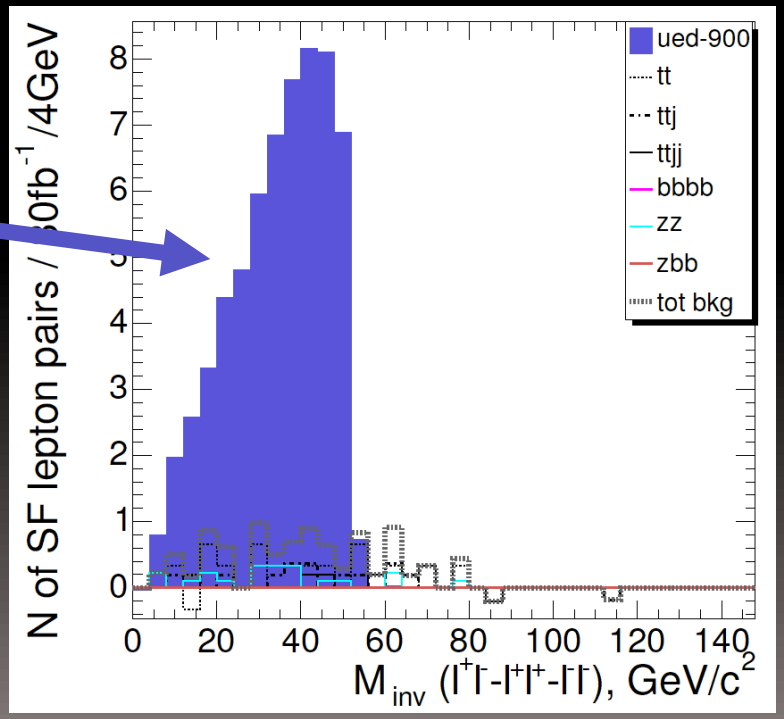

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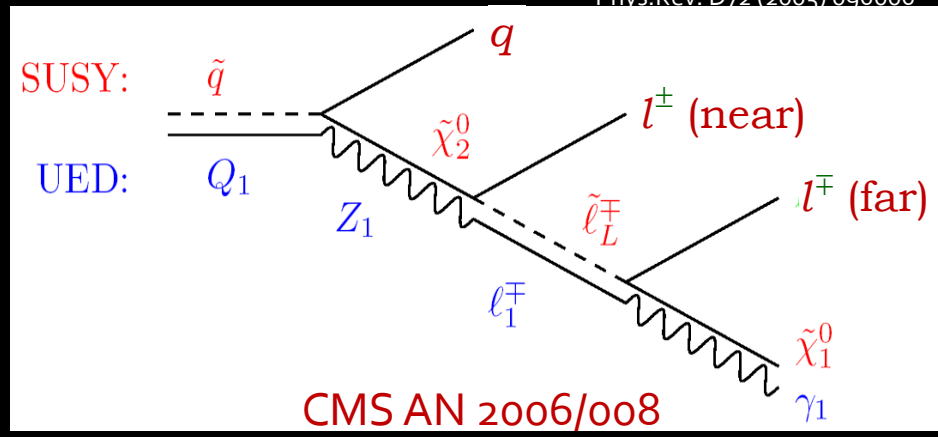


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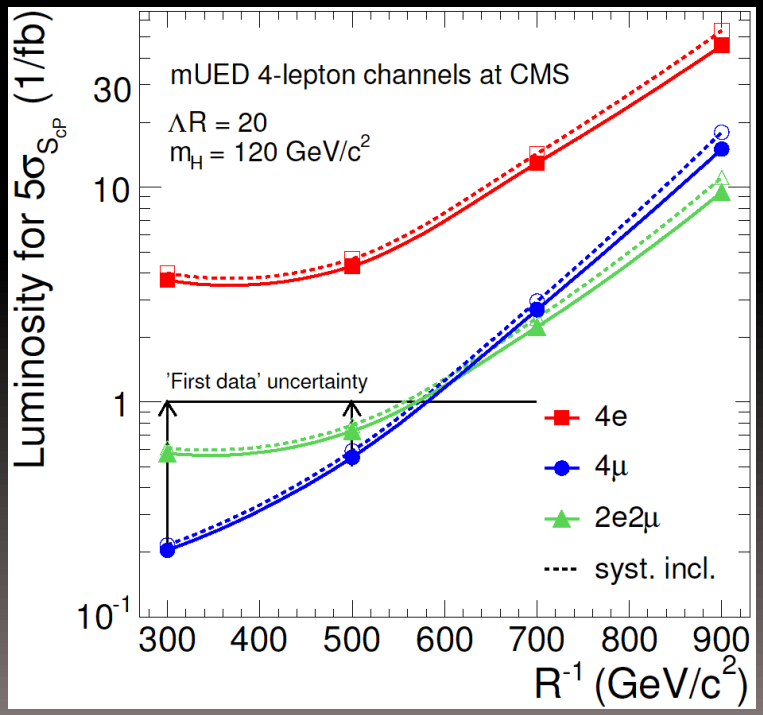
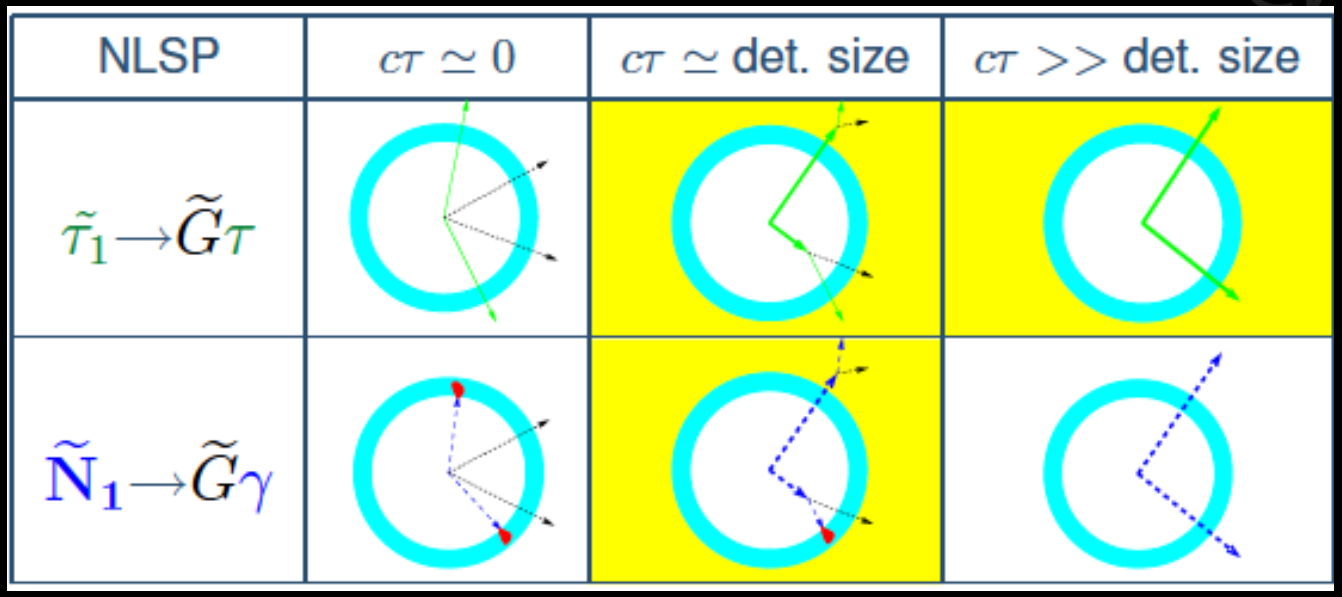


# Gauge mediated SUSY breaking (GMSB)

- SUSY breaking
  - Takes place in hidden sector via messenger particles having SM gauge interactions
    - Mass scale of messengers (which form complete SU(5) representations) is $M_m \ll M_P$
    - Gravitino Ğ: $M_{Ğ} \ll 1$ GeV is always the LSP
  - SUSY particle masses depend on the number of messenger generations $N_m$
    - They obtain their masses radiatively via gauge interactions with the messengers
  - $N_m$ also determines which is the NLSP
- $N_m = 1$
  - NSLP = Neutralino
    - Decays to $\gamma$Ğ
- $N_m = 2$
  - NSLP = stau
    - Decays to $\tau$Ğ
- The intrinsic SUSY-breaking order parameter (F) may not equal that seen by the messengers ($F_m$)
  - The larger $C=F/F_m$ is, the longer the NLSP Lives
- Bottom line:
  - The NLSP determines the phenomenology

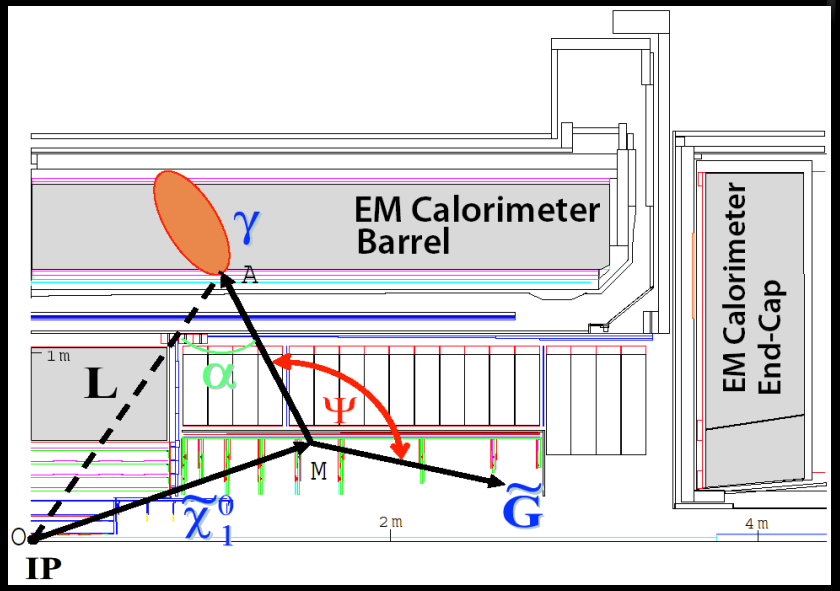
# GMSB

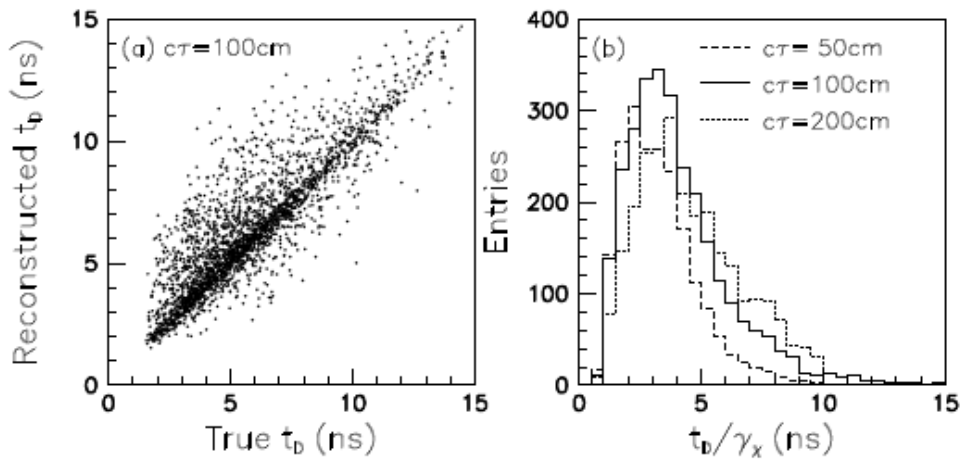



Non-pointing HCSP

- NLSP with $c\tau$~0: Excess of events with 2$\gamma$'s or 2$\tau$'s
- NLSP with $c\tau$ ~ few ns: See $\gamma$'s or $\tau$'s that do not point back to the event vertex
- NLSP with $c\tau \gtrsim 10$ ns : Look for heavy stable charged particles

# Non-pointing photons




Longitudinal segmentation of the ECAL of ATLAS allows for precise determination of the polar angle of a non-pointing photon with very good resolution of $0.06/\sqrt{E_\gamma/\mathrm{GeV}}$. More over, the arrival time could be measured with 100 ps resolution.

# Heavy Stable Charged Particles (HSCP)

- Heavy $\Rightarrow$ m $\gtrsim$100 GeV
  - Stable or long lived $\Rightarrow$ $c\tau$ ~ meters
  - Charged electrically or colored (R-hadron in final state)
- Signature: high momentum "muon-like"
  - No brehmsstrahlung
  - R-hadrons have nuclear interactions in which they pick up (are "dressed" by) light quarks or gluons
    - Can flip electric charge ("charge flipping") or become neutral
  - They're very slow
    - Time of flight
      - $\beta$ = 0.3: reaches muon chambers in ~ 38 ns (25 ns late)
    - Large ionization energy loss in tracker can also be used to estimate $\beta$

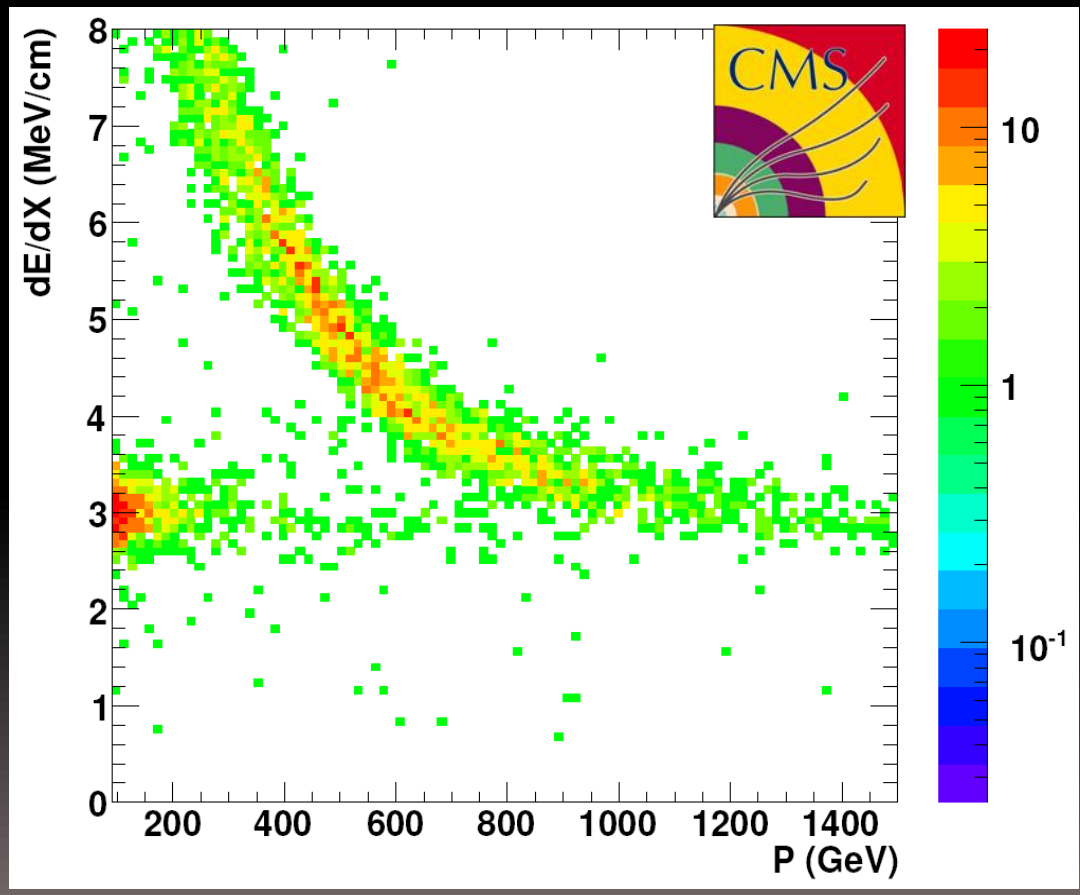
$$P = \beta\gamma mc \ , \quad m = P\sqrt{\frac{1}{\beta^2} - 1}$$

# β from dE/dx (silicon strip)

$$\beta^{-1} = \sqrt{K\frac{dE}{dX}}$$

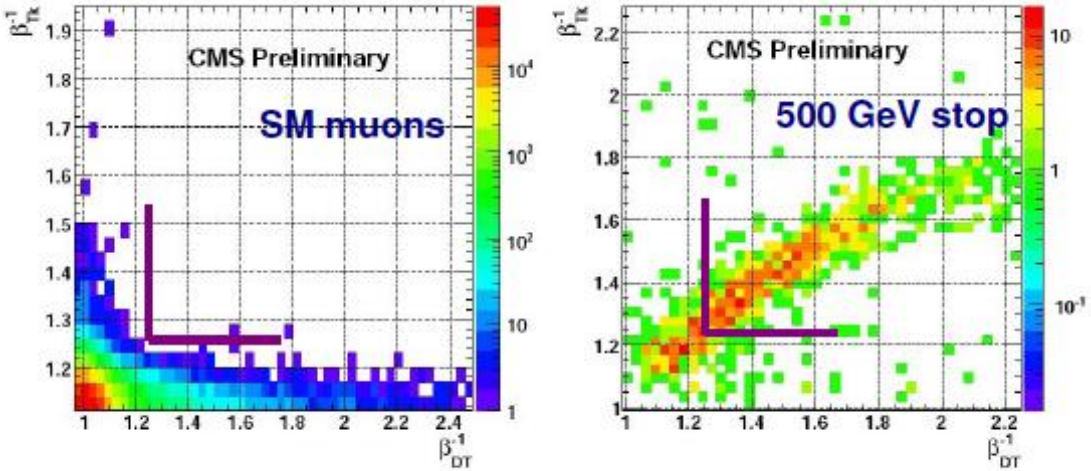
$0.1 < \beta\gamma < 0.9$ region

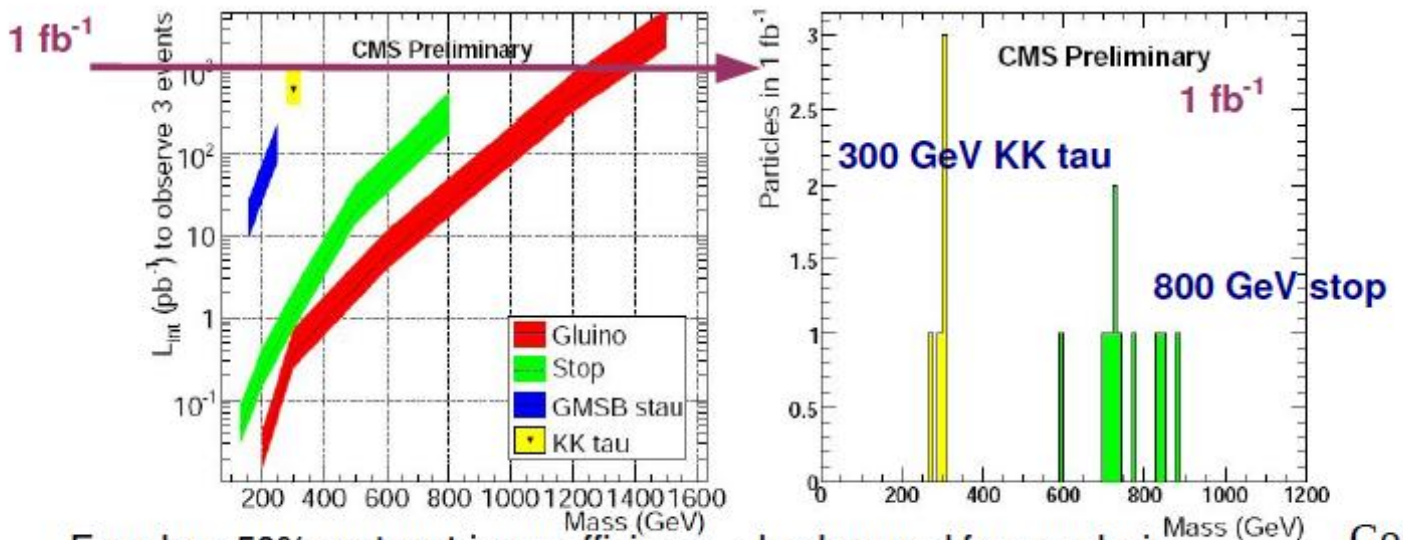
- O(10) dE/dx independent measurements from silicon strip tracker
- K can be obtained from protons
- Background
  - Tails from SM particles



# HSCP

- $\beta_{DT} < 0.80$ and $\sigma_{\beta^{-1}} < 0.1$
- $\beta_{Tk} < 0.80$
- $m_{avg} > 100$ GeV




Error bar: 50% syst on trigger efficiency - background free analysis

Goal: <1 bg event for L=1fb$^{-1}$

# HSCP arise in many models

**Models here:**

a) **SUSY GMSB** long lived Stau NLSP, LSP = gravitino
dominant production: from decay chain of squark/gluino

b) **mUED** – long-lived KK states
direct pair production of KK tau

c) **Split SUSY** (all scalar particles have high mass)
long-lived gluino (R-hadron)

d) **MSSM** with light stop as NLSP and small $\Delta M = M(st\text{-}\chi^0)$

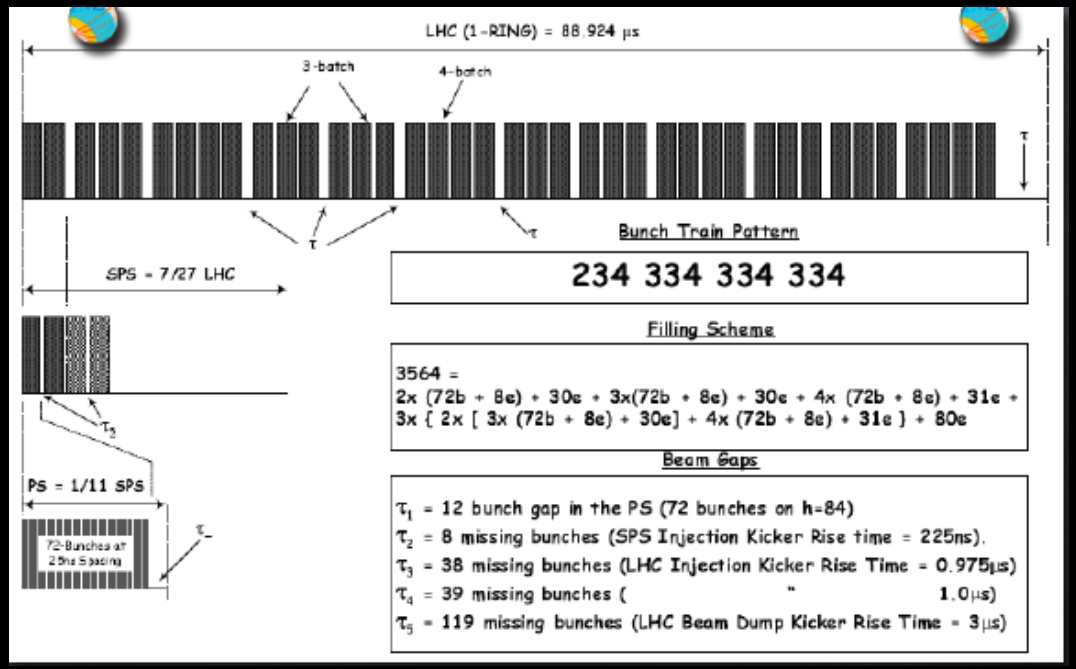
**Heavy:** **mass > 100 GeV** **(non relativistic)**
**Semi-stable:** **c tau > few m** **(escape the detector)**

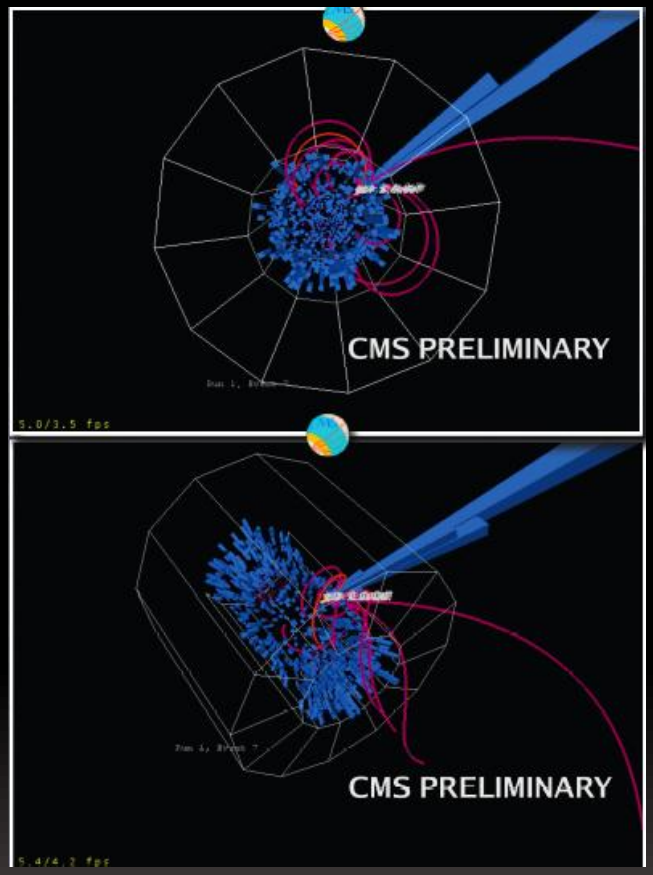
After production, $\tilde{g}$ and $\tilde{t}$ hadronise to metastable particle by combining with light quarks and gluons generically called **R-hadon**

| Data Sample | Cross section (pb) | HSCP in $\lvert\eta\rvert < 2.4$ (%) |
|---|---|---|
| $\tilde{\tau}_1$ (156 GeV) | 1.19 | 97.6 |
| $\tilde{\tau}_1$ (247 GeV) | 0.097 | 97.5 |
| KK tau (300 GeV) | 0.020 | 84.7 |
| $\tilde{g}$ (200 GeV) | $2.2 \times 10^3$ | 89.7 |
| $\tilde{g}$ (300 GeV) | 100 | 91.7 |
| $\tilde{g}$ (600 GeV) | 5.00 | 93.7 |
| $\tilde{g}$ (900 GeV) | 0.46 | 92.6 |
| $\tilde{g}$ (1200 GeV) | $61 \times 10^{-3}$ | 91.4 |
| $\tilde{g}$ (1500 GeV) | $10 \times 10^{-3}$ | 90.4 |
| $\tilde{t}_1$ (130 GeV) | $1.11 \times 10^3$ | 87.8 |
| $\tilde{t}_1$ (200 GeV) | $1.77 \times 10^2$ | 90.9 |
| $\tilde{t}_1$ (300 GeV) | 27.4 | 92.8 |
| $\tilde{t}_1$ (500 GeV) | 1.27 | 95.3 |
| $\tilde{t}_1$ (800 GeV) | $7.81 \times 10^{-2}$ | 96.9 |

# Stopped R-hadrons

SPLIT SUSY Long-lived gluinos to jet(s)(+MET)



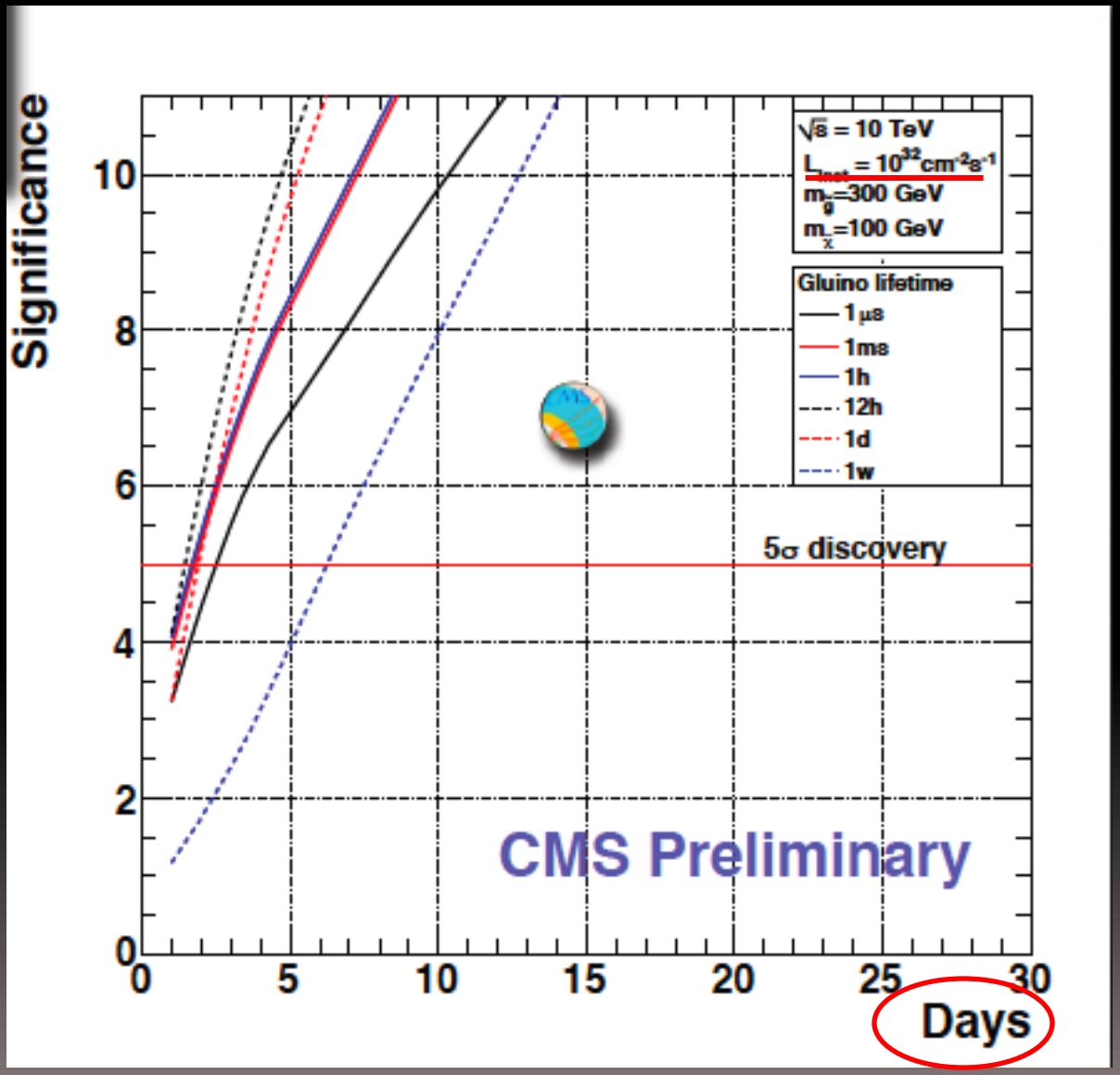

~10-20% of R-hadrons in mass range 100-2000 GeV get trapped in the detector (calorimeter, muon Fe ...)

Look for odd shaped jets when there is no beam in the detector

# Sensitivity

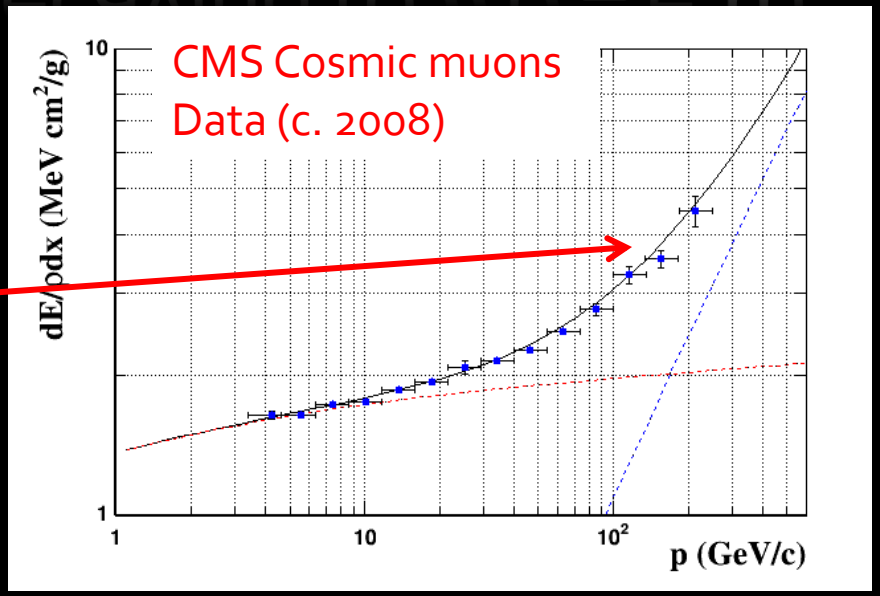
Significance of observation versus days of operation at E32 (i.e. low) luminosity

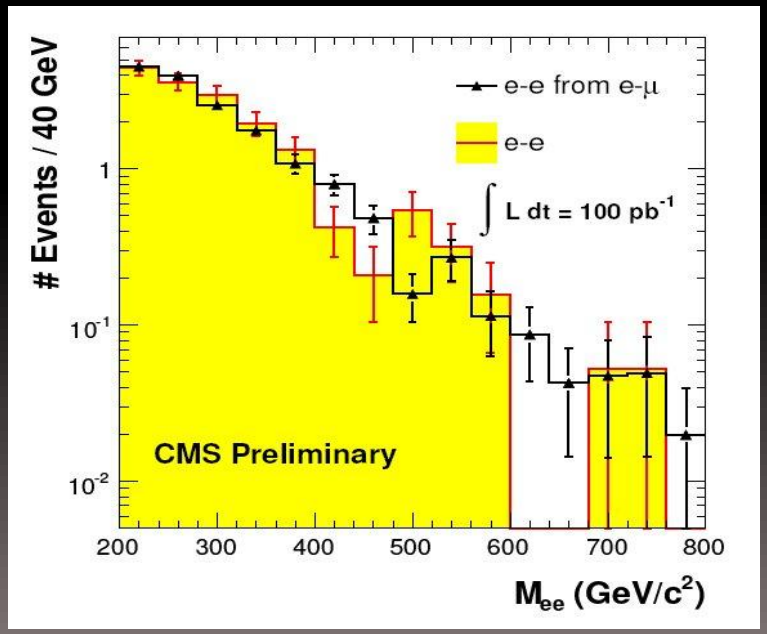
*300 GeV gluino and 100 GeV neutralino*



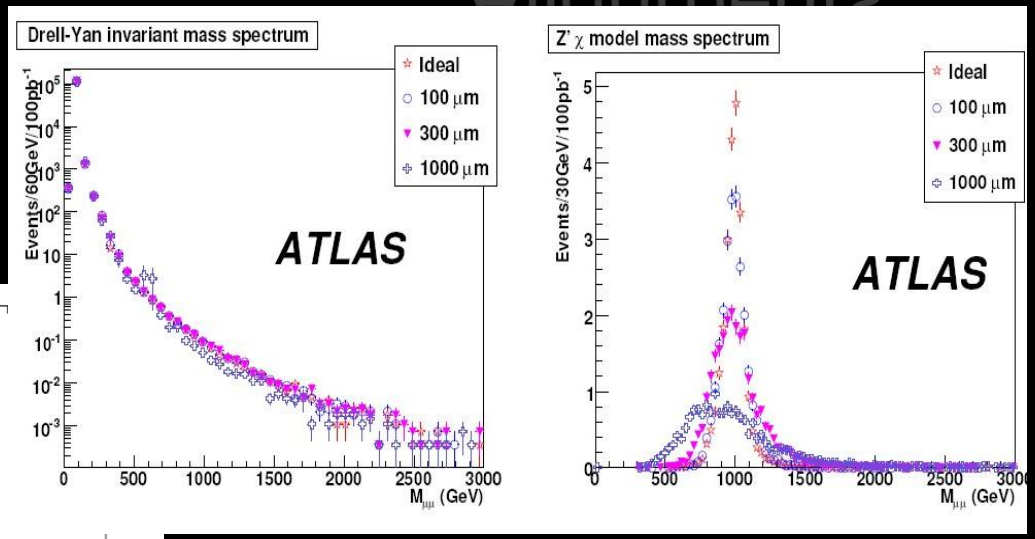
# Heavy Bosons decaying to $ll$ ($l$ = e,μ)

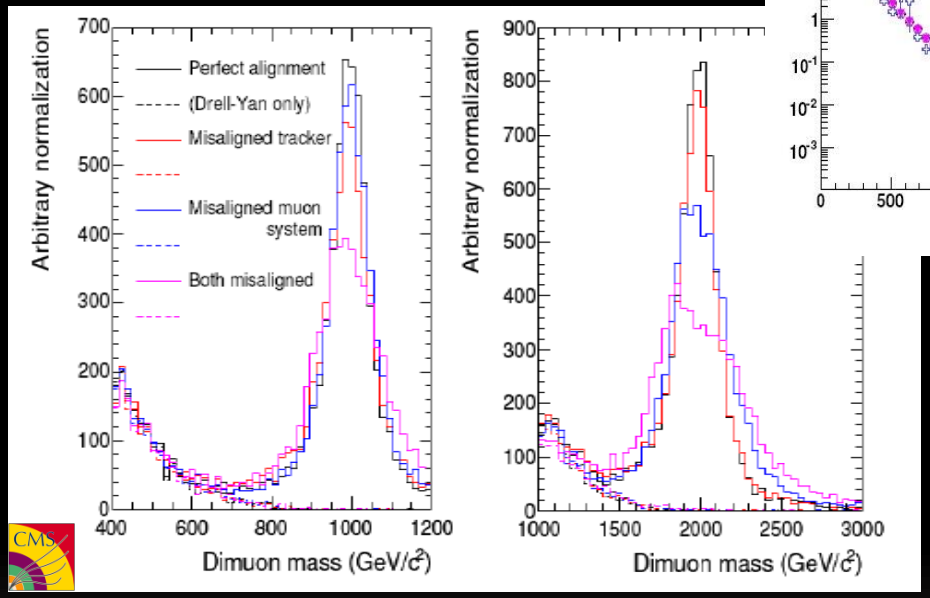
- Not all that easy:
  - Muons
    - $p_T$ resolution at high energies
    - Sensitivity to mis-alignments
    - Bremstrahlung at higher momenta
  - Electrons
    - Calo saturation at v.high energy
    - Leakage into had calorimeter reduces utility of longitudinal shower shape variables
  - Isolation affected by brem. photon conversions
- Not easy to understand efficiencies, systematics
  - No resonance yielding ~TeV leptons to use (until you have discovered one ☺)
  - MC efficiencies flat from control to signal regions… hopefully this is true in reality!
- Use eμ events to estimate flavor symmetric backgrounds like tt



# Alignments



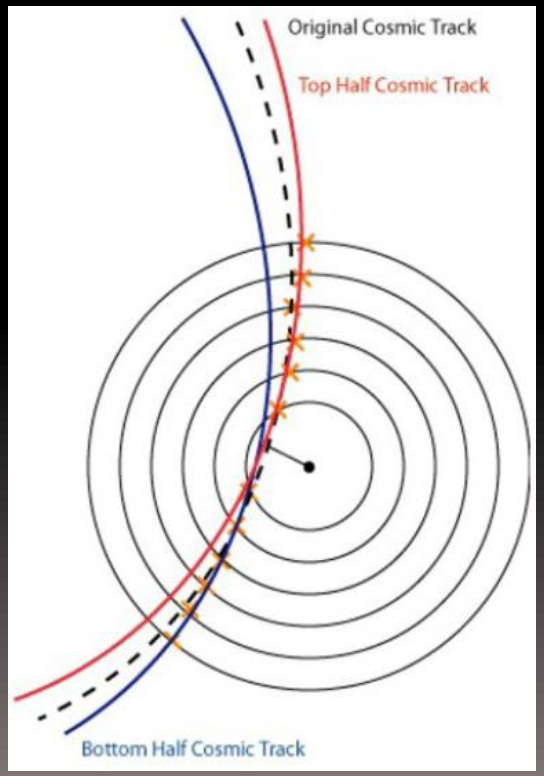

Efficiency loss due to charge mis-ID as function of muon system alignments

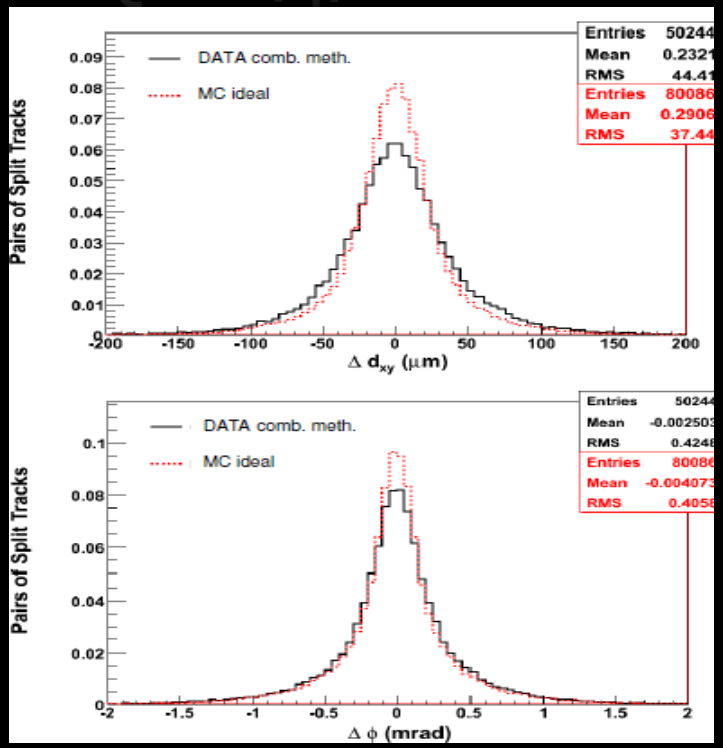
| Alignment level | Efficiency |
|---|---|
| Ideal | 0.98 |
| 300 μm | 0.97 |
| 1000 μm | 0.88 |

- Larger misalignments increase the integrated luminosity required for a statistically significant signal.
  - But in the past year, LHC experiments have used cosmics to align their tracking and muon systems.

# Tracking Performance after Alignment

- Split track validation method
  - Split track at the Point of Closest Approach (PCA) to the nominal beam line
  - Refit separately top and bottom legs and compare the track parameters at the PCA



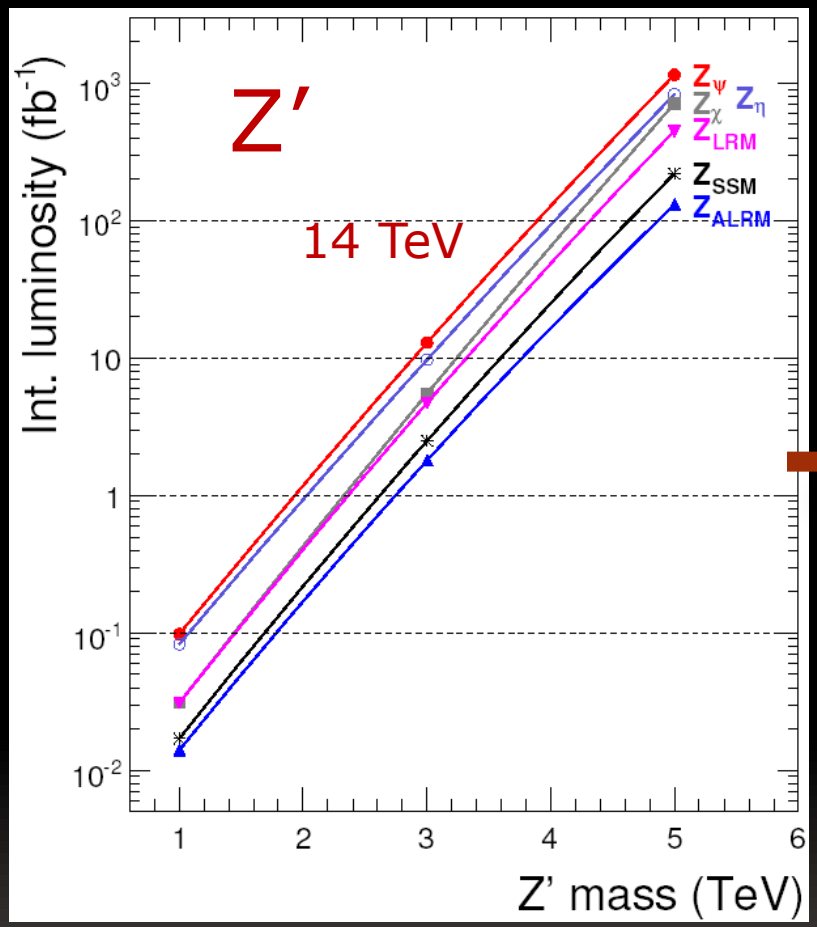




Alignments already as originally expected for = somewhere between 10 and 100 $pb^{-1}$

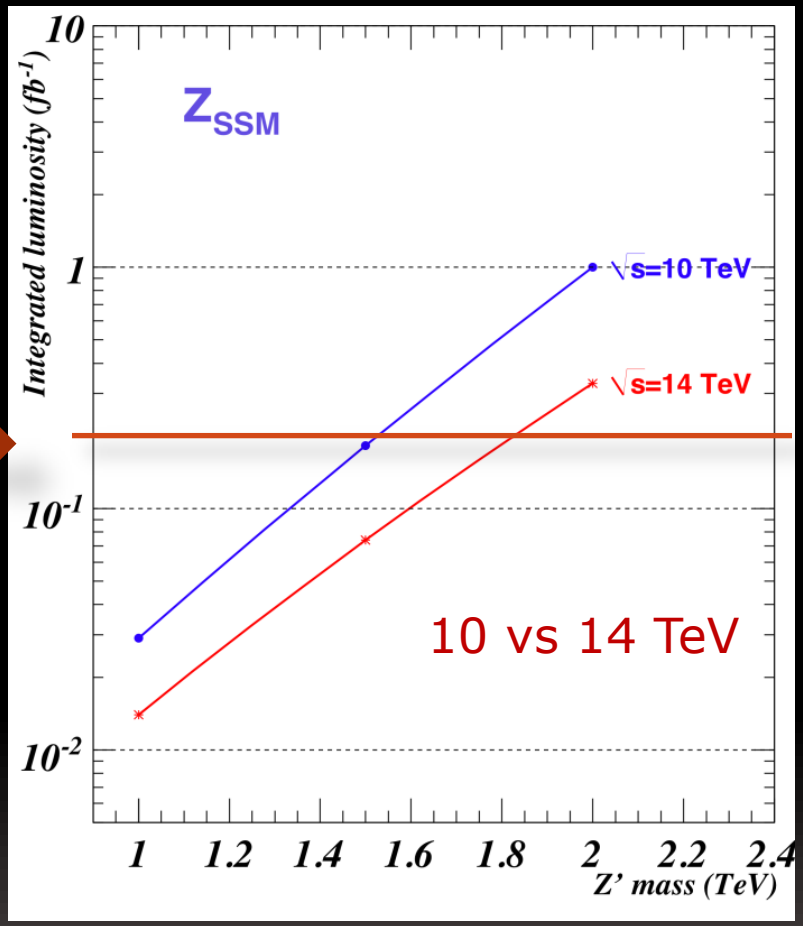
Mass resolution ~7 (10) % at 1 (2) TeV with alignments expected for 100 $pb^{-1}$

1-2 TeV Z′ should be visible

# Z′, Graviton, large extra dimensions…




Luminosity needed for discovery

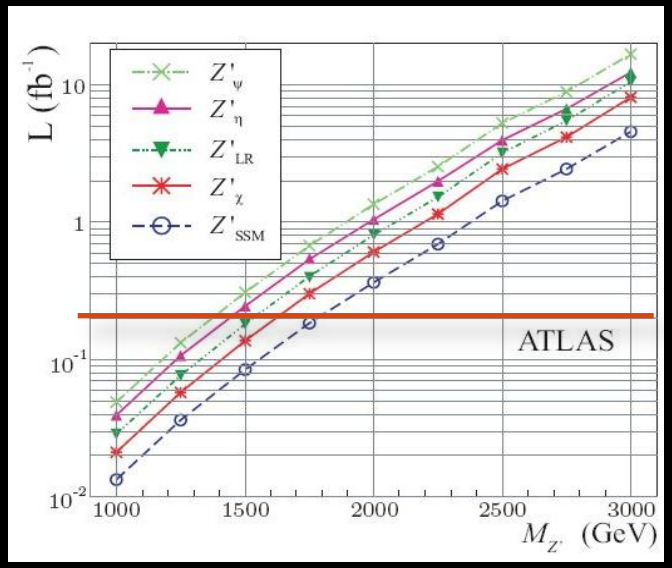



| Mass [GeV] | σ [fb] | $\mathcal{A}$*$\epsilon$ | N |
|---|---|---|---|
| 1000 | 230 | 0.67 | 31 |
| 1250 | 83 | 0.68 | 11 |
| 1500 | 33 | 0.69 | 5 |

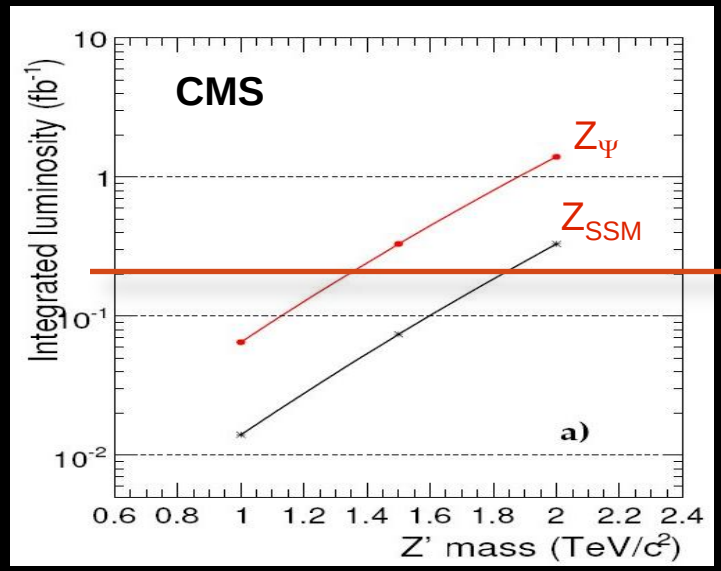
200 pb$^{-1}$ at 10 TeV

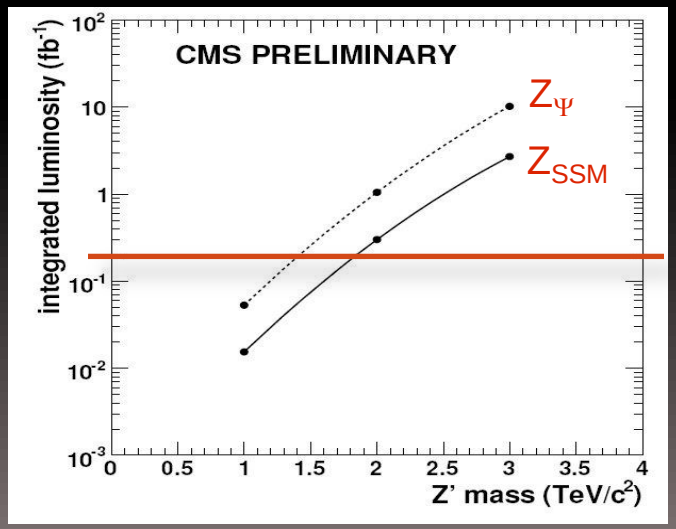
# Discovery potential for Z′ →ee, μμ

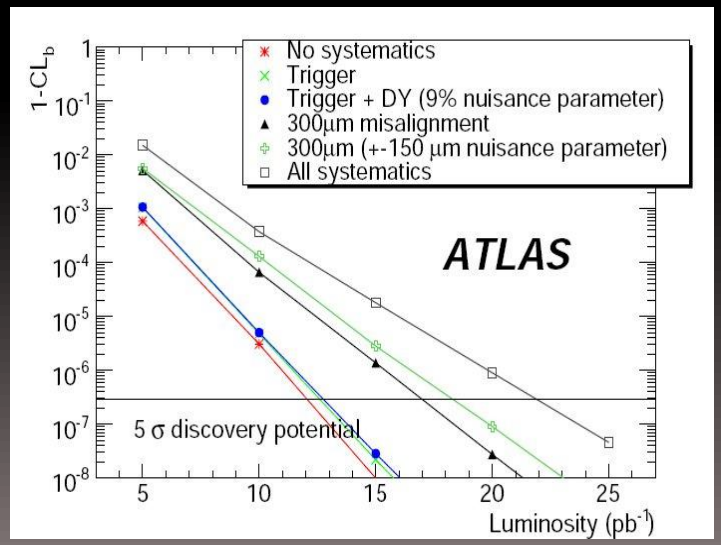
Z′ →ee




Z′ → μμ

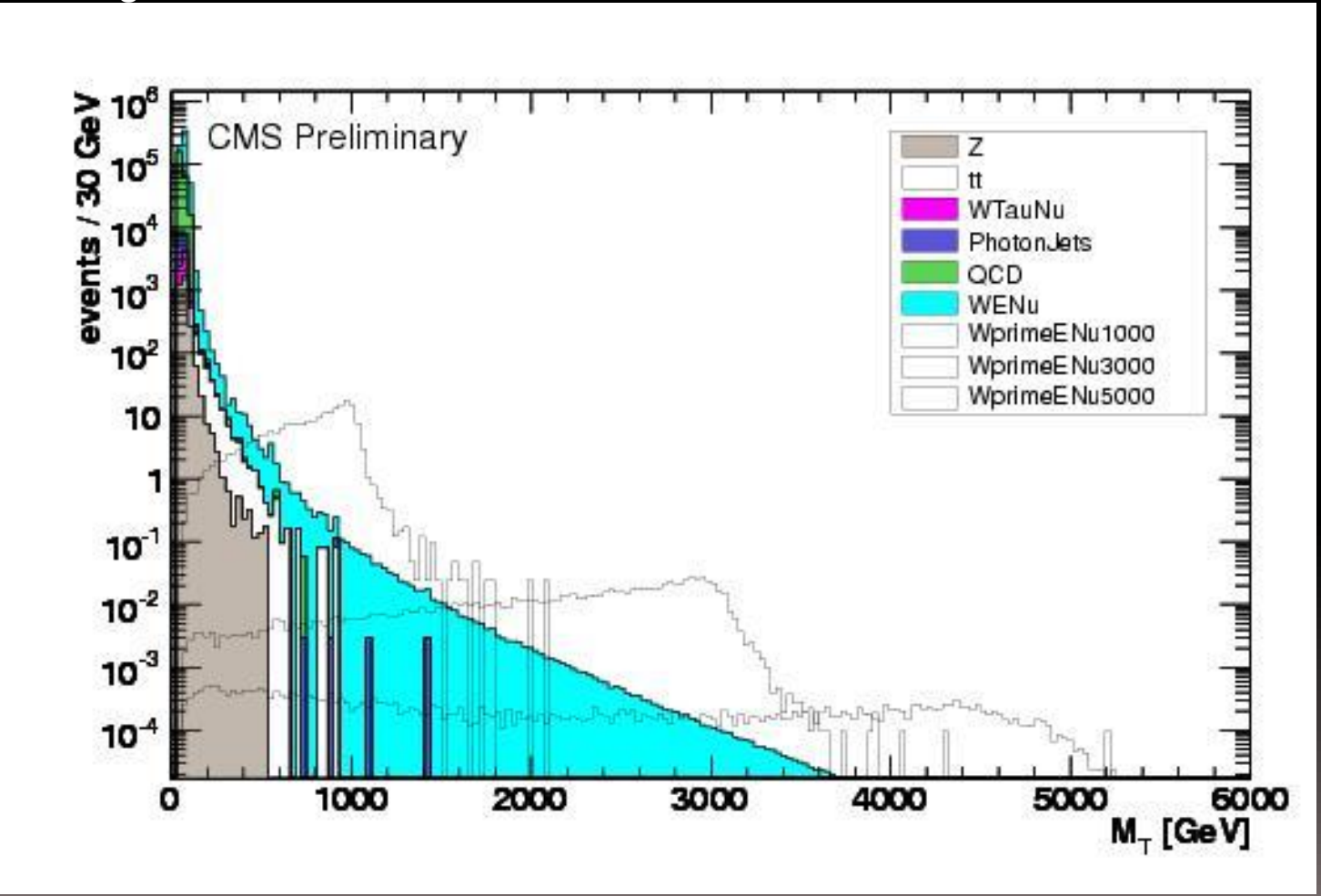


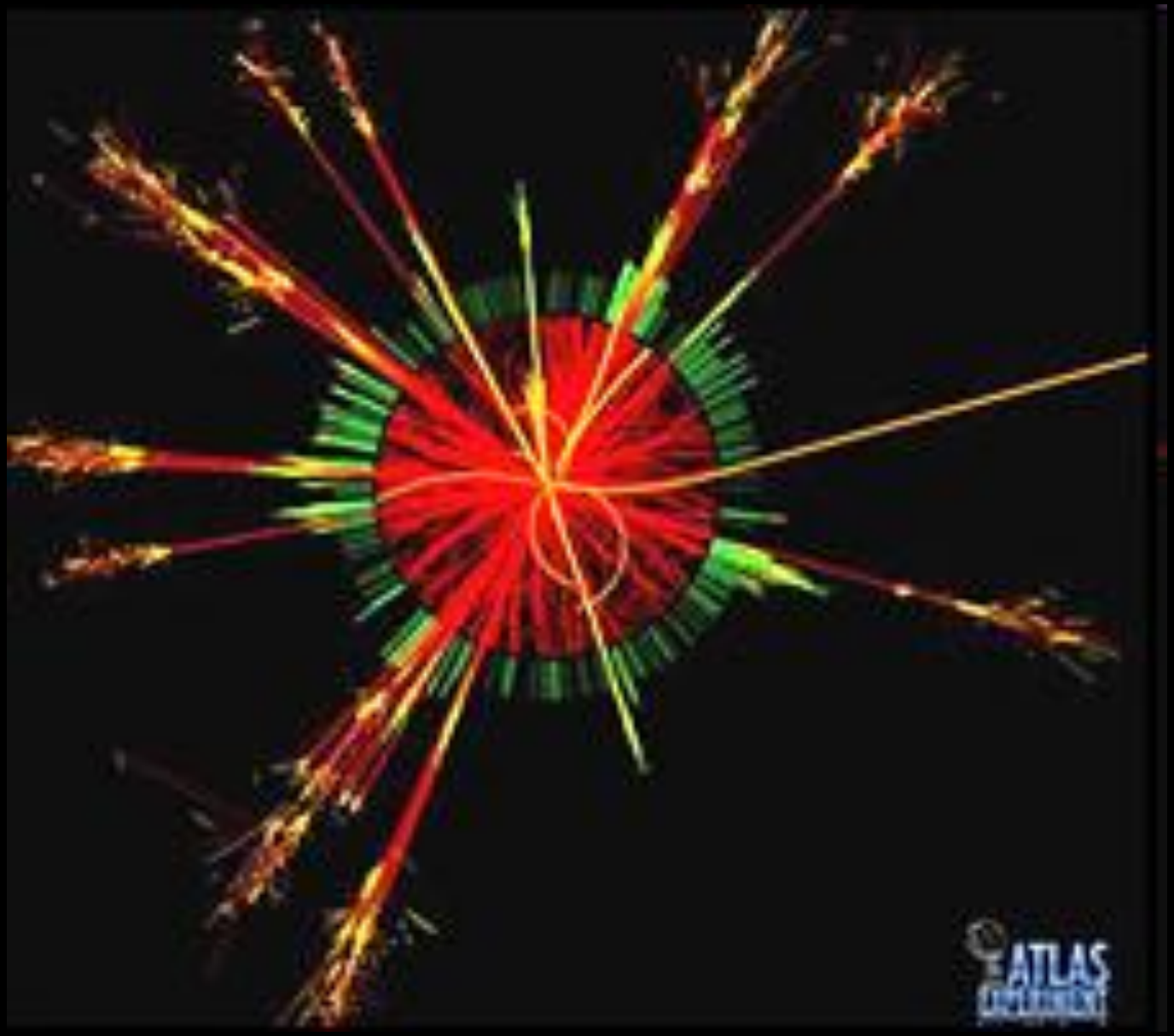



# W′

Similar to but harder than Z′ search.
SM Backgrounds W, $t\bar{t}$ etc.



# Extra Dimensions and Black Holes



# Search for Black Holes

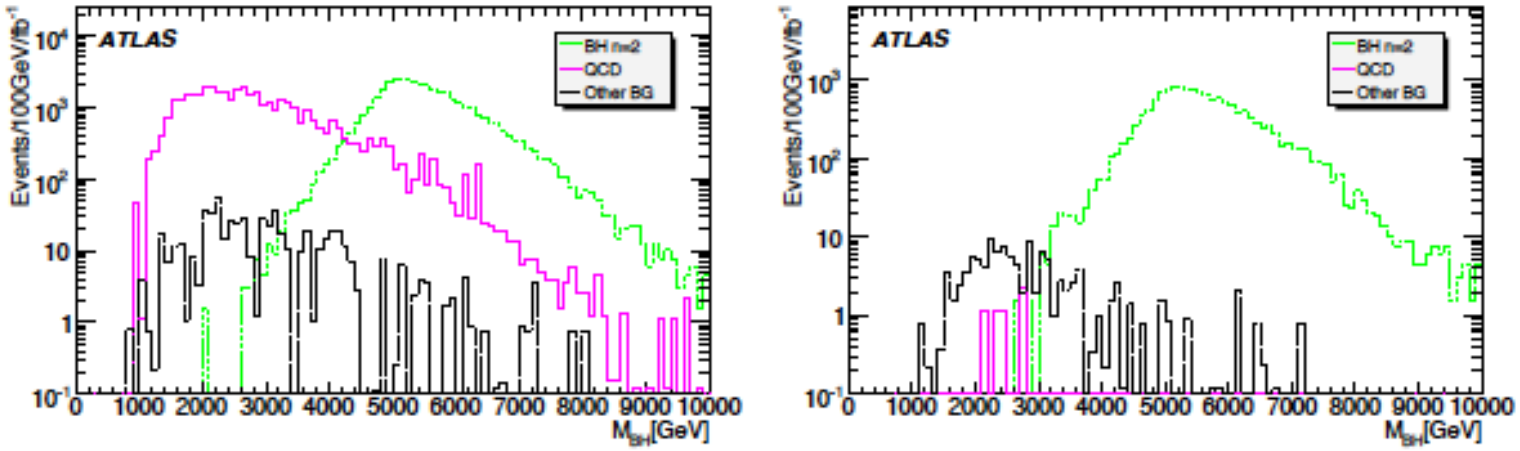



Figure 14: Black hole mass distribution for the signal sample with $n = 2$ and $m > 5$ TeV and backgrounds (see Table 7) after multiplicity requirement of at least 4 objects with $p_T > 200$ GeV (left plot) and an additional requirement of a lepton (electron or muon) with $p_T > 200$ GeV (right plot).

Could be an overwhelming signal if the true Planck scale is ~1 TeV

# Early LHC Discovery Potential



Early LHC Runs: 0.1 to 1 $fb^{-1}$

| Model | Mass reach | Luminosity ($fb^{-1}$) | Early Systematic Challenges |
|---|---|---|---|
| Contact Interaction | $\Lambda$ < 2.8 TeV | 0.01 | Jet Eff., Energy Scale |
| Z' ALRM<br>Z' SSM<br>Z' LRM<br>Z' E6, SO(10) | M ~ 1 TeV<br>M ~ 1 TeV<br>M ~ 1 TeV<br>M ~ 1 TeV | 0.01<br>0.02<br>0.03<br>0.03 – 0.1 | Alignment |
| Excited Quark | M ~0.7 – 3.6 TeV | 0.1 | Jet Energy Scale |
| Axigluon or Colouron | M ~0.7 – 3.5 TeV | 0.1 | Jet Energy Scale |
| E6 diquarks | M ~0.7 – 4.0 TeV | 0.1 | Jet Energy Scale |
| Technirho | M ~0.7 – 2.4 TeV SM | 0.1 | Jet Energy Scale |
| ADD Virtual $G_{KK}$ | $M_D$~ 4.3 - 3 TeV, n = 3-6<br>$M_D$~ 5 - 4 TeV, n = 3-6 | 0.1<br>1 | Alignment |
| ADD Direct $G_{KK}$ | $M_D$~ 1.5-1.0 TeV, n = 3-6 | 0.1 | MET, Jet/photon Scale |
| SUSY<br>Jet+MET+0 lepton<br>Jet+MET+1 lepton<br>Jet+MET+2 leptons | M ~1.5 – 1.8 TeV<br>M ~0.5 TeV<br>M ~0.5 TeV<br>M ~0.5 TeV | 1<br>0.01<br>0.1<br>0.1 | MET, Jet Energy Scale, Multi-Jet backgrounds, Standard Model backgrounds |
| mUED | M ~0.3 TeV<br>M ~ 0.6 TeV | 0.01<br>1 | ibid |
| $TeV^{-1}$ ($Z_{KK}^{(1)}$) | $M_{Z1}$ < 5 TeV | 1 | |
| RS1<br>di-jets<br>di-muons | <br>$M_{G1}$~0.7- 0.8 TeV, c=0.1<br>$M_{G1}$~0.8- 2.3 TeV, c=0.01-0.1 | <br>0.1<br>1 | <br>Jet Energy Scale<br>Alignment |

# Early LHC Discovery Potential



Early LHC Runs: 0.1 to 1 $fb^{-1}$

| Model | Mass reach | Luminosity ($fb^{-1}$) | Early Systematic Challenges |
|---|---|---|---|
| Contact Interaction | $\Lambda$ < 2.8 TeV | 0.01 | Jet Eff., Energy Scale |
| Z' ALRM<br>Z' SSM<br>Z' LRM<br>Z' E6, SO(10) | M ~ 1 TeV<br>M ~ 1 TeV<br>M ~ 1 TeV<br>M ~ 1 TeV | 0.01<br>0.02<br>0.03<br>0.03 – 0.1 | Alignment |
| Excited Quark | M ~0.7 – 3.6 TeV | 0.1 | Jet Energy Scale |
| Axigluon or Colouron | M ~0.7 – 3.5 TeV | 0.1 | Energy Scale |
| E6 diquarks | M ~0.7 – 4.0 TeV | 0.1 | Jet Energy Scale |
| Technirho | M ~0.7 – 2.4 TeV | 0 | Jet Energy Scale |
| ADD Virtual $G_{KK}$ | $M_D$~ 4.3 - 3 TeV, n = 3-6<br>$M_D$~ 5 - 4 TeV, n = 3-6 | 1 | Alignment |
| ADD Direct $G_{KK}$ | $M_D$~ 1.5-1.0 TeV, n = 3 | 0.1 | MET, Jet/photon Scale |
| SUSY<br>Jet+MET+0 lepton<br>Jet+MET+1 lepton<br>Jet+MET+2 leptons | M ~1.5 – 1.8 Te<br>M ~0.5 Te<br>M ~<br>eV | 1<br>0.01<br>0.1<br>0.1 | MET, Jet Energy Scale, Multi-Jet backgrounds, Standard Model backgrounds |
| mUED | ~0.3 TeV<br>M ~ 0.6 TeV | 0.01<br>1 | ibid |
| $TeV^{-1}$ ($Z_{KK}^{(1)}$) | $M_{Z1}$ < 5 TeV | 1 | |
| RS1<br>di-jets<br>di-muons | <br>$M_{G1}$~0.7- 0.8 TeV, c=0.1<br>$M_{G1}$~0.8- 2.3 TeV, c=0.01-0.1 | <br>0.1<br>1 | <br>Jet Energy Scale<br>Alignment |

SM

Not an exhaustive list!!

# Summary

- The LHC modifications are nearly completed.
  - A long run will start late this year
- ATLAS and CMS are ready
  - We will commission everything: detector, online, and physics analyses
  - Then explore the Standard Model at 10 TeV
    - Start to understand the “LHC environment”
  - We may see something early
    - Fingers crossed

# End

- Many thanks to many people
  - Sarah Eno, Chris Hill,, Ian Hinchliffe, Karl Jacobs, Oliver Buchmuller, Ian Low, Albert De Roeck, Peter Jenni, Henry Frisch, Paris Sphicas, Claudio Campagnari, Chris Quigg, Philip Schuster, Natalia Toro, …and…
  - … many others from UA1, UA2, CDF, D0, OPAL, ALEPH, CMS, ATLAS…
- And especially to all the people who did the work represented in these slides

# ADDITIONAL INFORMATION

# Bibliography: Comprehensive physics reports

- ATLAS
  - Expected Performance of the ATLAS Experiment
    - Detector, Trigger and Physics – 2008, 1852 p.
- **CMS**
  - **CMS physics : Technical Design Report**
    - Volume v.1 : Detector performance and software – 2006, 521 p.
    - Volume v.2 : Physics performance - 2006, 669 p.
- Recent results
  - CMS Physics recent results
  - ATLAS Physics recent results

# Bibliography :CMS studies Higgs &New Physics

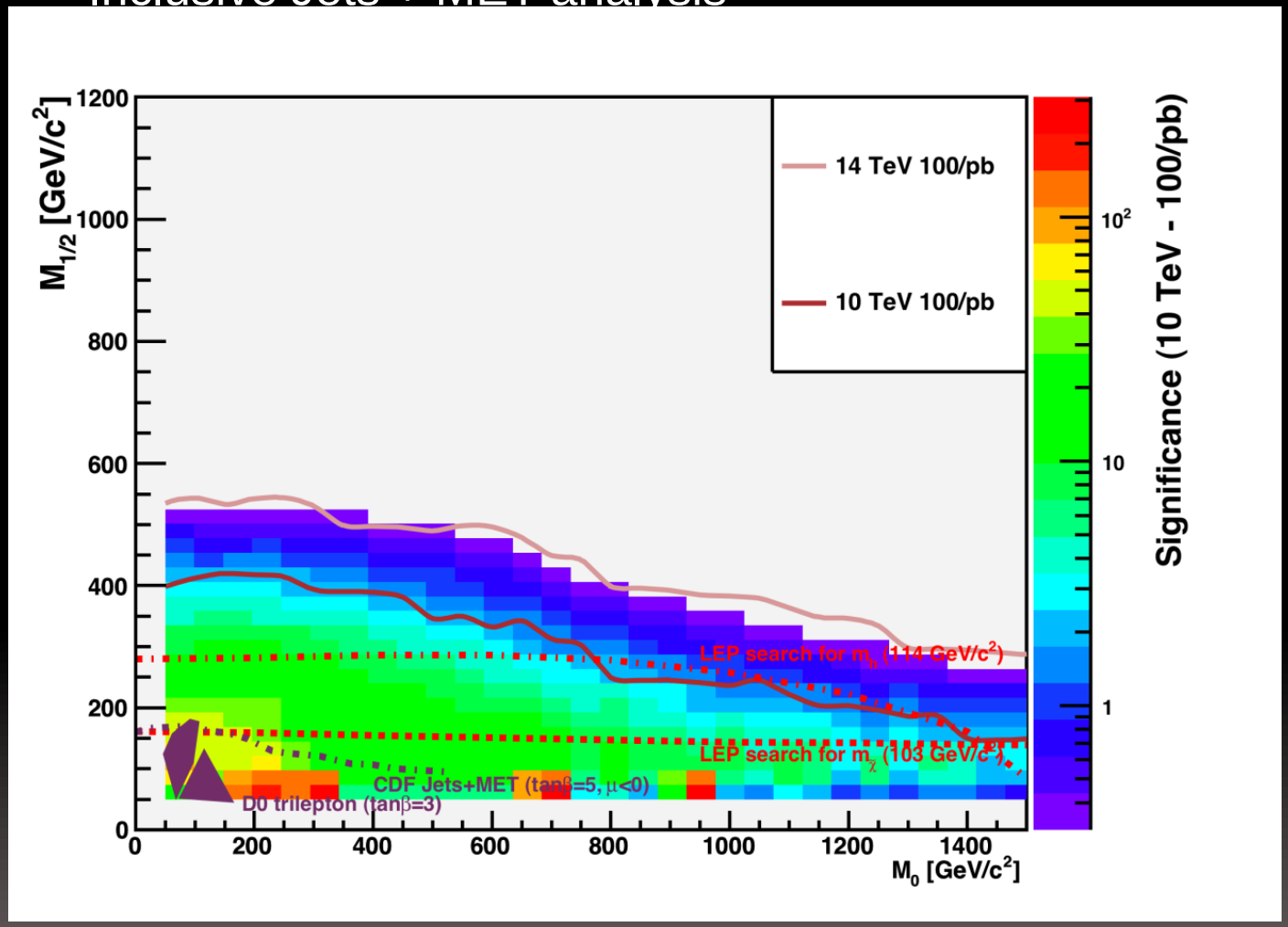
- Higgs
  - HIG-08-003: Search for Higgs to ZZ* (January 2009).
  - HIG-08-006: Search for Higgs to WW* (January 2009). This analysis supersedes the following older analysis: HIG-07-001: Higgs to WW*
  - HIG-08-008: Higgs to tau-tau (October 2008)
  - HIG-08-001: ggH production, with H-->tau-tau
- Searches for New Physics
  - EXO-08-013: Search for Low Mass b' Production (July 2009)
  - EXO-09-003: Searching for Majorana Neutrinos in the Like-Sign Dilepton Final State at 10 TeV (July 2009)
  - EXO-08-008: Search for Exotic Partners of the Top Quark (July 2009)
  - EXO-09-012: Search for A Fourth Generation b' Quark in tW Final State at 10 TeV (July 2009)
  - EXO-09-010: Search for Second Generation Scalar Leptoquarks (July 2009)
  - EXO-09-007: Search for Technicolor (July 2009)
  - SUS-09-001: Search strategy for exclusive multi-jet events from supersymmetry (July 2009)
  - EXO-09-011: Search for Scalar and Tensor Unparticles in the Diphoton Final State (July 2009)
  - EXO-09-009: Search for Randall-Sundrum Gravitons in the Diphoton Final State (July 2009)
  - EXO-09-004: Search for large Extra Dimensions in the diphoton final state (June 2009)
  - SUS-09-004: Data-Driven Background Estimates for SUSY Di-Photon Searches (July 2009)
  - EXO-09-008: Search for heavy narrow t-tbar resonances in muon-plus-jets final states with the CMS detector (July 2009)
  - EXO-09-006: Search for high-mass resonances decaying into an electron pair -- at 10 TeV with 100 pb−1 (July 2009)
  - EXO-09-013: Search for Mono-Jet Final States from ADD Extra-Dimensions at 10 TeV (July 2009)
  - SUS-09-002: Discovery potential and measurement of a dilepton mass edge in SUSY events at 10 TeV (July 2009)
  - EXO-09-002: Search for High-Mass Resonances Decaying into Top-Antitop Pairs in the All-Hadronic Mode (July 2009)
  - EXO-09-001: Searching for Stopped Gluinos during Beam-off Periods (May 2009)
  - EXO-08-009: Search for a b' (October 2008)
  - EXO-08-011: Search for extra dimensions with monojets (October 2008)
  - EXO-08-005: MUSIC -- deviations between data and Monte Carlo simulation (September 2008)
  - SUS-08-005: SUSY search with dijet events (September 2008)
  - SUS-08-001: Dilepton+Jet+MET channel: Observation and Measurement of x2 --> x1 ll (July 2008)
  - SUS-08-002: Data driven estimation of the Z->invisible background for the early SUSY searches (July 2008)
  - EXO-08-001: Search for Z'-->ee (July 2008)
  - EXO-08-004: Search for W'-->enu (July 2008)
  - SBM-07-002: Search for Z' --> mumu
  - SBM-07-001: Searches for New Physics using high ET dijet events
  - EXO-08-003: Search for Heavy Stable Charged Particles

# Bibliography :CMS studies Object Identification


- JME-09-010: Performance of Track-Corrected Missing ET in CMS (July 2009)
- JME-09-007: Measurement of the Jet Energy Resolutions and Jet Reconstruction Efficiency at CMS (July 2009)
- JME-09-005: Determination of the jet energy scale using Z->e+e− + jet pT balance and a procedure for combining data-driven corrections (July 2009)
- JME-09-004: Jet energy calibration with photon+jet events (July 2009)
- JME-09-002: Jet Plus Tracks Algorithm for Calorimeter Jet Energy Corrections (July 2009)
- BTV-09-001: Algorithms for b Jet Identification in CMS (July 2009)
- JME-09-001: A Cambridge-Aachen (C-A) based Jet Algorithm for boosted top-jet tagging (July 2009)
- JME-09-009: Jet energy correction using Z-->mumu Jet PT balance (June 2009)
- JME-08-002: Jet Corrections to Parent Parton Energy (May 2009)
- JME-09-003: Offset Energy Correction for Cone Jets (May 2009)
- JME-08-003: Determination of the Relative Jet Energy Scale from Dijet Balance (May 2009)
- PFT-09-001: Particle–Flow Event Reconstruction in CMS and Performance for Jets, Taus, and ETmiss (April 2009)
- JME-08-001: Performance of Jet Reconstruction with Charged Tracks only (September 2008)
- PFT-08-001: Tau Reconstruction using the Particle Flow Technique (July 2008)
- JME-07-002: Plans for Jet Energy Corrections at CMS (July 2008)
- BTV-07-003: Effect of misalignment on b-tagging (July 2008)
- JME-07-003: Performance of Jet Algorithms in CMS
- JME-07-001: Performance of missing ET reconstruction
- BTV-07-001: b tag efficiency from System 8 & Ptrel Method
- BTV-07-002: Measuring uds mistag rate of b tag using negative tags
- EGM-07-001: Measuring Electron Efficiencies with Early Data

# SUSY @ 100 pb$^{-1}$

- Inclusive Jets + MET analysis




*CMS AN 2009/016*

# W+ vs W-: TeVatron and LHC

arXiv:0812.2571

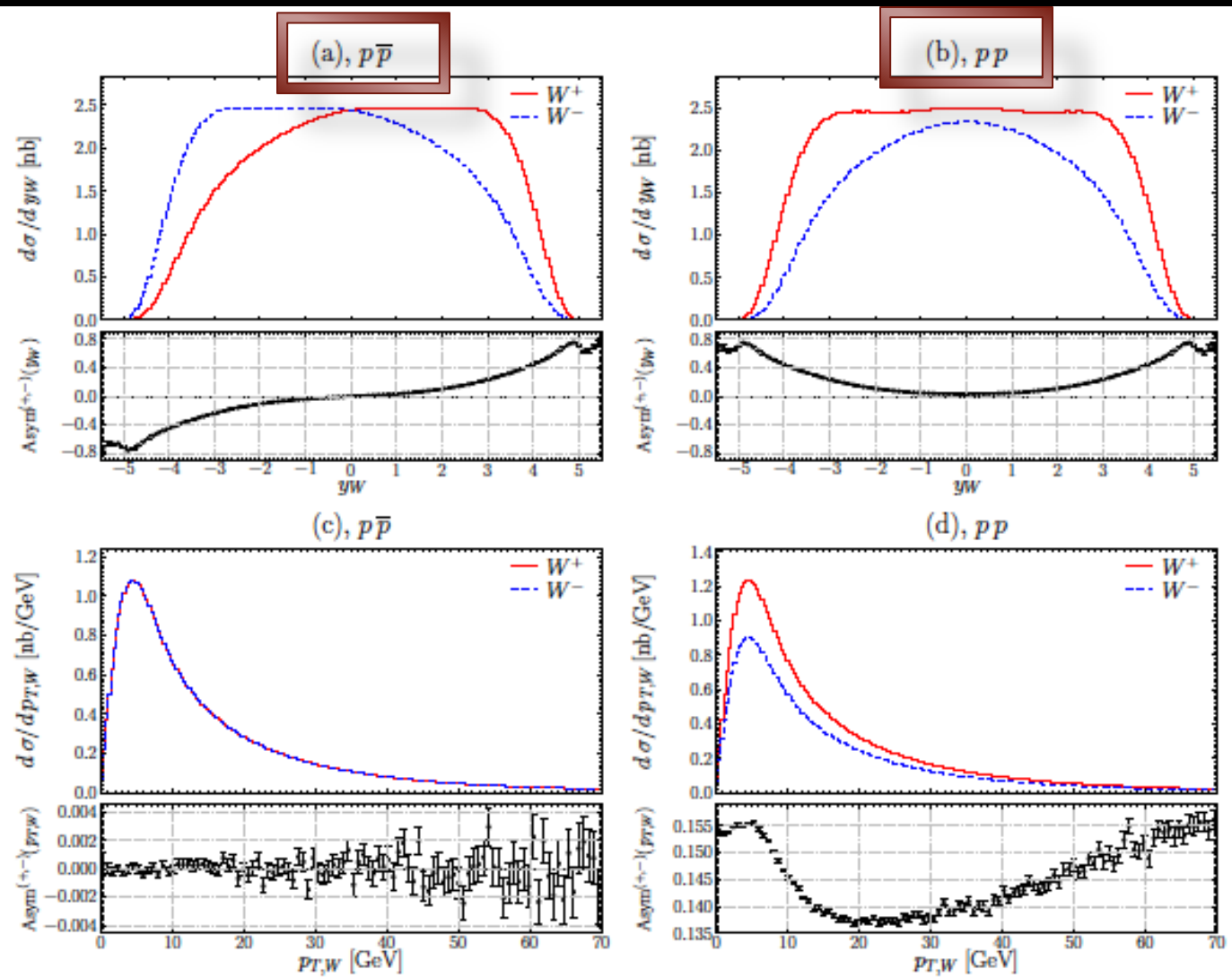
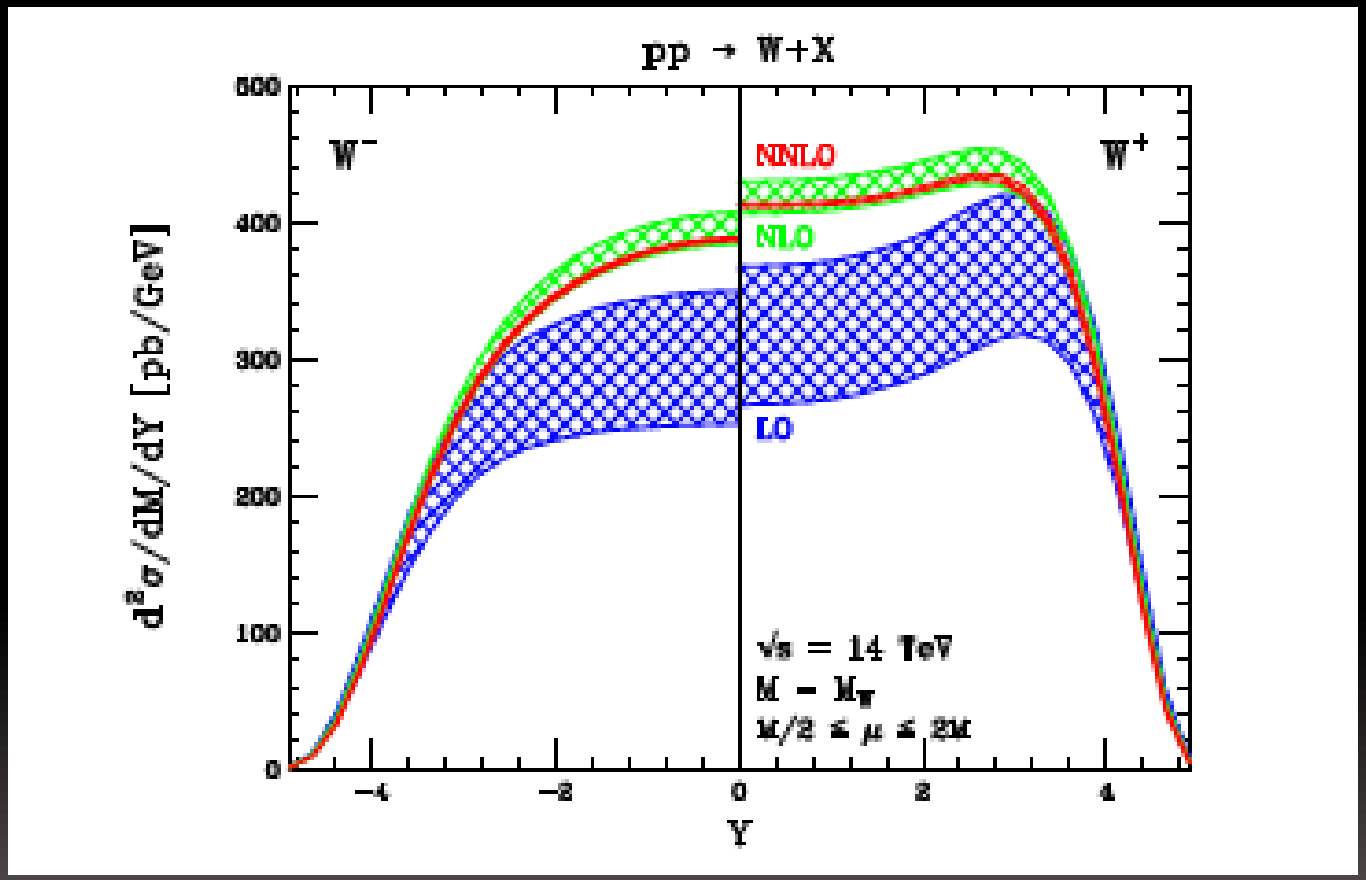



Figure 1: The rapidity $y_W$ and transverse momentum $p_{T,W}$ distributions of the $W$-bosons and their charge asymmetries for the $p\bar{p}$ (a, c) and $pp$ (b, d) collisions.

# Rapidity W+


pp → W+X
W⁻
W⁺
NNLO
NLO
LO
√s = 14 TeV
M = M_W
M/2 ≤ μ ≤ 2M
d²σ/dM/dY [pb/GeV]
Y
500
400
300
200
100
0
−4
−2
0
2
4

# General Observations

- only SM Higgs has a well-defined signal (like top, single top, etc)
- Want big cross section and clean signature
- The earliest results may come from something that couples to gluons and a final state with high pT leptons (or other dramatic signature)

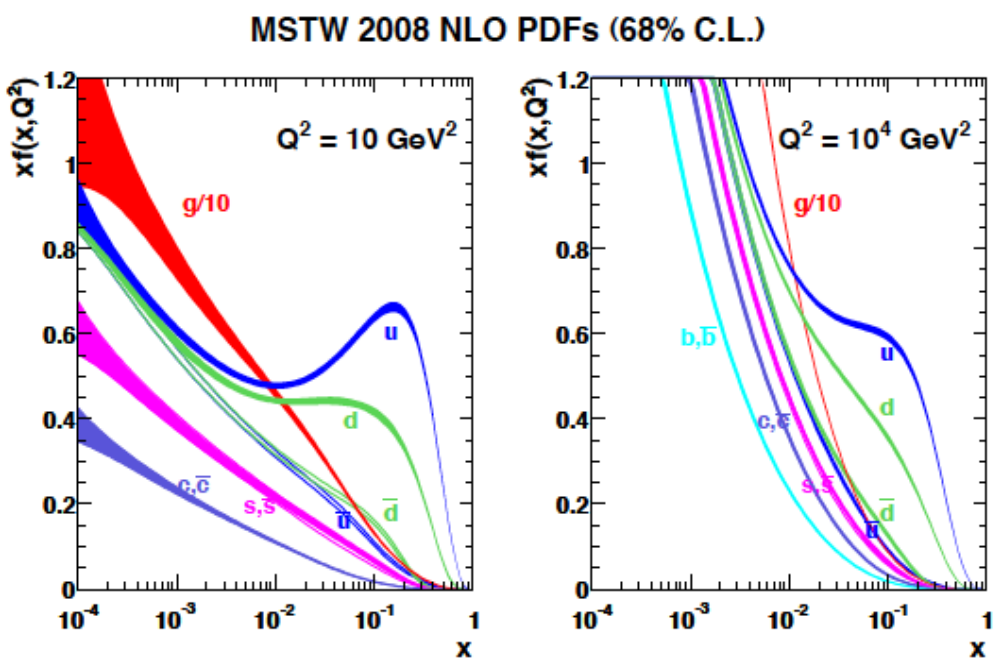
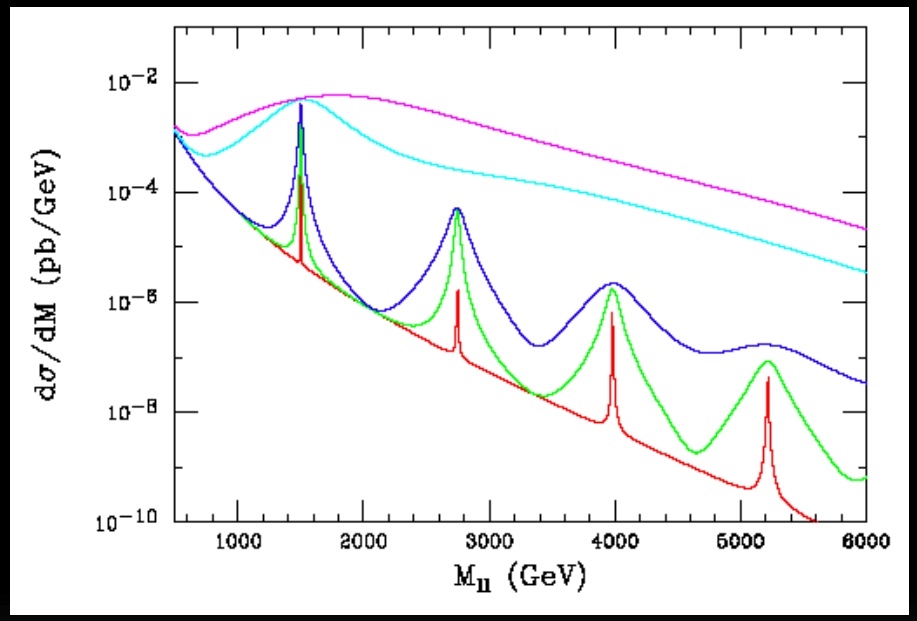
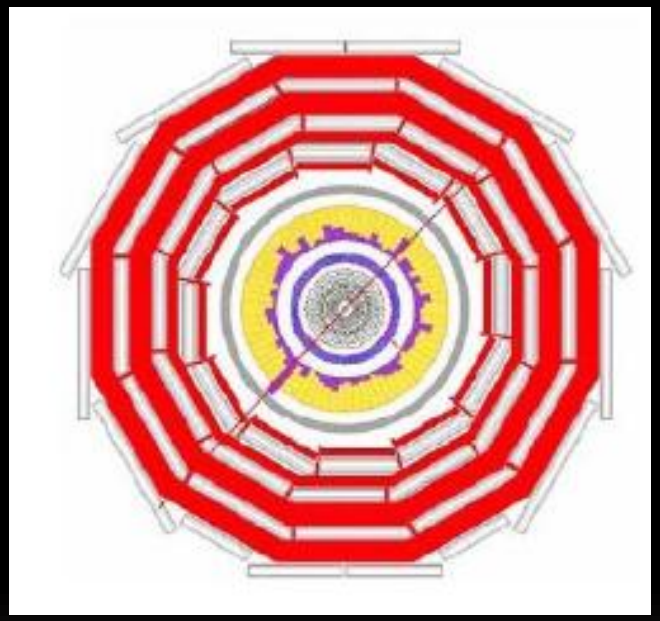



Figure 1: MSTW 2008 NLO PDFs at $Q^2 = 10$ GeV$^2$ and $Q^2 = 10^4$ GeV$^2$.

# Heavy Bosons to ee, μμ

Predicted in many theories: TeV$^{-1}$ ED, RS ED, little higgs, L-R symmetric, etc.



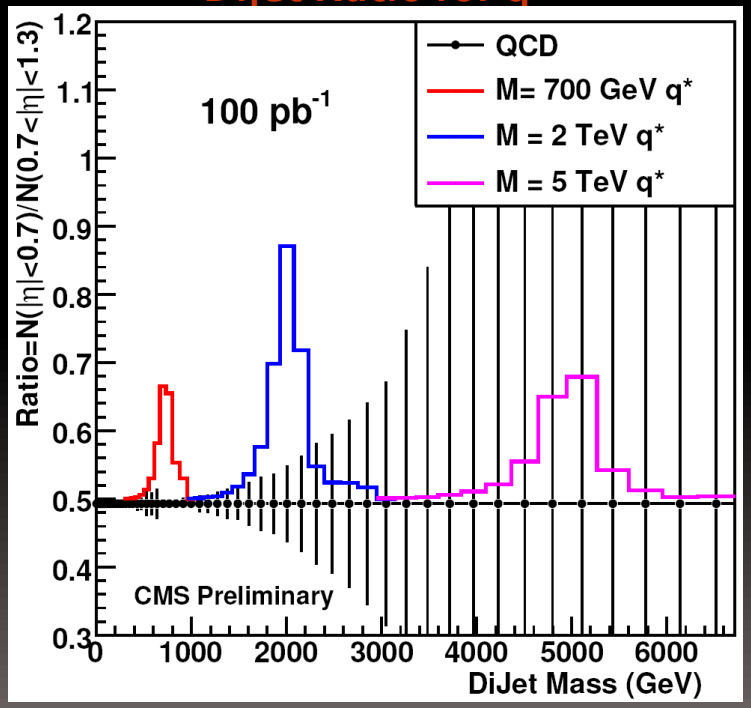



Main background is DY production. Smoothly and quickly falling with mass.

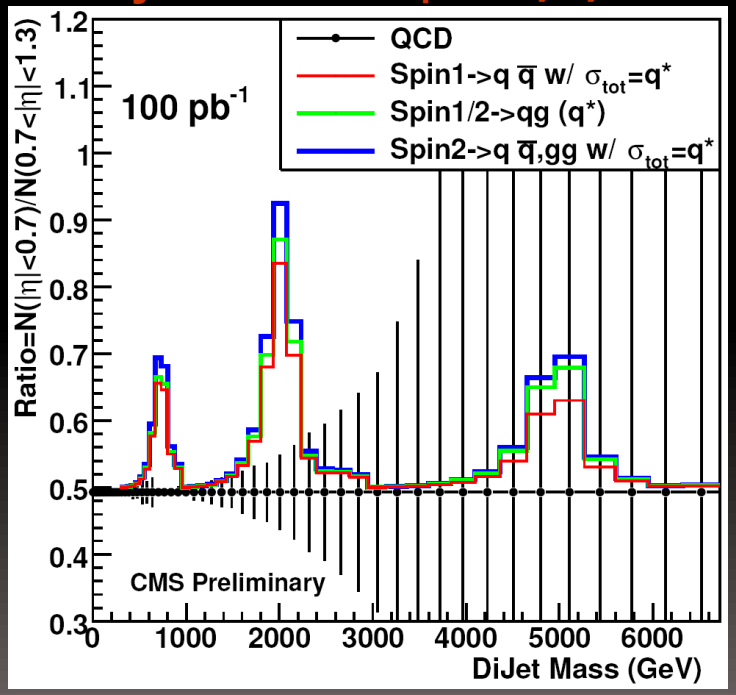
# Dijet Resonances with Dijet Ratio

- Dijet ratio from signal + QCD compared to statistical errors for QCD alone
  - Resonances normalized with q* cross section for |η|<1.3 to see effect of spin.
- Convincing signal for 2 TeV strong resonance in 100 $pb^{-1}$ regardless of spin.
- Promising technique for discovery, confirmation, and eventually spin measurement.

Dijet Ratio for q*




Dijet Ratio for Spin ½, 1, 2

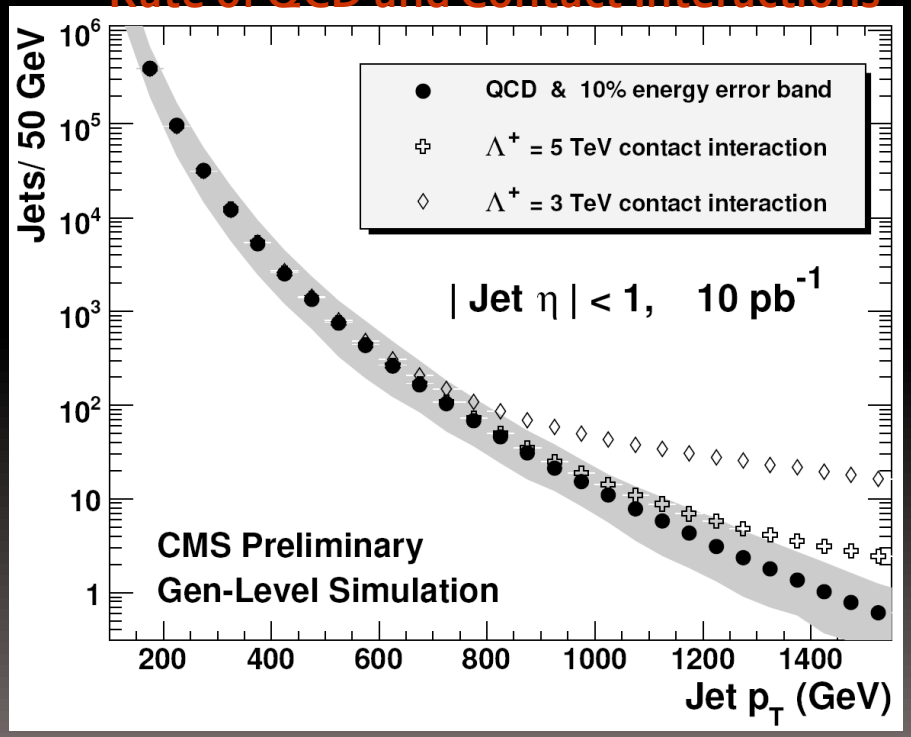


# Inclusive Jet $P_T$ and Contact Interactions

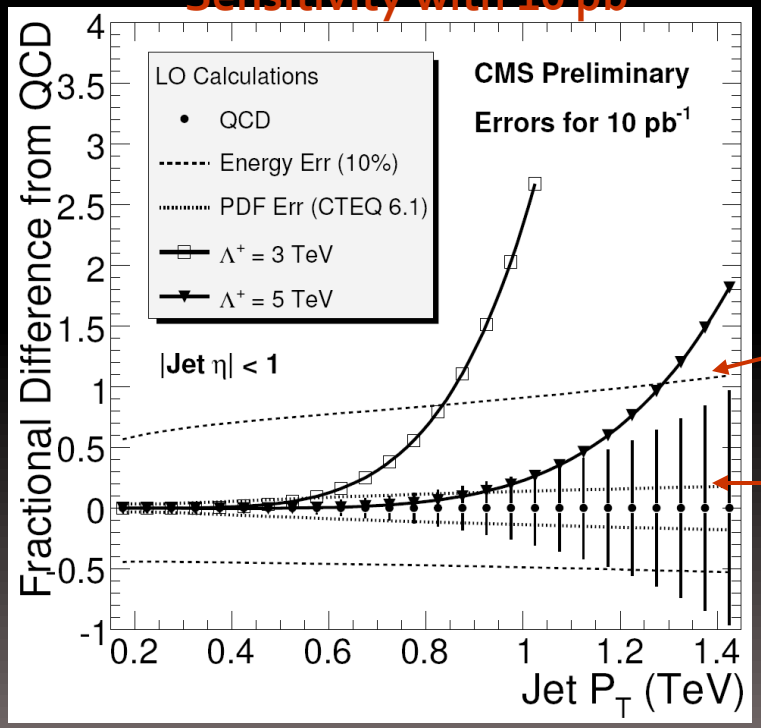
- Contact interactions create large rate at high $P_T$ and immediate discovery possible
  - Error dominated by jet energy scale (~10%) in early running (10 $pb^{-1}$)
    - $\Delta E$~ 10% not as big an effect as $\Lambda^+$= 3 TeV for $P_T$>1 TeV.
  - PDF "errors" and statistical errors (10 $pb^{-1}$) smaller than E scale error

- With 10 $pb^{-1}$ we can see new physics beyond Tevatron exclusion of $\Lambda^+ < 2.7$ TeV.

Rate of QCD and Contact Interactions




Sensitivity with 10 $pb^{-1}$



# SUSY models

To go beyond this kind of generic discussion, need to introduce models.

May not be right, but like those practice problems in the back of the book, is very useful to get us trained.

## Unconstrained MSSM is the most "economic" version of SUSY

- Minimal gauge group $SU(3)_C x SU(2)_L x U(1)_Y$
- Minimal particle content; tree generation of spin ½ quarks and leptons [no right handed neutrino] as in SM; The two Higgs doublets leads to five Higgs particles : **two CP even h, H bosons, a pseudoscalar A boson and two charged $H^{+/-}$ bosons**
- R parity conservation: $Rp = (-1)^{2S+3B+L}$
- Minimal set of soft SUSY-breaking terms
- Unconstrained MSSM has 124 free parameters (104 from SUSY breaking terms + 19 parameters of the SM)

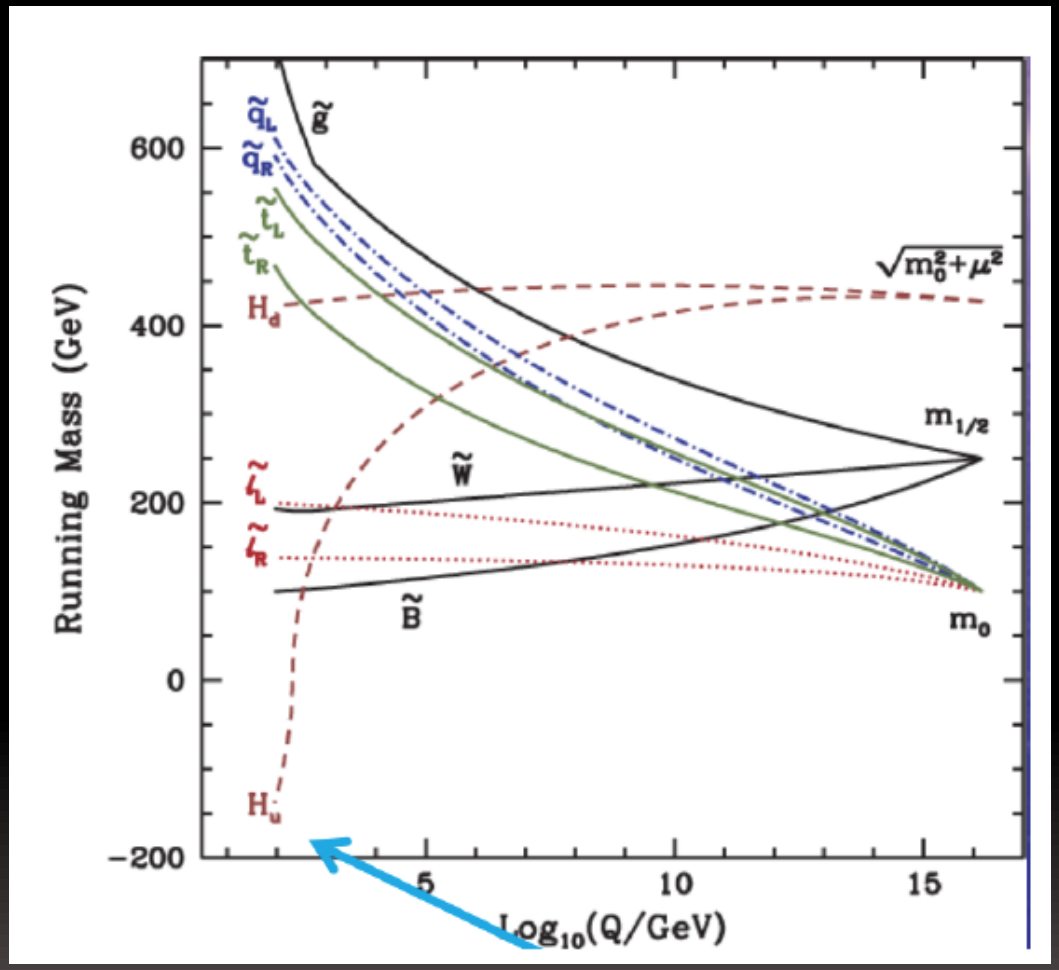
## Constrained MSSM (or phenomenological MSSM) reduces number of free parameters to 22

- all the soft SUSY-breaking parameters are real => no new source of CP-violation in addition to the one from CKM matrix
- no FCNC at tree level
- the soft SUSY-breaking masses and trilinear couplings of the 1st and 2nd sfermion generations are the same at low energy

# mSUGRA

- Thus, the idea is the following:
  - The many (>100) parameters of weak-scale SUSY should be derived from a minimal set of parameters at the unification scale.
- mSUGRA: the “canonical” model
  - 5 main parameters
    - $m_o$ , $m_{1/2}$ , $A_o$ , tan($\beta$), and sign($\mu$)
  - $m_o$ , $m_{1/2}$ are universal scalar and fermion masses
    - Like the couplings, one assumes that the spectra of fundamental particles derives from fundamental masses
  - $m_{3/2}$ is a 6$^{th}$ free parameter
    - Gravitino - could be LSP but in most of the literature it is assumed to be very heavy and ignored.

# mSUGRA masses




EWK symmetry breaking

# "Vanilla" SUSY: mSUGRA

- Region 1: in this region, the gluinos are heavier than any of the squarks. The decay chains of the produced sparticles are expected to be

$$\tilde{g} \to \tilde{q}\bar{q}\ ,\ \tilde{q} \to q\chi$$

less jets, harder MET

- Region 2: in this region some squarks are heavier, other are lighter than the gluino. Hence, rather complicated decay chains are possible, for instance

$$\tilde{q}_L \to \tilde{g}q\ ,\ \tilde{g} \to \tilde{b}\bar{b}\ ,\ \tilde{b} \to b\chi \qquad (3.6)$$

t, b quarks

as the $\tilde{q}_L$ of the first two generations are expected to be among the heaviest squarks and the $\tilde{b}_1$ (and $\tilde{t}_1$) among the lightest.

- Region 3: in this region, the gluinos are lighter than any of the squarks. A typical decay chain is then

$$\tilde{q} \to \tilde{g}q\ ,\ \tilde{g} \to q\bar{q}\chi$$

More jets, softer MET

$q_L$ tend to decay directly to lsp, $q_R$ has non-negligible BR to below

$$\tilde{\chi}_2^0 \to \tilde{l}l, \qquad (13.8)$$
$$\tilde{\chi}_2^0 \to \tilde{\nu}\nu, \qquad (13.9)$$
$$\tilde{\chi}_2^0 \to h^0\tilde{\chi}_1^0, \qquad (13.10)$$
$$\tilde{\chi}_2^0 \to Z^0\tilde{\chi}_1^0, \qquad (13.11)$$
$$\tilde{\chi}_2^0 \to l^+l^-\tilde{\chi}_1^0 \qquad (13.12)$$

$$\tilde{\chi}_1^\pm \to \tilde{l}\nu, \qquad (13.13)$$
$$\tilde{\chi}_1^\pm \to \tilde{\nu}l, \qquad (13.14)$$
$$\tilde{\chi}_1^\pm \to W^\pm\tilde{\chi}_1^0, \qquad (13.15)$$
$$\tilde{\chi}_1^\pm \to H^\pm\tilde{\chi}_1^0, \qquad (13.16)$$
$$\tilde{\chi}_1^\pm \to l^\pm\nu\tilde{\chi}_1^0, \qquad (13.17)$$

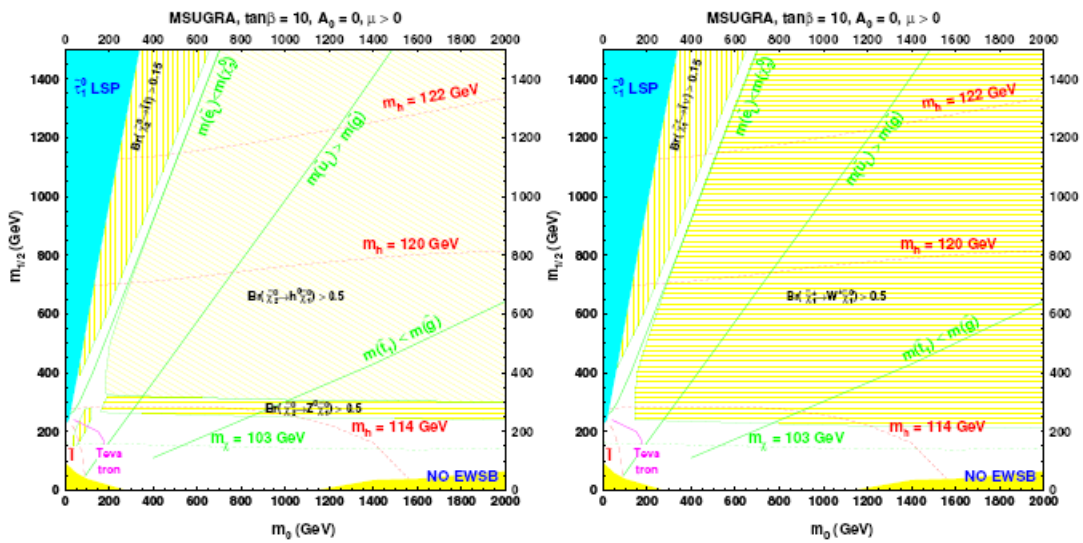



Figure 13.2: Regions of the $m_0$ versus $m_{1/2}$ plane with main $\chi_2^0$ decays (left) and main decays of $\tilde{\chi}_1^\pm$ (right).

CMS pTDR V2

# mSUGRA

- **Point LM1** :
  - Same as post-WMAP benchmark point B′ and near DAQ TDR point 4.
  - $m(\tilde{g}) \geq m(\tilde{q})$, hence $\tilde{g} \to \tilde{q}q$ is dominant
  - $B(\tilde{\chi}_2^0 \to \tilde{l}_R l) = 11.2\%$, $B(\tilde{\chi}_2^0 \to \tilde{\tau}_1 \tau) = 46\%$, $B(\tilde{\chi}_1^\pm \to \tilde{\nu}_l l) = 36\%$
- **Point LM2** :
  - Almost identical to post-WMAP benchmark point I′.
  - $m(\tilde{g}) \geq m(\tilde{q})$, hence $\tilde{g} \to \tilde{q}q$ is dominant ($\tilde{b}_1 b$ is 25%)
  - $B(\tilde{\chi}_2^0 \to \tilde{\tau}_1 \tau) = 96\%$ $B(\tilde{\chi}_1^\pm \to \tilde{\tau}\nu) = 95\%$

Lots of leptons and taus

Lots of taus, few e,mu

- **Point LM3** :
  - Same as NUHM point $\gamma$ and near DAQ TDR point 6.
  - $m(\tilde{g}) < m(\tilde{q})$, hence $\tilde{g} \to \tilde{q}q$ is forbidden except $B(\tilde{g} \to \tilde{b}_{1,2} b) = 85\%$
  - $B(\tilde{\chi}_2^0 \to ll\tilde{\chi}_1^0) = 3.3\%$, $B(\tilde{\chi}_2^0 \to \tau\tau\tilde{\chi}_1^0) = 2.2\%$, $B(\tilde{\chi}_1^\pm \to W^\pm \tilde{\chi}_1^0) = 100\%$
- **Point LM4** :
  - Near NUHM point $\alpha$ in the on-shell $Z^0$ decay region
  - $m(\tilde{g}) \geq m(\tilde{q})$, hence $\tilde{g} \to \tilde{q}q$ is dominant with $\tilde{g} \to \tilde{b}_1 b = 24\%$
  - $B(\tilde{\chi}_2^0 \to Z^0 \tilde{\chi}_1^0) = 97\%$, $B(\tilde{\chi}_1^\pm \to W^\pm \tilde{\chi}_1^0) = 100\%$
- **Point LM5** :
  - In the $h^0$ decay region, same as NUHM point $\beta$.
  - $m(\tilde{g}) \geq m(\tilde{q})$, hence $\tilde{g} \to \tilde{q}q$ is dominant with $B(\tilde{g} \to \tilde{b}_1 b) = 19.7\%$ and $B(\tilde{g} \to \tilde{t}_1 t) = 23.4\%$
  - $B(\tilde{\chi}_2^0 \to h^0 \tilde{\chi}_1^0) = 85\%$, $B(\tilde{\chi}_2^0 \to Z^0 \tilde{\chi}_1^0) = 11.5\%$, $B(\tilde{\chi}_1^\pm \to W^\pm \tilde{\chi}_1^0) = 97\%$
- **Point LM6** :
  - Same as post-WMAP benchmark point C′.
  - $m(\tilde{g}) \geq m(\tilde{q})$, hence $\tilde{g} \to \tilde{q}q$ is dominant
  - $B(\tilde{\chi}_2^0 \to \tilde{l}_L l) = 10.8\%$, $B(\tilde{\chi}_2^0 \to \tilde{l}_R l) = 1.9\%$, $B(\tilde{\chi}_2^0 \to \tilde{\tau}_1 \tau) = 14\%$, $B(\tilde{\chi}_1^\pm \to \tilde{\nu}_l l) = 44\%$

Lots of W's, b's

On-shell Z's and W's, b's

Lots of higgs to bbbar

Like LM1, but fewer taus

CMS pTDR V2

# More..

- **Point LM7 :**
  - Very heavy squarks, outside reach, but light gluino.
  - $m(\tilde{g}) = 678\,\mathrm{GeV/c^2}$, hence $\tilde{g} \to$ 3-body is dominant
  - $B(\tilde{\chi}_2^0 \to ll\tilde{\chi}_1^0) = 10\%$, $B(\tilde{\chi}_1^\pm \to \nu l\tilde{\chi}_1^0) = 33\%$
  - EW chargino-neutralino production cross-section is about 73% of total.
- **Point LM8 :**
  - Gluino lighter than squarks, except $\tilde{b}_1$ and $\tilde{t}_1$
  - $m(\tilde{g}) = 745\,\mathrm{GeV/c^2}$, $M(\tilde{t}_1) = 548\,\mathrm{GeV/c^2}$, $\tilde{g} \to \tilde{t}_1 t$ is dominant
  - $B(\tilde{g} \to \tilde{t}_1 t) = 81\%$, $B(\tilde{g} \to \tilde{b}_1 b) = 14\%$, $B(\tilde{q}_L \to q\tilde{\chi}_2^0) = 26 - 27\%$,
  - $B(\tilde{\chi}_2^0 \to Z^0\tilde{\chi}_1^0) = 100\%$, $B(\tilde{\chi}_1^\pm \to W^\pm\tilde{\chi}_1^0) = 100\%$
- **Point LM9 :**
  - Heavy squarks, light gluino. Consistent with EGRET data on diffuse gamma ray spectrum, WMAP results on CDM and mSUGRA [674]. Similar to LM7.
  - $m(\tilde{g}) = 507\,\mathrm{GeV/c^2}$, hence $\tilde{g} \to$ 3-body is dominant
  - $B(\tilde{\chi}_2^0 \to ll\tilde{\chi}_1^0) = 6.5\%$, $B(\tilde{\chi}_1^\pm \to \nu l\tilde{\chi}_1^0) = 22\%$
- **Point LM10 :**
  - Similar to LM7, but heavier gauginos.
  - Very heavy squarks, outside reach, but light gluino.
  - $m(\tilde{g}) = 1295\,\mathrm{GeV/c^2}$, hence $\tilde{g} \to$ 3-body is dominant
  - $B(\tilde{g} \to t\bar{t}\tilde{\chi}_4^0) = 11\%$, $B(\tilde{g} \to tb\tilde{\chi}_2^\pm) = 27\%$

Squarks decouple

Lots of top

Squarks decouple

Lots of top

CMS pTDR V2

# ATLAS benchmarks

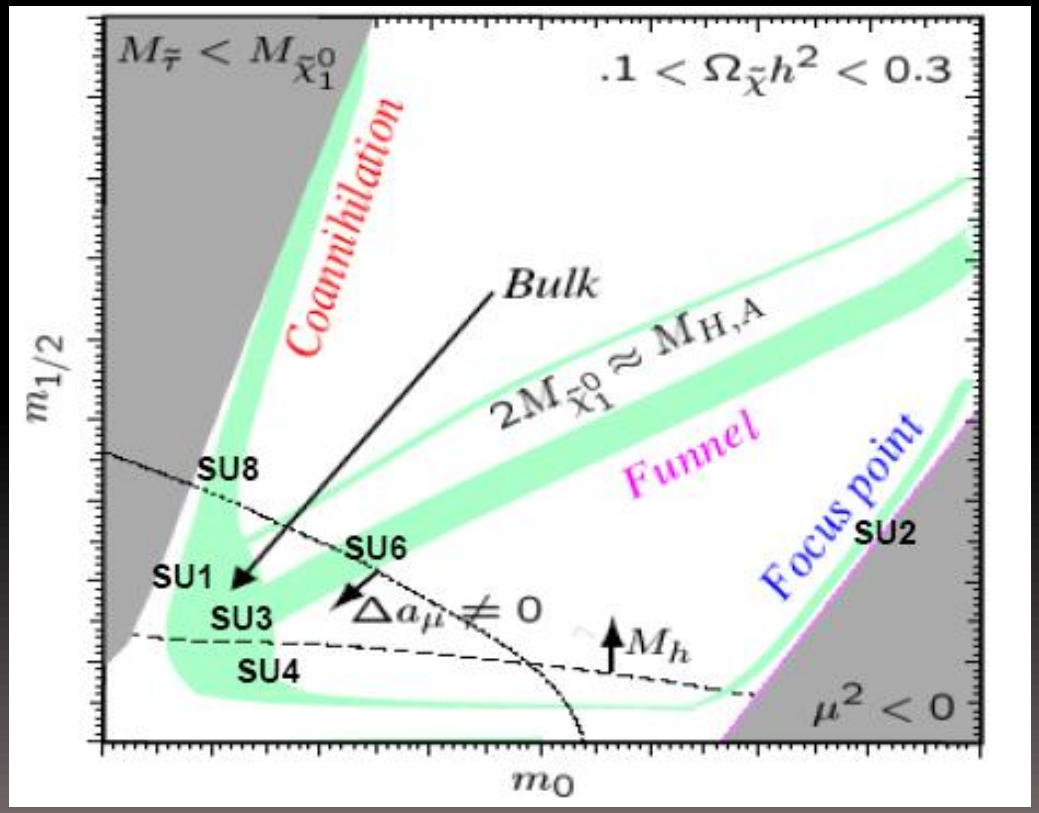
- Benchmarks have been chosen requiring that neutralino relic density matches DM constraints
- **SUn** = m**SU**gra benchmark **n** (no reference to symmetry groups!)

*Coannihilation:* Light $\tilde{\tau}_1$ in equilibrium with $\tilde{\chi}_1^0$, so annihilate via $\tilde{\chi}_1^0\tilde{\tau}_1 \to \gamma\tau$.

*Bulk:* bino $\tilde{\chi}_1^0$; light $\tilde{\ell}_R$ enhances annihilation.

*Funnel:* $H, A$ poles enhance annihilation for $\tan\beta \gg 1$.

*Focus point:* Small $\mu^2$, so Higgsino $\tilde{\chi}_1^0$ annihilate. Heavy s-fermions, so small FCNC.



# ATLAS benchmarks

SU1 $m_0 = 70$ GeV, $m_{1/2} = 350$ GeV, $A_0 = 0$, $\tan\beta = 10$, $\mu > 0$. Coannihilation region where $\tilde{\chi}_1^0$ annihilate with near-degenerate $\tilde{\ell}$.

SU2 $m_0 = 3550$ GeV, $m_{1/2} = 300$ GeV, $A_0 = 0$, $\tan\beta = 10$, $\mu > 0$. Focus point region near the boundary where $\mu^2 < 0$. This is the only region in mSUGRA where the $\tilde{\chi}_1^0$ has a high higgsino component, thereby enhancing the annihilation cross-section for processes such as $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to WW$.

SU3 $m_0 = 100$ GeV, $m_{1/2} = 300$ GeV, $A_0 = -300$ GeV, $\tan\beta = 6$, $\mu > 0$. Bulk region: LSP annihilation happens through the exchange of light sleptons.

SU4 $m_0 = 200$ GeV, $m_{1/2} = 160$ GeV, $A_0 = -400$ GeV, $\tan\beta = 10$, $\mu > 0$. Low mass point close to Tevatron bound.

SU6 $m_0 = 320$ GeV, $m_{1/2} = 375$ GeV, $A_0 = 0$, $\tan\beta = 50$, $\mu > 0$. The funnel region where $2m_{\tilde{\chi}_1^0} \approx m_A$. Since $\tan\beta \gg 1$, the width of the pseudoscalar Higgs boson $A$ is large and $\tau$ decays dominate.

SU8.1 $m_0 = 210$ GeV, $m_{1/2} = 360$ GeV, $A_0 = 0$, $\tan\beta = 40$, $\mu > 0$. Variant of coannihilation region with $\tan\beta \gg 1$, so that only $m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0}$ is small.

SU9 $m_0 = 300$ GeV, $m_{1/2} = 425$ GeV, $A_0 = 20$, $\tan\beta = 20$, $\mu > 0$. Point in the bulk region with enhanced Higgs production

| 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 |

# HSCP

**Key element: measurement of velocity β**

Two techniques:

- time of flight measurement by muon DT
- using specific ionisation in tracker

calculate particle mass $m = p/(\beta\gamma c)$

CMS

**Lepton-like HSCP**

- Can penetrate the whole detector
- High ionization energy loss
- Delayed with respect to lightspeed particles

**R-Hadron-like HSCP**

- Heavy parton behaves as a spectator
- Does not shower in the calorimeters
- The charge can change in hadronic interactions with matter while crossing the detector

**HSCP triggering:**

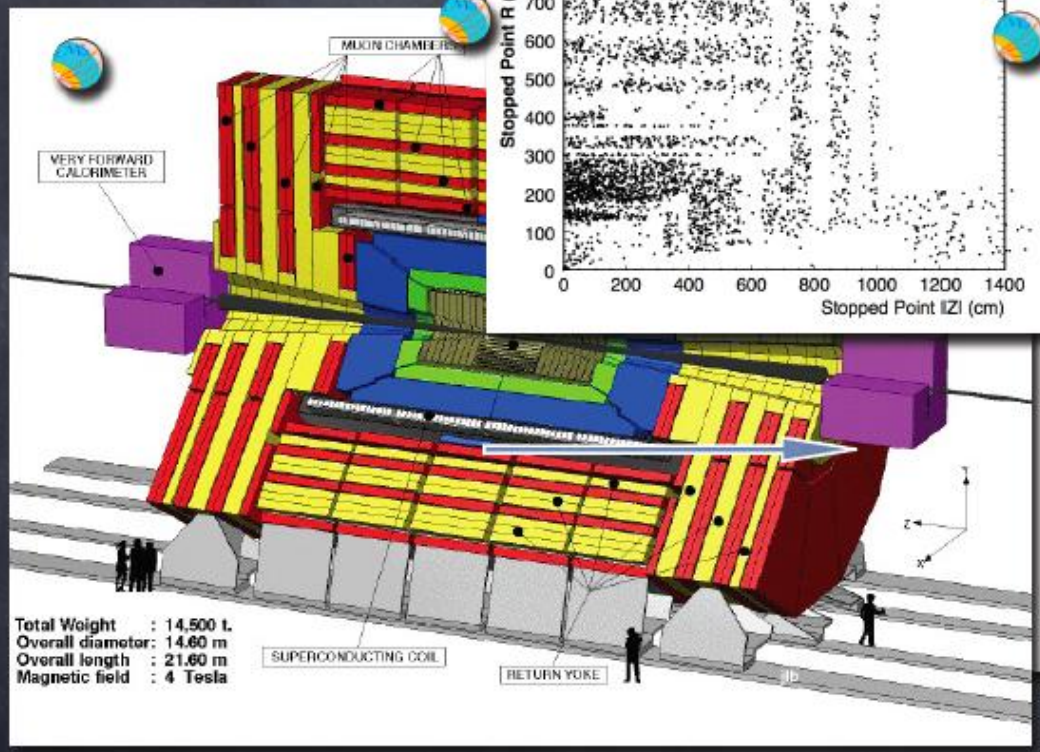
- Timing issue important:
  L1/HLT not prepared for slow particle which can be reco in different BX

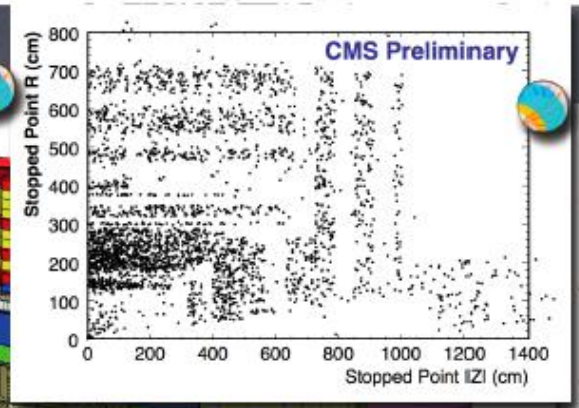
- **Two main trigger paths:**
  - Muon HLT path: trigger by HSCP or SM muon
  - MET HLT path: MET present in many models (from cascade) – indep of timing problems

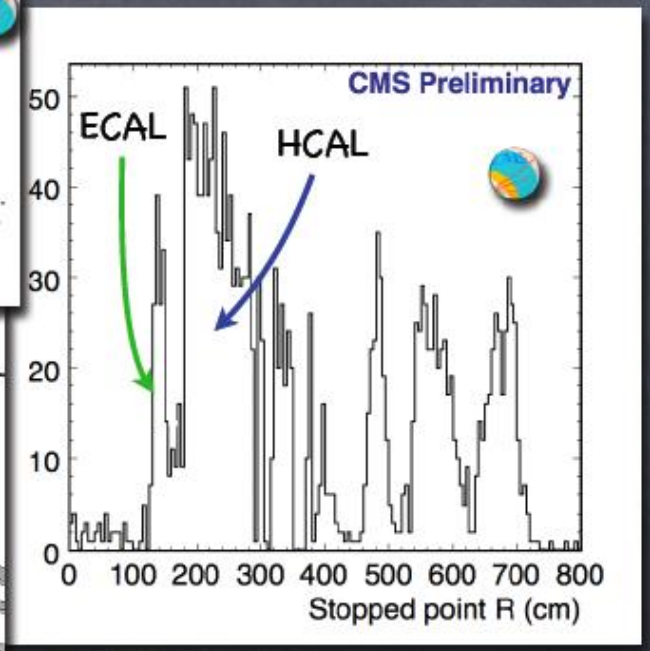
**Final trigger efficiency:**

~70% for lepton-like HSCP

~40-95 % for R-Hadrons

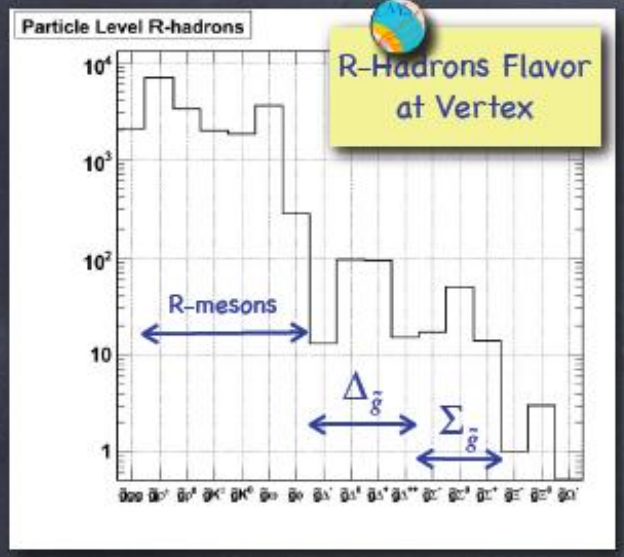


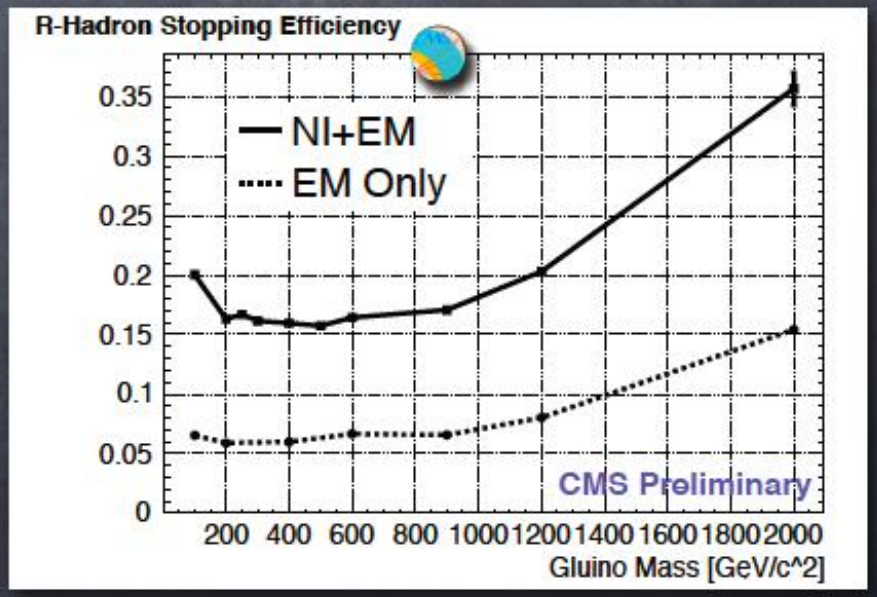

- Significant amount of R-hadrons are stopped in the detector: mostly in calorimeters and in return yokes

# Long-lived gluinos




R-Hadrons Flavor at Stopping Point

| R-Hadron flavor | $\Delta_{\tilde{g}}^{++}$ | $\Delta_{\tilde{g}}^{+}$ | $\Delta_{\tilde{g}}^{-}$ | R-mesons |
|---|---|---|---|---|
| Fraction in stopping state | 49% | 20% | 25% | 6% |




- ~15% of R-hadrons is stopped in detector volume
- Flat in the mass range of interest

# A specific Analysis

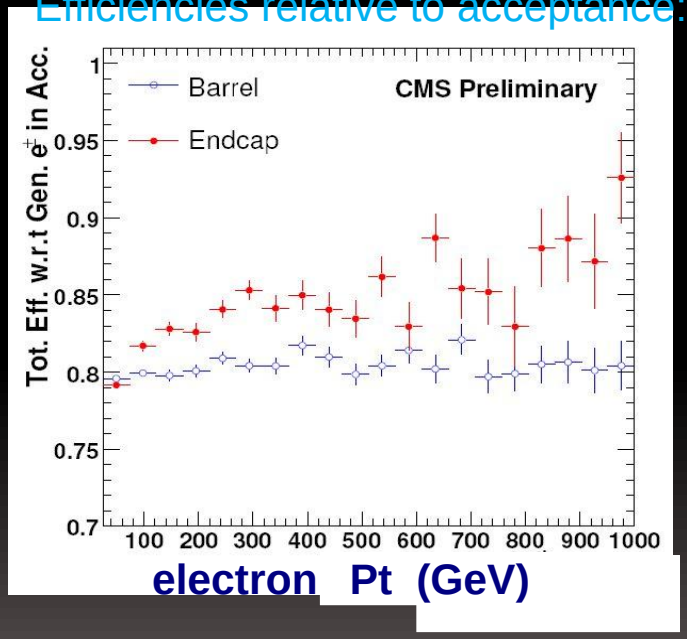
ATLAS Phys TDR
CMS PAS EXO-08-004
CMS PAS EXO-08-001
CMS BSM 07-002

**Example: selection for Z' ➔ee:**

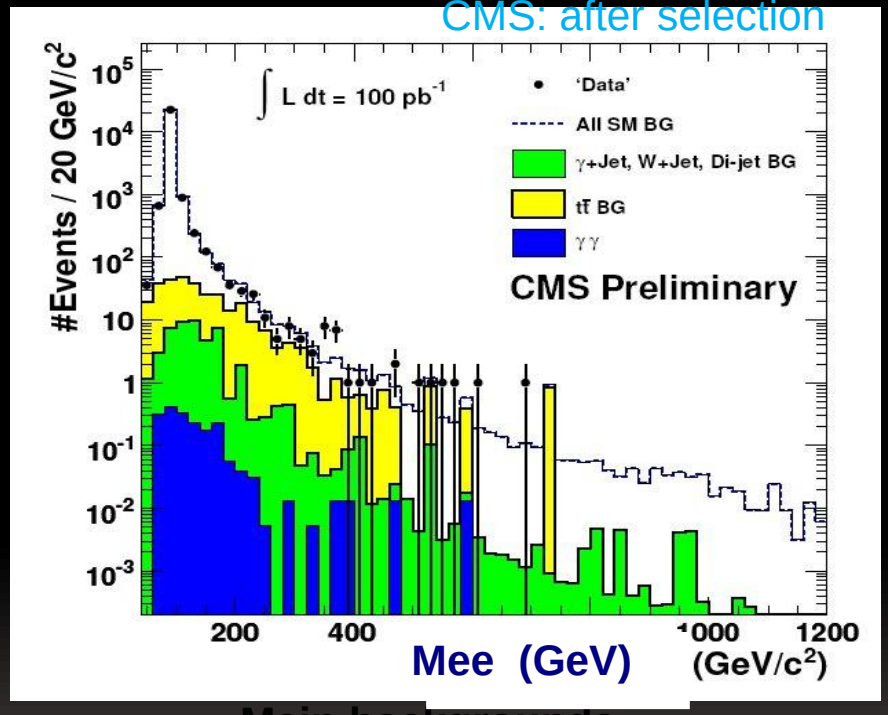
- 2 electrons in |η| 2.5, pt 0 GeV
- electron ID (cluster-track matching)
- e isolated in tracker/ECAL/HCAL

**High pt electron reconstruction**

Efficiencies relative to acceptance:




CMS: after selection




**Main backgrounds:**

Drell-Yan (irreducible)

ttbar, W+jets, QCD (reducible)

Tevatron limit is: 700-1000 GeV