Discovery Physics at the LHC

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Lecture Themes

I. Phenomenology beyond the Standard Model

- Empirical & theoretical limitations of the Standard Model
- Supersymmetry
- Extra Dimensions
- Little Higgs

II. Experimental Searches

- LHC, ATLAS and CMS: Experimental Challenges
- Searches at the LHC: SUSY, Extra Dimensions, Little Higgs

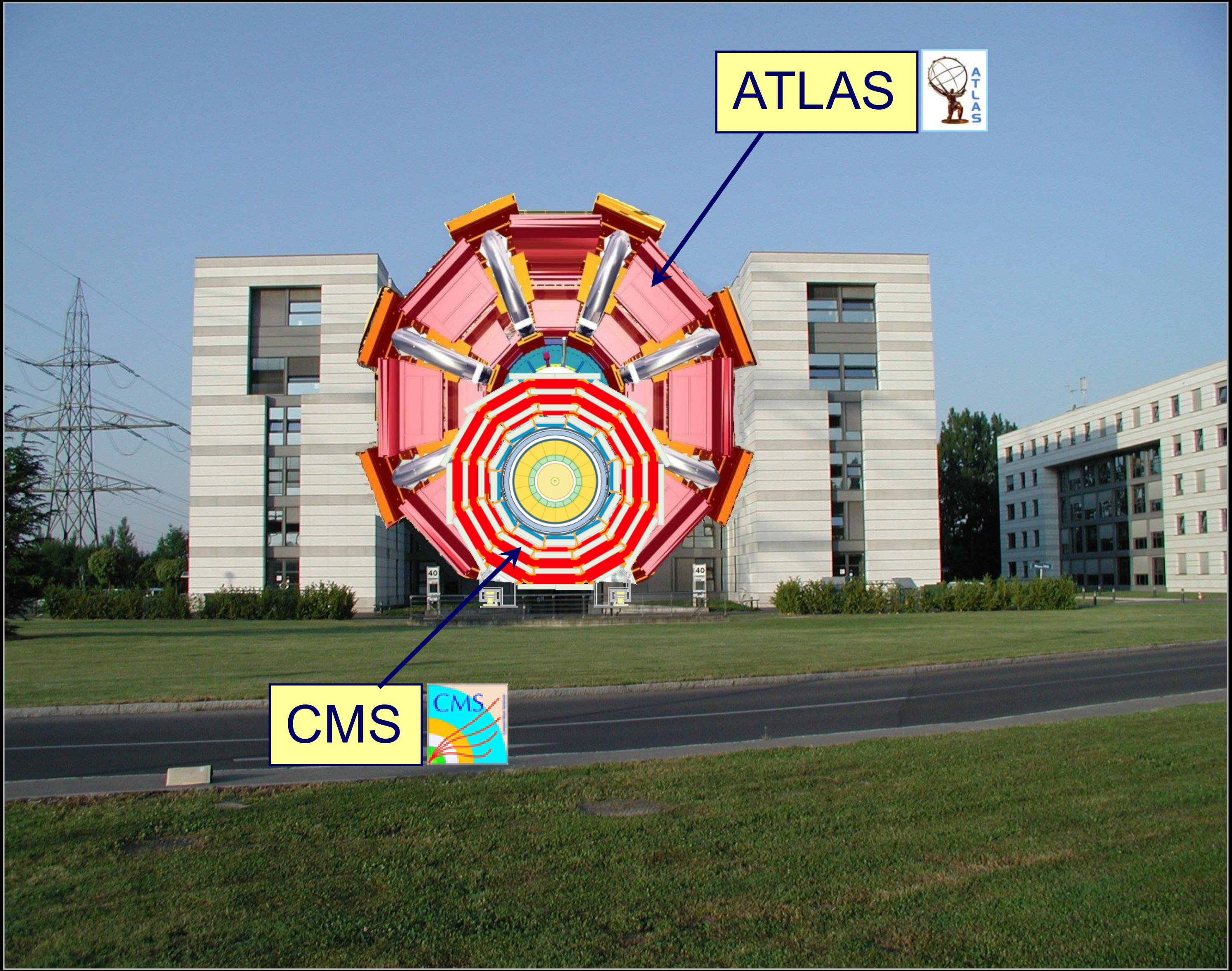
III. *CP* Violation and the Genesis of a Matter World
(out-of-series lecture)

Lectures based on many, many sources… please contact me for the list

LHC, ATLAS and CMS

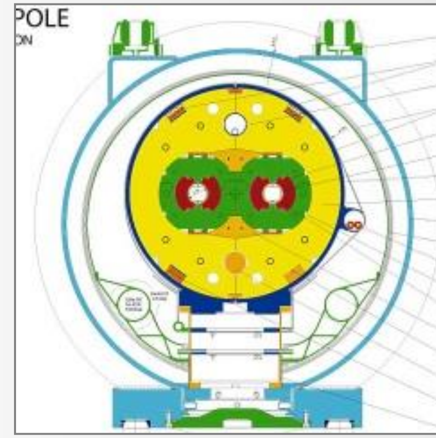
Experimental Challenges

(Brief overview only – many more details in Fido Dittus' lecture)


ATLAS
CMS

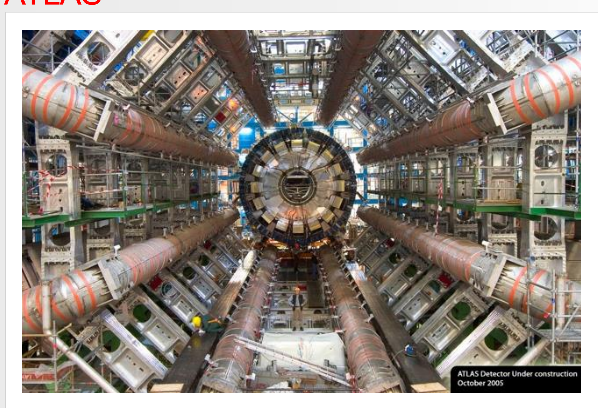
LHC: The Accelerator Challenge

- The search for new phenomena must exploit smaller and smaller distances → larger and larger energies
- The LHC collides protons at E_{CM} = 14 TeV → probing a distance of $1.4\ 10^{-18}$ cm ? … not quite, since protons are composites
- Want to produce rare new particles → need high intensity beams
- Proton energy is limited by magnets that guide the circular beams
- $E_{proton} \sim 0.3 \cdot B \cdot r$: since radius is fixed, use as strong fields as possible (> 8 T), and fill all free LHC sections with magnets (~2/3)

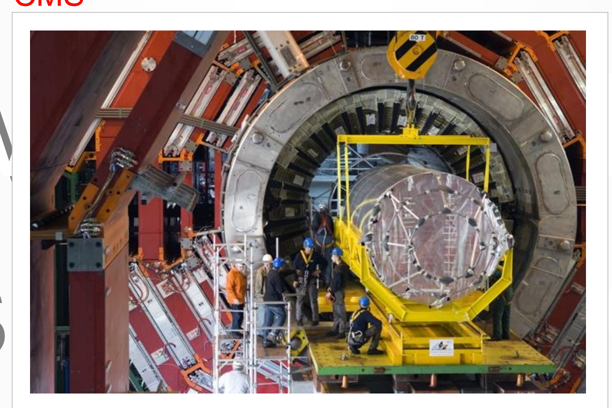


LHC dipole section. Proton-proton acceleration requires two beam pipes

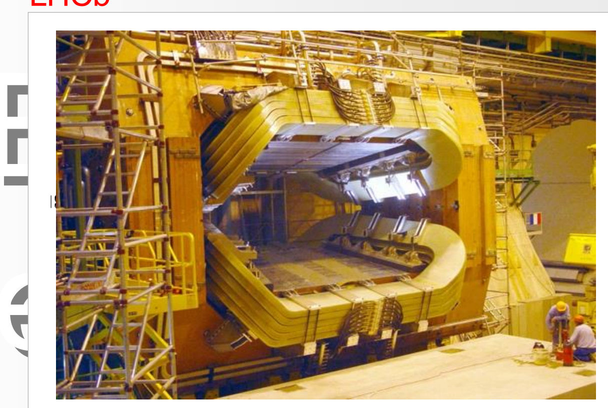
ATLAS



CMS



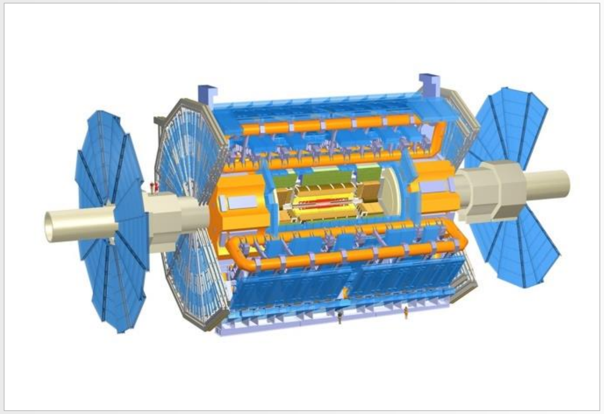
LHCb



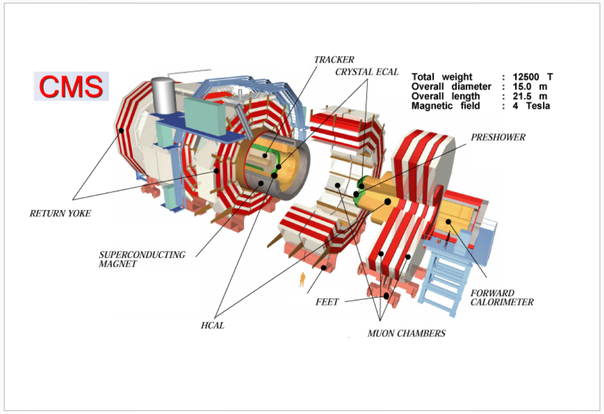
and also ALICE !

The LHC and its Experiments

ATLAS



CMS



ALTAS and CMS have same physics goals: concentrate on "high-p_T" discovery physics

The detector concepts are however different: this provides redundancy and fruitful competition

(→ lecture by F. Dittus)

LHCb

ALICE

Will concentrate on high-p_T physics in this lecture

L
e
b
low-p_T B physics

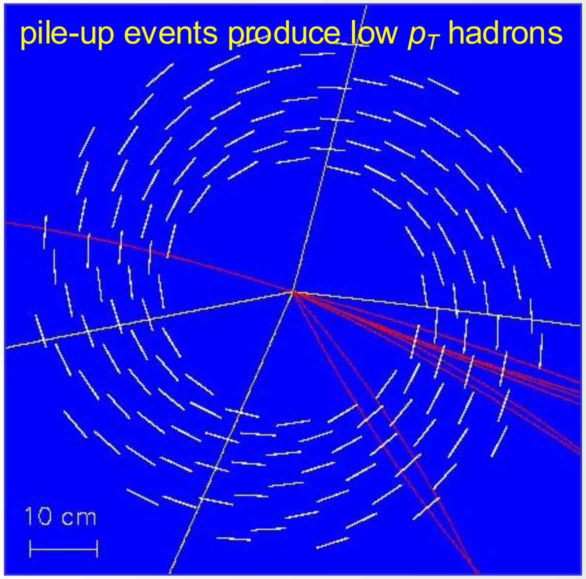
(→ lectures by O. Buchmüller and R. Fleischer)

There are two more (much smaller) experiments at the LHC: TOTEM (measuring elastic and diffractive processes), and LHCf (testing cosmic shower models)

ALICE will exploit high-energetic nucleus-nucleus ("heavy-ion") collisions

The Experimental Challenges

- At high luminosity (10^{34} cm^{-2}s^{-1}), ~25 “pile-up” interactions will occur in one bunch crossing
  - Need extremely fast detector response within 25 ns “exposure time” (= 40 MHz bunch crossing rate)
  - Need fine granular detector to “reconstruct” and filter out interesting events
- Basic detector concepts:
  - Symmetric beams → symmetric detector, pointing geometry
  - Collision products move from the interaction point outwards
  - Trajectories of charged particles bending in *B* field are measured
  - Calorimeters measure electron, photon, hadron energy deposits
  - Tracks of remaining (unabsorbed) muons are measured
- Event reconstruction:
  - “Trigger” on (= flag) an interesting event, and read out detector
  - Reconstruction starts with detector signals:
    - space points from ionization by charged particles in tracking systems
    - energies from showers in calorimeter cells/crystals
    - signals from particle-identification detectors (sensitive to mass of particles)
  - “Fit” track helixes to space points
  - “Cluster” adjacent calorimeter energy deposits



18 superimposed pp collisions in CMS tracker (there are also 4 muons from Higgs decay...)

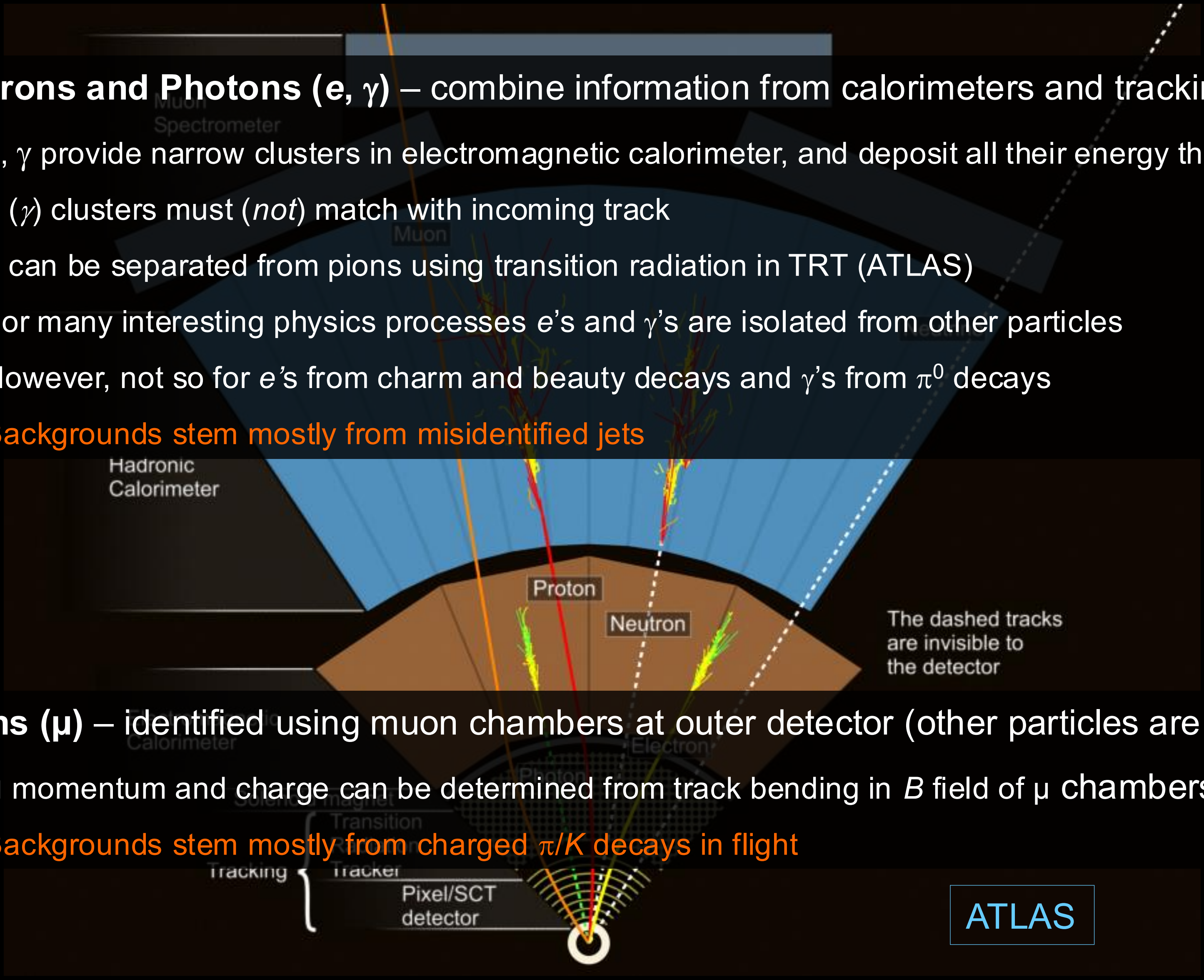
After applying a cut on p_T > 2 GeV (in yellow 4 muons from the Higgs decay...)

ATLAS & CMS: Performance Overview

	ATLAS	**CMS**
INNER TRACKER	• Silicon pixels + strips • TRT with particle identification • B = 2T • $\sigma/p_T \sim$ 2.6% (at 100 GeV, η = 0)	• Silicon pixels + strips • No dedicated particle identification • B = 4T • $\sigma/p_T \sim$ 1.2% (at 100 GeV, η = 0)
MAGNETS	• Solonoid + Air-core muon toroids • Calorimeters outside field • 4 magnets	• Solenoid • Calorimeters inside field • 1 magnet
EM CALORIMETER	• Pb-liquid argon • $\sigma/E \sim 10\% / \sqrt{E}$ • Uniform longitudinal segmentation • Saturation at ~ 3 TeV	• PbWO4 crystals • $\sigma/E \sim 3–5\% / \sqrt{E}$ • No longitudinal segmentation • Saturation at 1.7 TeV
HAD CALORIMETER	• Fe+scint. + Cu-liquid argon (10 [illegible]) • $\sigma/E \sim 50\% / \sqrt{E} \oplus 0.03$	• Brass+scint. • $\sigma/E \sim 100\% / \sqrt{E} \oplus 0.05$
MUON	• Air $\rightarrow \sigma/p_T \sim$ 10.5% at 1 TeV (standalone)	• Fe $\rightarrow \sigma/p_T \sim$ 4.5% at 1 TeV (combined with tracker)

Electron, Photon and Muon Identification

- **Electrons and Photons (*e*, γ)** – combine information from calorimeters and tracking devices
  - e, γ provide narrow clusters in electromagnetic calorimeter, and deposit all their energy therein
  - *e* (γ) clusters must (*not*) match with incoming track
  - *e* can be separated from pions using transition radiation in TRT (ATLAS)
  - For many interesting physics processes *e*'s and γ's are isolated from other particles
  - However, not so for *e*'s from charm and beauty decays and γ's from π^0 decays
  - Backgrounds stem mostly from misidentified jets

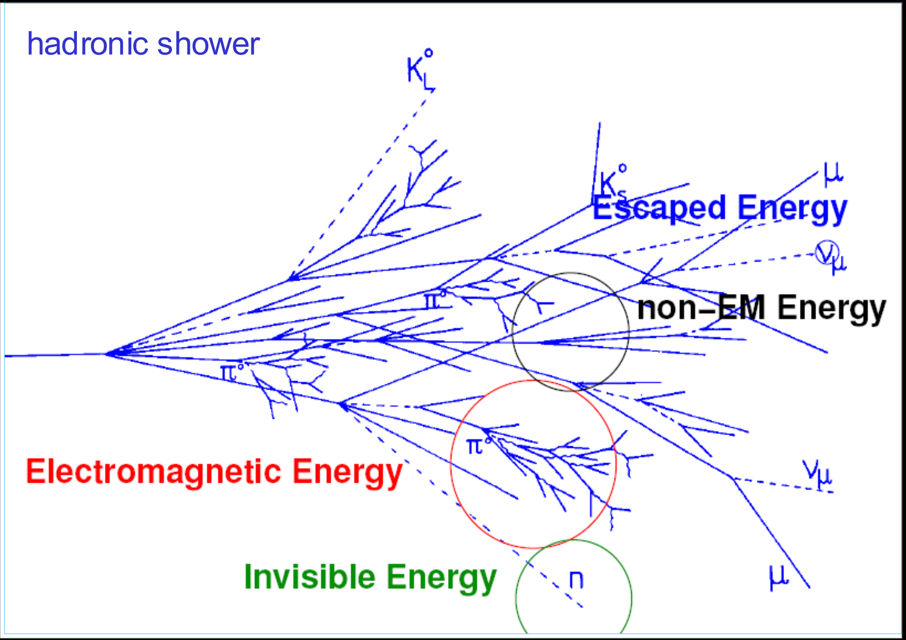


- **Muons (μ)** – identified using muon chambers at outer detector (other particles are absorbed)
  - μ momentum and charge can be determined from track bending in *B* field of μ chambers
  - Backgrounds stem mostly from charged π/K decays in flight

ATLAS

Jets and "Missing Transverse Energy"

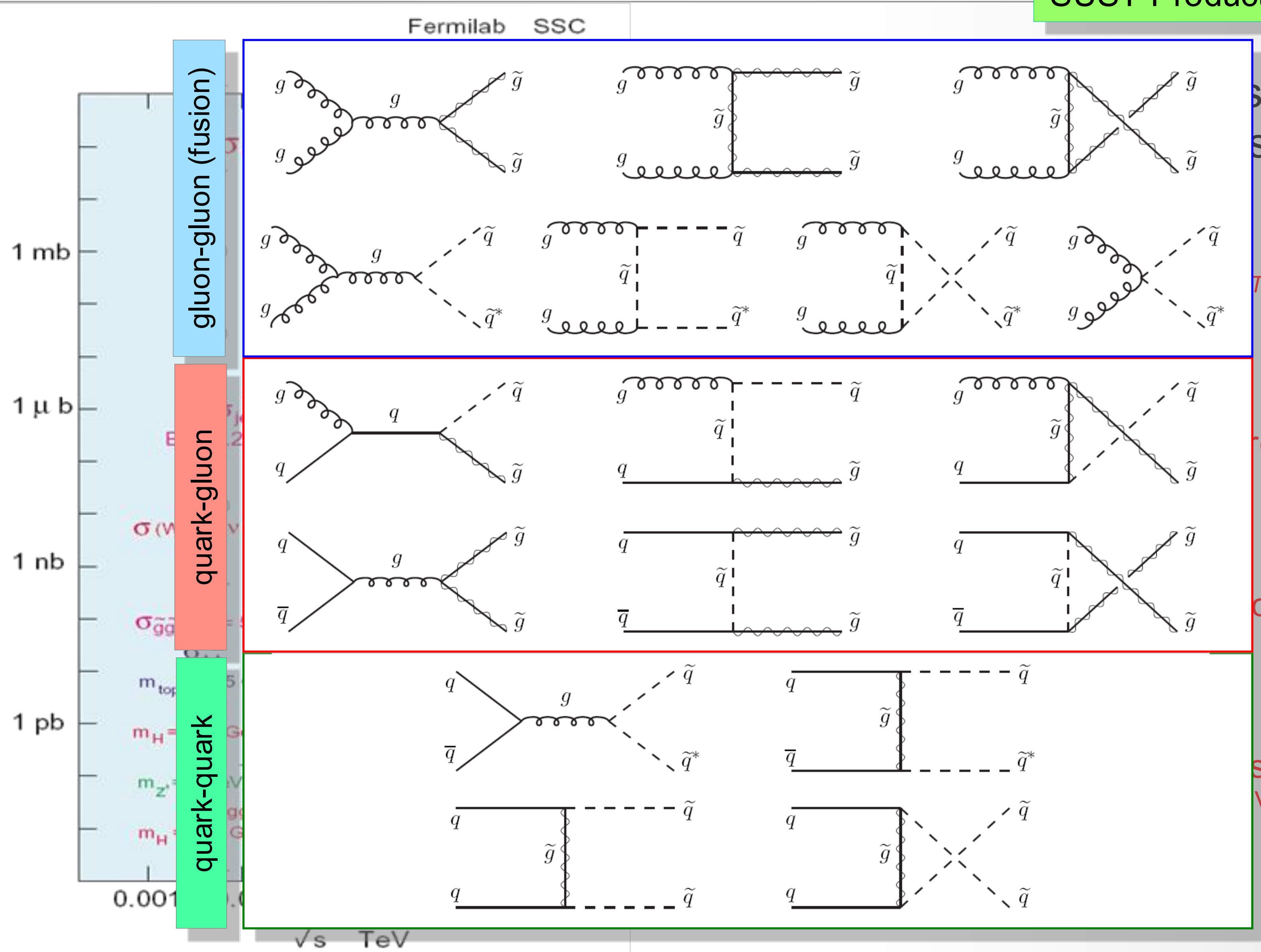
- **Jets** – reconstruction in calorimeters (use of tracking devices can help)
  - Jets are QCD hard scattering processes
  - Because of QCD confinement, the outgoing quarks and gluons "hadronize" into colorless hadrons (and other particles)
  - Jets dominate high-p_T cross section at LHC
  - While jets are interesting in its own right
  - …they are dominant background for rare processes, like decays of Higgs particles
  - Reconstruction rather bold: take all clusters (and tracks) within some cone around jet axis
  - Jet energy calibration is a major headache



- **Missing Transverse Energy**
  - In principle: $E_{T,\mathrm{miss}} = \sum_{l,j} E_{T,i} E_{T,j} \cos(\phi_l - \phi_j) = 0$ at LHC
  - If $E_{T,\mathrm{mis}} \neq 0$, particles may have escaped detection (*e.g.*, neutrinos, or New Physics)
  - Fake $E_{T,\mathrm{mis}}$ can be easily created by acceptance effects, miscalibration, instrumental failures

Cross Sections

SUSY Production at LHC



s

ss section

QCD jets

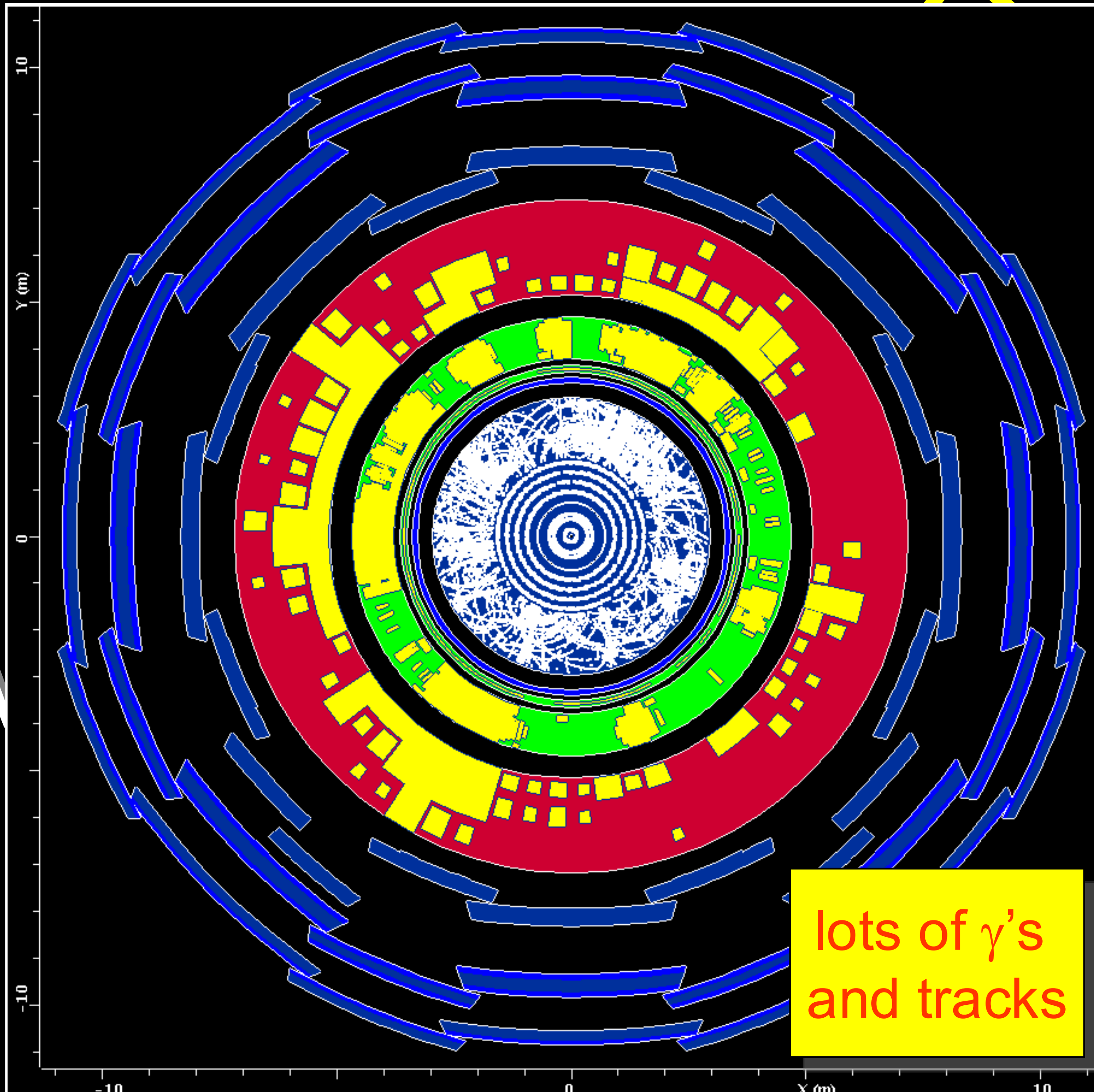
roduction

o-Higgs fusion

s, gluinos

V)

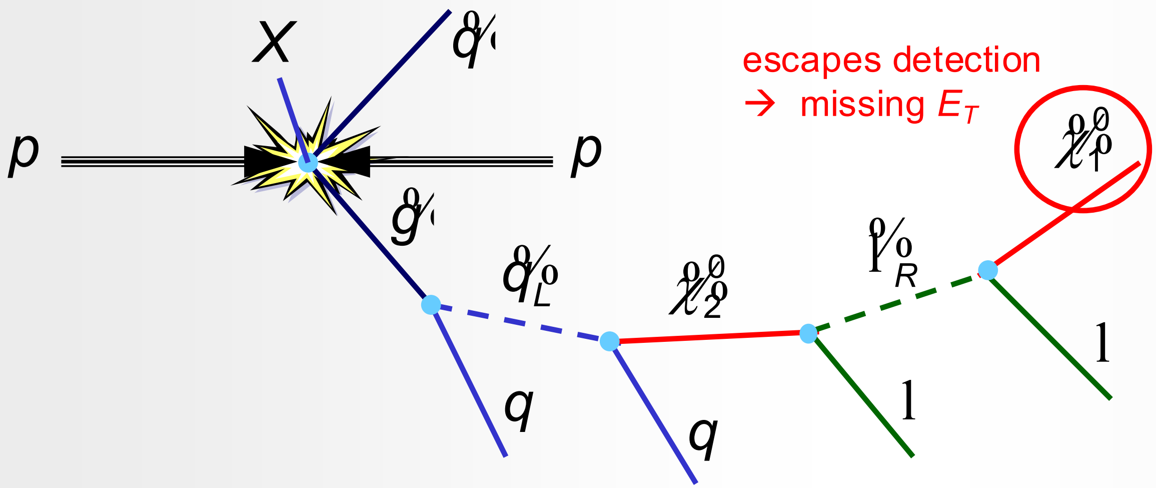
Micro Black Hole ?
accepted by Trigger



Supersymmetry Searches at the LHC

Characteristic SUSY "Cascades" at the LHC

- Conserved ***R*-parity** requires existence of a **lightest stable SUSY particle** = "LSP". Since no exotic strong or EM bound states (isotopes) have been observed, the LSP should be neutral and colourless → **WIMP** !
- The experimental signature of the LSP would be just as the one of a heavy neutrino !
- The LSP is typically found to be a spin-½ "**neutralino**", a linear combination of gauginos (in much of the SUSY parameter space the neutralino is a mixture of photino and zino)



"Typical" SUSY decay chain at the LHC

But why the "*T*" in missing E_T ?

The hard-scattering processes are not longitudinally balanced

Hence, we do not know what longitudinal energy to expect

Fortunately, the events are transversely balanced !

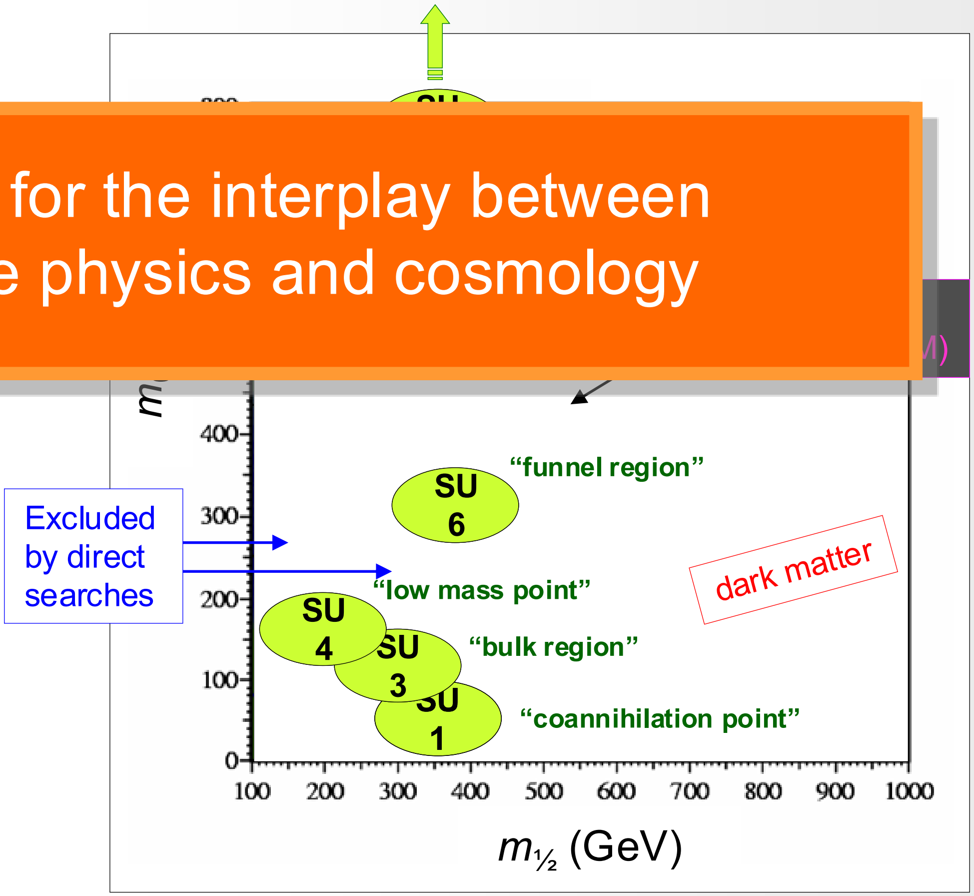
Inclusive SUSY Searches

- SUSY searches are prepared by studying simulated data ("Monte Carlo"): since SUSY parameters are unknown, simplify the task by choosing "minimal SUGRA" scenarios

- Choose a few "characteristic" points

A wonderful example for the interplay between contemporary particle physics and cosmology

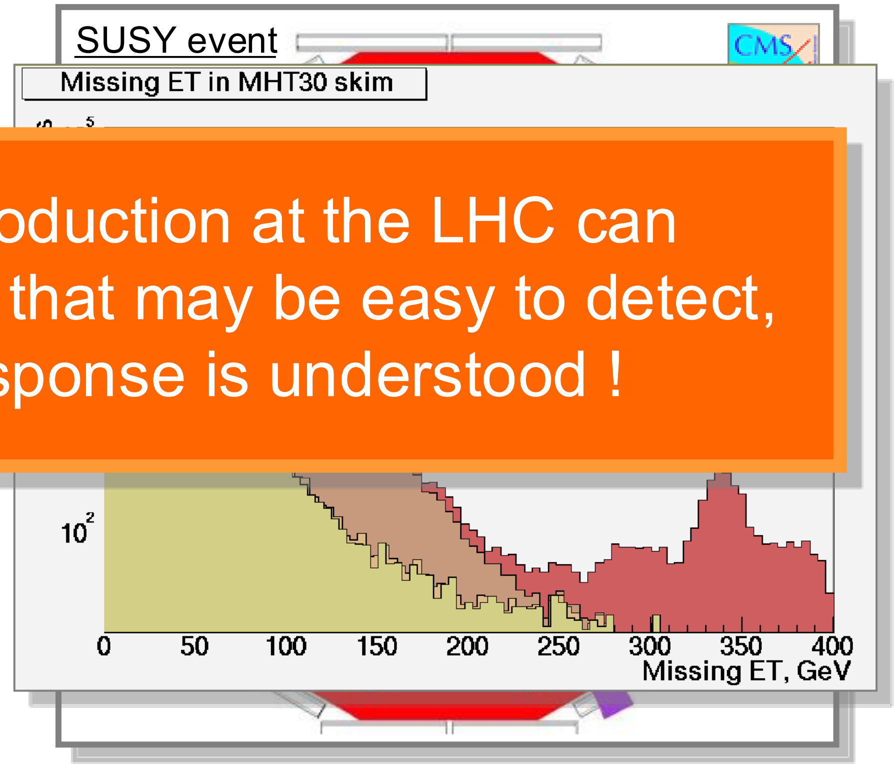
- Since mSUGRA has only 5 parameters, it is highly constraining …and can quite well be constrained from data already !
  - From direct accelerator searches
  - From indirect accelerator searches
  - From cosmology



Inclusive SUSY Searches … continued

- The precise signatures of the SUSY “cascades” are driven by the masses of the SUSY particles

Measuring missing energy is a tough task !



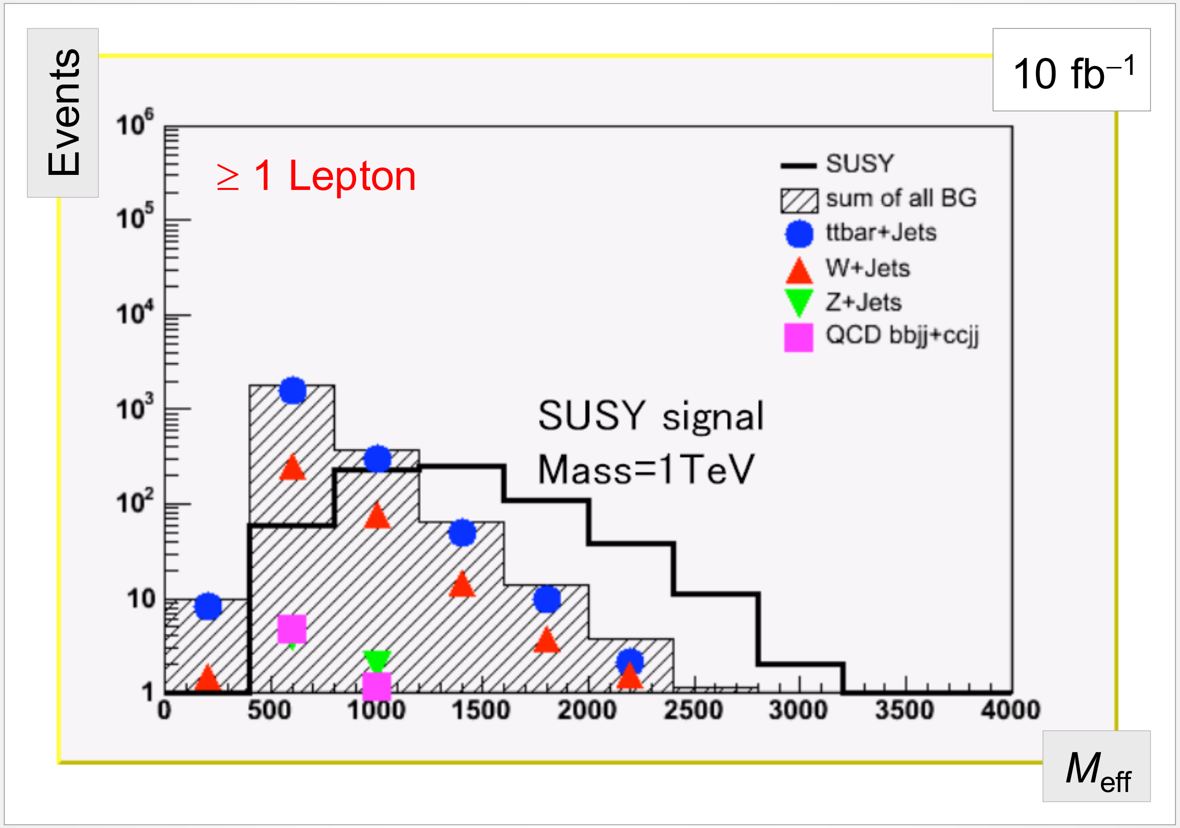
Strong squarks and gluino production at the LHC can have a spectacular signature that may be easy to detect, once … once the detector response is understood !

- ➔ This lays out an **inclusive** search strategy

- Detector requirements:
  - Excellent jet-energy measurement
  - Excellent lepton identification
  - Hermeticity of the detector (good acceptance)

Inclusive SUSY Searches … continued

- A sensitive variable to detect SUSY decays is the "**effective mass**": $M_{\text{eff}} = E_{T,\text{miss}} + \sum_{\text{jets, leptons}} p_T$



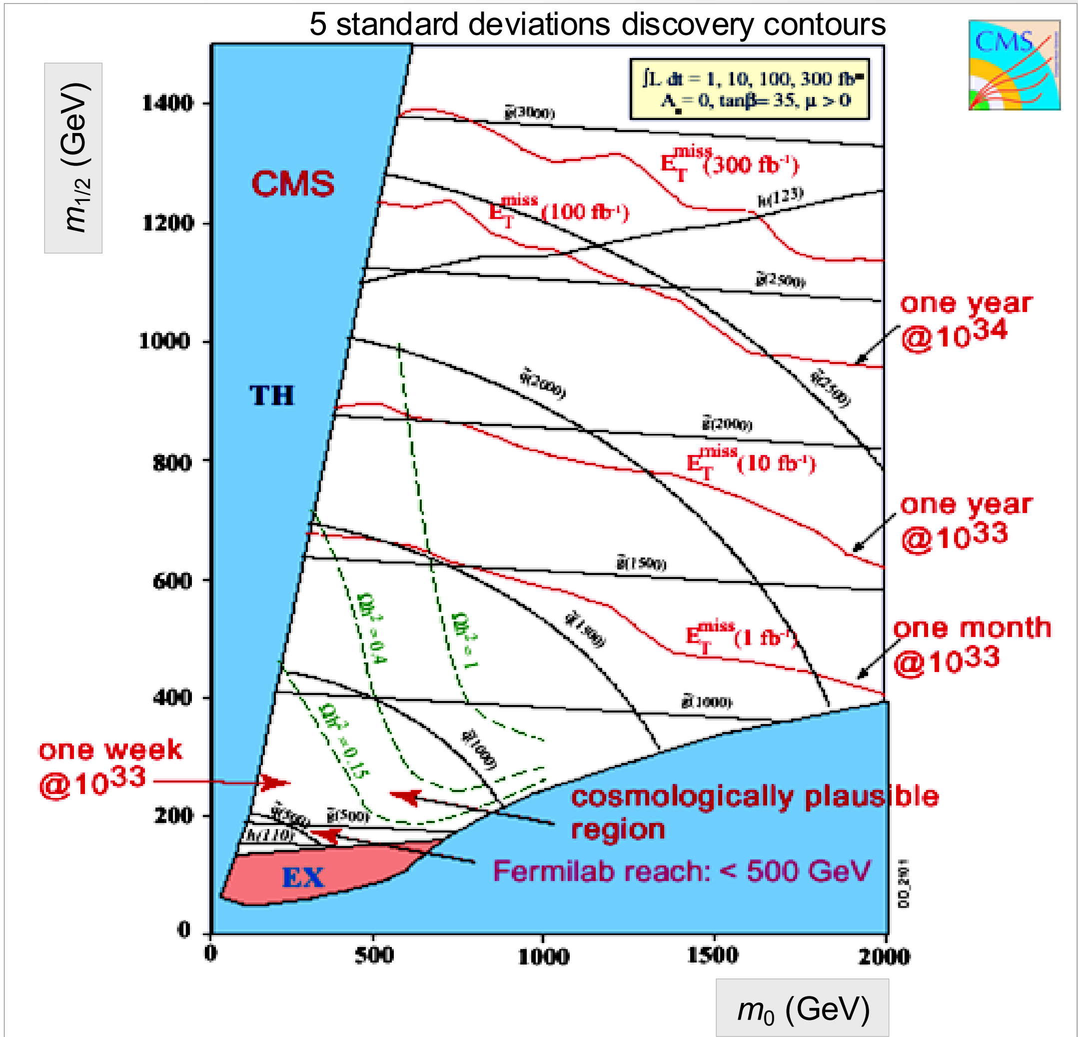
- Requiring at least one lepton reduces QCD background by factor of 20–30, with signal loss of only factor of ~3 → better signal-to-background ratio than fully inclusive analysis

Squarks and Gluinos: Reach of the LHC

- Current limit on squark and gluino masses from the **TEVATRON** experiments (example: D0)
- Experiments evaluate their SUSY discovery potential using some “standard” mSUGRA setup

5σ discovery reach for SUSY:

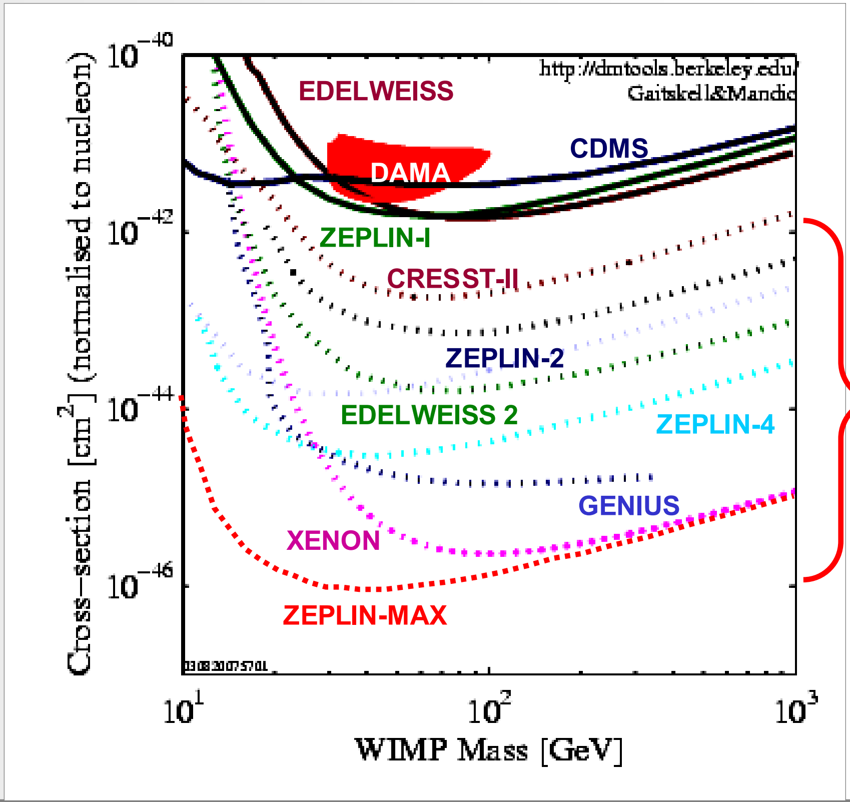
Time period	Luminosity [$cm^{-2}s^{-1}$]	squark/gluino masses
1 month	10^{33}	~1.3 TeV
1 year	10^{33}	~1.8 TeV
1 year	10^{34}	~2.5 TeV
Ultimate	$\int = 300\ fb^{-1}$	~2.5–3 TeV
D0 & CDF	$\int = 0.3\ fb^{-1}$	$>_{(2\sigma)}$ 0.35 TeV

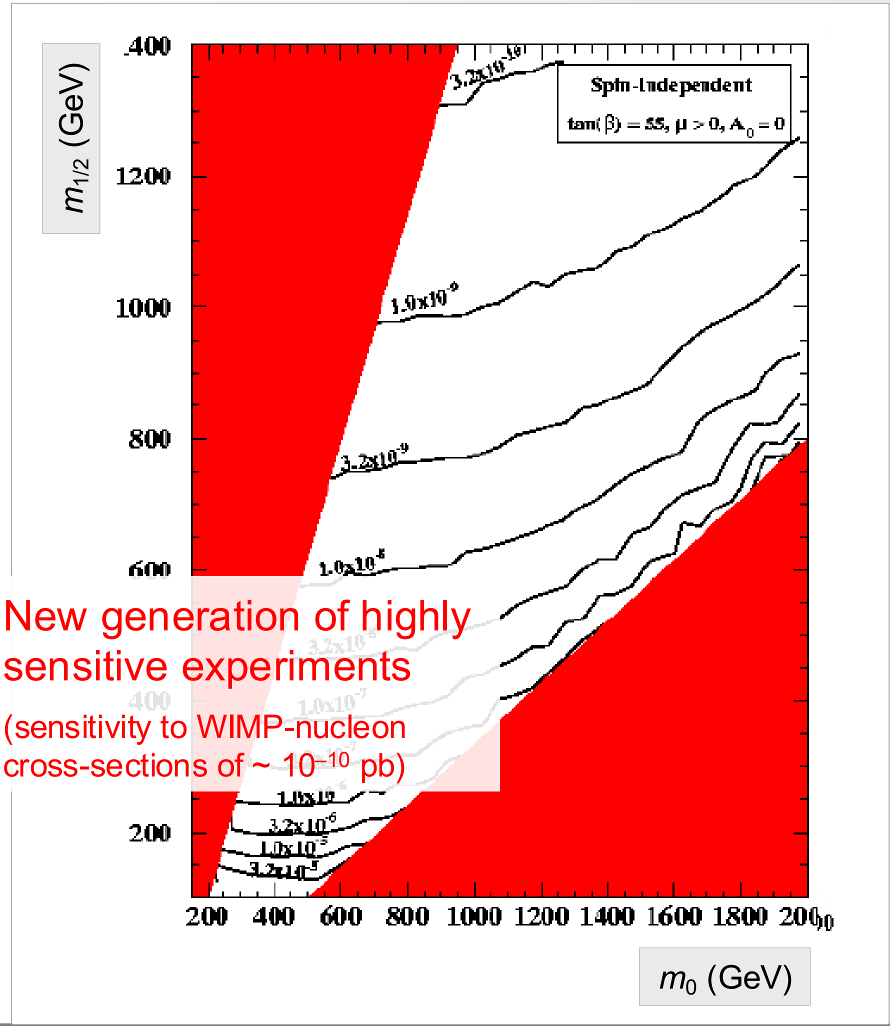


Comparison with Direct Dark Matter Searches

- Not mentioned so far: there exist direct searches for WIMP's through elastic scattering between cosmic WIMP (*e.g.*, a neutralino) and nucleus, generating a recoil of the nucleus

- Complementary sensitivity to mSUGRA masses, in particular for large tanβ values





Once SUSY has been Discovered … Measure it !

- **Inclusive SUSY discovery** will provide indications about underlying scenario:
  - SUSY mass scale and cross section
  - *R*-parity ($E_{T,miss}$ spectrum), Gauge-mediated SB (hard γ's, NLSP's, long-lived charged sleptons), large tanβ (τ's)

- However, fundamental SUSY parameters (**masses**, **couplings**, **spins**, …) can only be inferred from direct measurements of **sparticle properties**

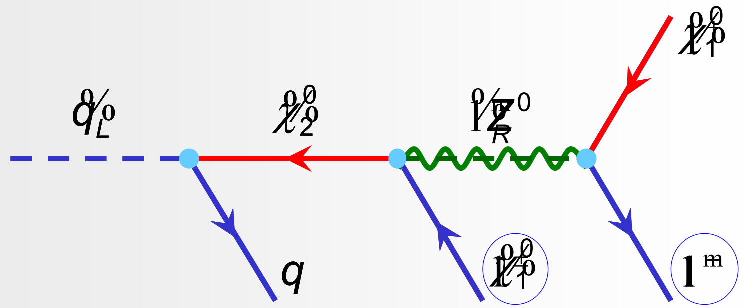
- **Exclusive reconstruction** of SUSY final states is possible:
  - Select final state signatures that identify exclusive decay chains
  - Apply kinematic constraints to eliminate escaped particles (*e.g.*, LSP)
  - Fit, *e.g.*, masses of particles in decay chain

- Remarks:
  - *R*-parity conservation: at least two LSP's in event → no direct mass peaks, but kinematic "endpoints"
  - These endpoints depend on the masses of the involved particles
  - When cascade of at least 3 consecutive two-body decays occurred → full kinematics reconstructable

Exclusive Reconstruction: An Example

- Let's look again at the process: $pp \to X + \tilde{g} + \tilde{g}\left(\to q + \tilde{q}_L\left(\to q + \tilde{\chi}^0_2\left(\to \ell^\pm + \tilde{\ell}_R\left(\to \ell^\mp + \tilde{\chi}^0_1\big|_{LSP}\right)\right)\right)\right)$

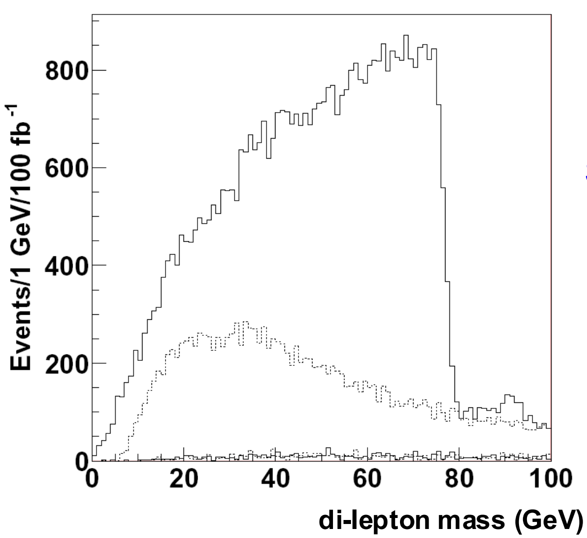
3 two-body decays ! $(m_{\tilde{\ell}_R} < m_{\tilde{\chi}^0_2})$



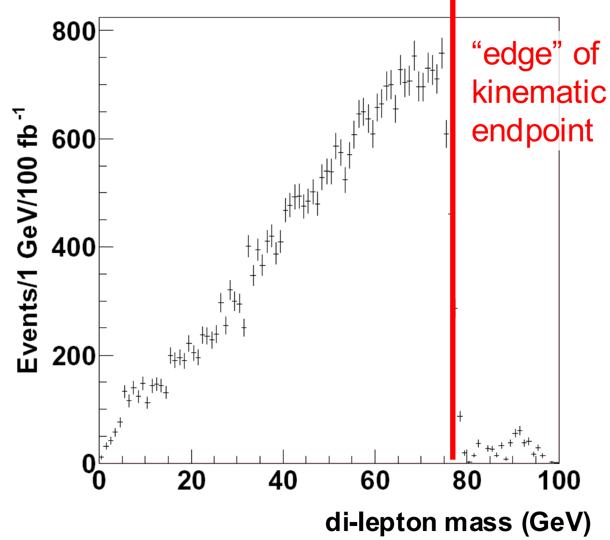
leptons have same flavour !
(use for background fighting)

Di-lepton kinematic endpoint:

$$m_{\ell\ell}^{\max} = \frac{1}{m_{\tilde{\ell}_R}}\sqrt{\left(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{\ell}_R}\right)\left(m^2_{\tilde{\ell}_R} - m^2_{\tilde{\chi}^0_1}\right)}$$



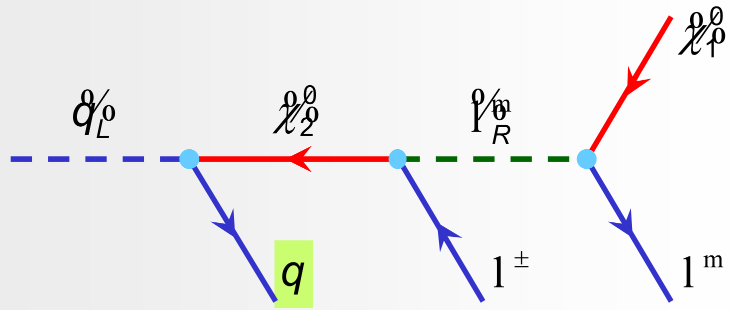
Subtracting $\ell \neq \ell'$ background



… Also Reconstructing the Jet

- We can also use jets from: $pp \to X + \tilde{g} + \tilde{g}\left(\to q + \tilde{q}_L\left(\to q + \tilde{\chi}_2^0\left(\to \ell^\pm + \tilde{\ell}_R^\mp\left(\to \ell^\mp + \tilde{\chi}_1^0\big|_{LSP}\right)\right)\right)\right)$

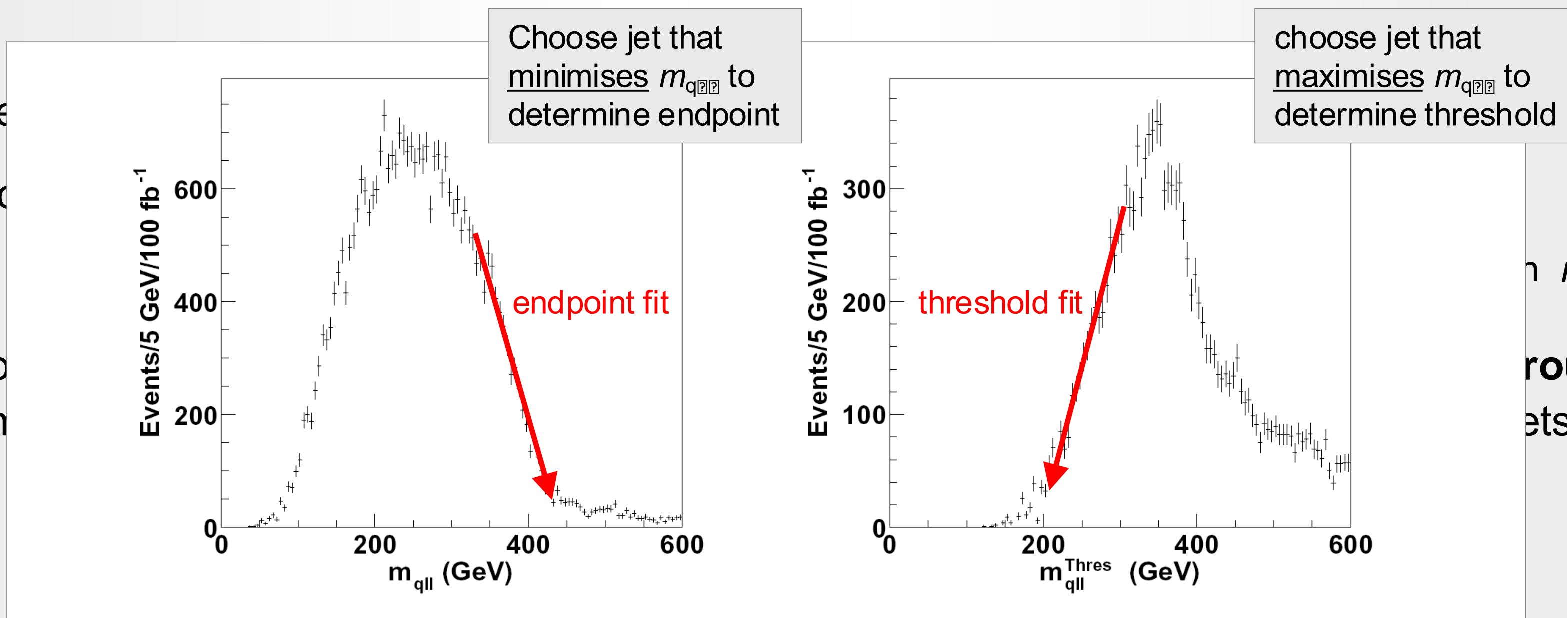
3 two-body decays ! $(m_{\tilde{\ell}_R} < m_{\tilde{\chi}_2^0})$



Theoretical kinematic endpoint of the $q\ell^+\ell^-$ system:

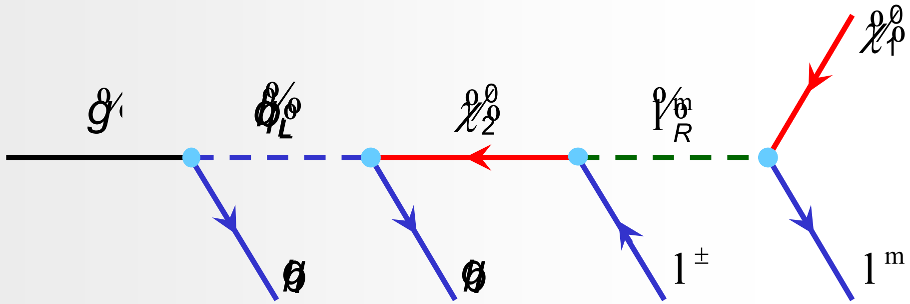
$$m_{q\ell\ell}^{max} = \frac{1}{m_{\tilde{\chi}_2^0}}\sqrt{\left(m^2_{\tilde{q}_L} - m^2_{\tilde{\chi}_2^0}\right)\left(m^2_{\tilde{\chi}_2^0} - m^2_{\tilde{\chi}_1^0}\right)}$$

- One
- In t
  - n $m_{\tilde{q}_L}$
- Tho … rounds
  fron … ets



… Reconstructing sbottom and gluino Masses

- Let's look again at the full decay chain:



To reject combinatorial background, use only b jets

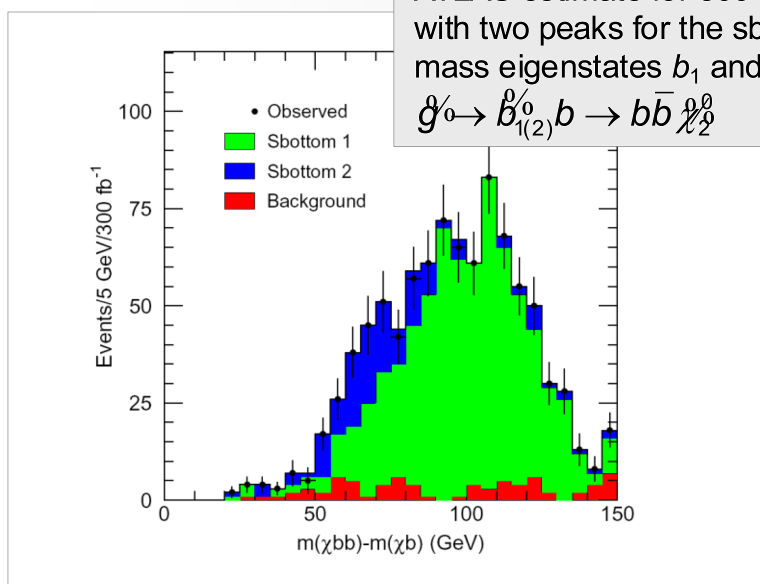
Close to the $\ell^+\ell^-$ endpoint, the χ_2 (~in rest) has residual momentum:

$$\vec{p}\left(\tilde{\chi}_2^0\right) \approx \left(1+\frac{m_{\tilde{\chi}_1^0}}{m_{ll}}\right)\cdot \vec{p}\left(l^+l^-\right)$$

The neutralino masses are known from the preceding analysis
→ **χ_2 4-vector is known**

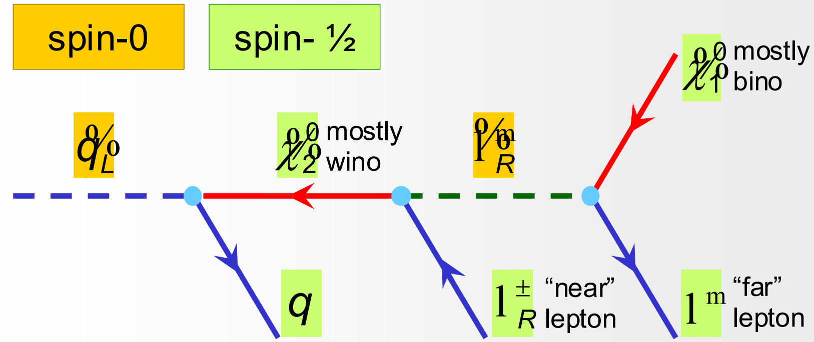
- The gluino and sbottom masses are then obtained from the $bb\chi_2$ and $b\chi_2$ invariant masses
- The sbottom mass is then best obtained from mass difference (reduces errors)
- One can do better by using all events (not only those at the $\ell^+\ell^-$ endpoint) together with a global fit using the full decay kinematics

ATLAS estimate for 300 fb^{-1}, with two peaks for the sbottom mass eigenstates b_1 and b_2
$\tilde{g} \to \tilde{b}^0_{1(2)} b \to b\bar{b}\,\tilde{\chi}_2^0$



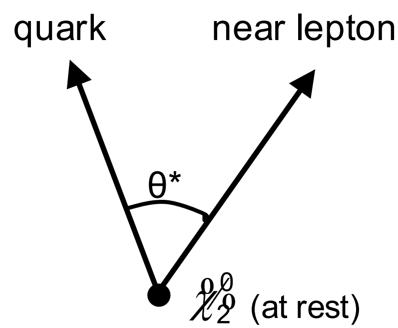
If we Discovered Something… was it SUSY ?

- If observed, the signatures discussed so far provide **strong hints for SUSY**
- To verify that the new fields are indeed the SM Superpartners → **measure their spins**
- Not easy at LHC, but possible



Decay chain sensitive to fermionic character of χ_2

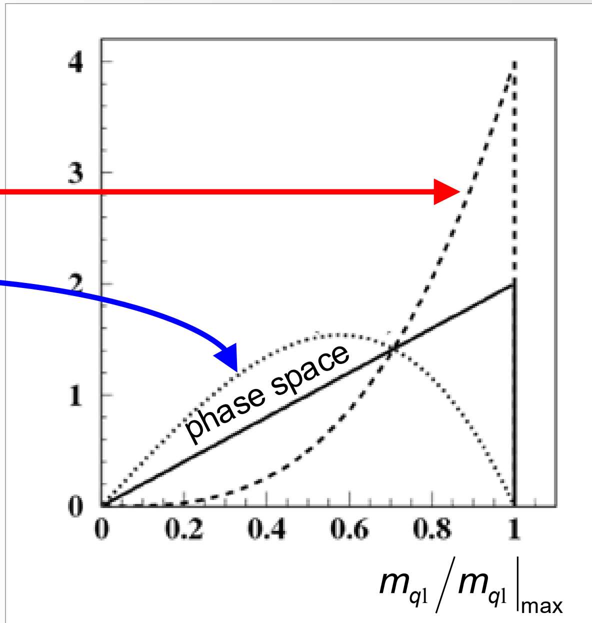
- Invariant mass of quark-lepton system depends on the polarization of neutralino



Invariant mass of $q\ell$ system strongly charge-dependent

$$m^2_{ql^+} = m^2_{ql^+}\Big|_{\max} \cdot \sin^2\left(\theta^*/2\right)$$

$$m^2_{ql^-} = m^2_{ql^-}\Big|_{\max} \cdot \cos^2\left(\theta^*/2\right)$$



- Problem: this effect is <u>inverted</u> for anti-squark decay !

Measuring the χ_2 Spin

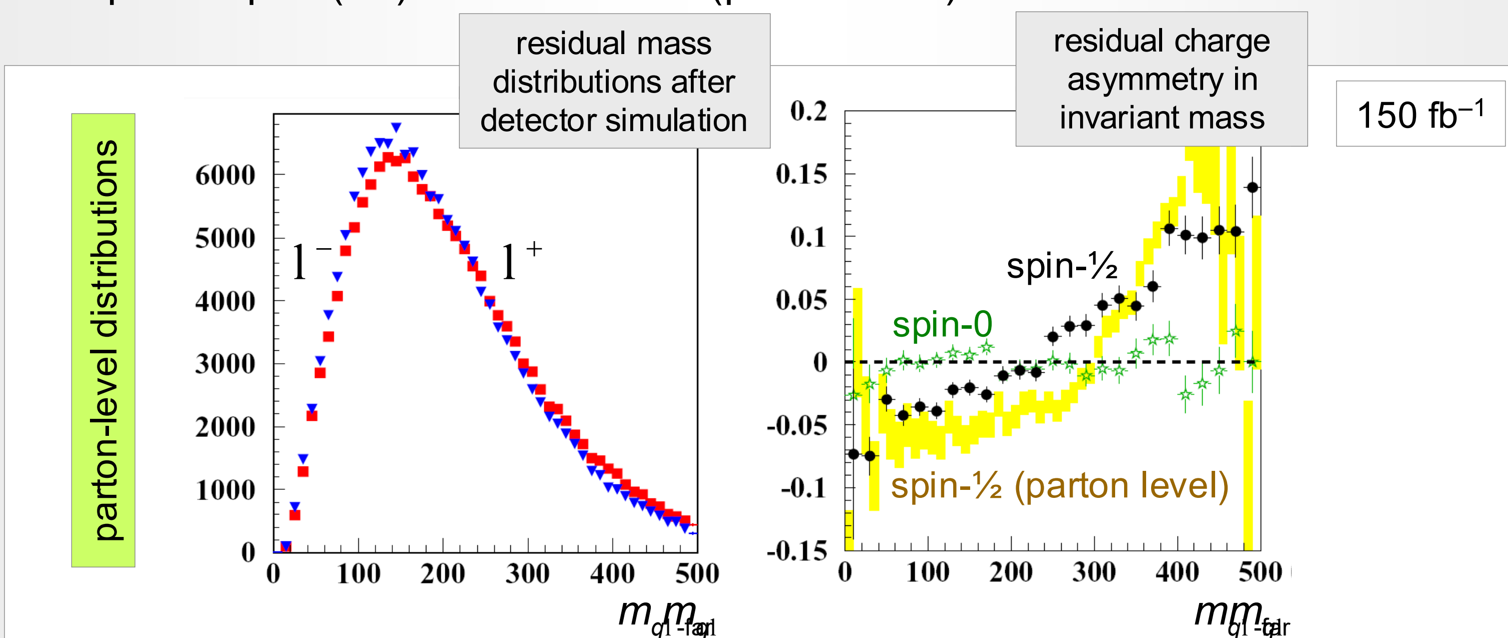
- Experimental Problems:

1) Cannot distinguish "near" from "far" lepton → Plot $m_{q\ell}$ for both leptons
2) Cannot distinguish quark from anti-quark jet → Fortunately: LHC produces ~2x more squarks than anti-squarks

- Measure the asymmetry $A(\sin(\theta^*/2)) = \frac{dN/dm_{q\ell^+} - dN/dm_{q\ell^-}}{dN/dm_{q\ell^+} + dN/dm_{q\ell^-}} = \begin{cases} A^{q\bar{q}}(2\sin(\theta^*/2)-1), & \text{if } |s_{\tilde{\chi}_2^0}| = 1/2 \\ 0, & \text{if } |s_{\tilde{\chi}_2^0}| = 0 \end{cases}$

To 1): Some residual asymmetry left from boost of slepton in the χ_2 rest frame

→ see quark-lepton(far) invariant mass (parton-level):



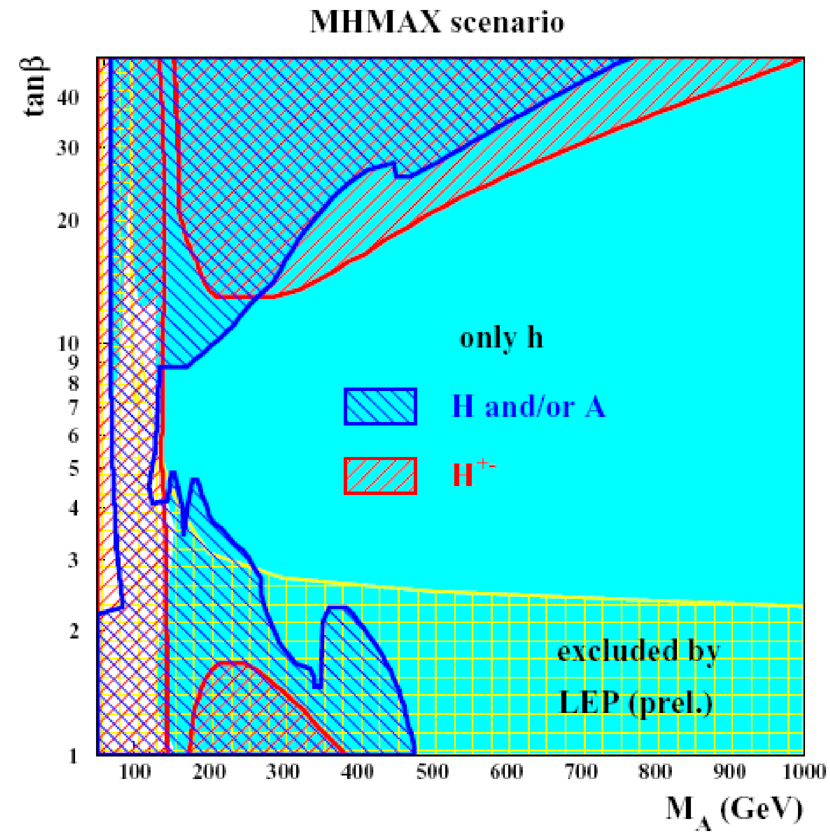
SUSY Higgs Discovery Potential

- Search strategies for lightest SUSY and SM Higgs are similar
- The neutral and charged bosons of the two Higgs doublets are produced via:
- Since the Higgs couples to masses, interactions with heavy particles (top, τ) are preferred

h, H, A: gluon-gluon-, vector-boson-fusion, $q\bar{q}$ scattering with associated vector boson or heavy quark

$H^{\pm}$: top decay, gluon-bottom fusion, light *qq'* annihilation

5σ contours



300 fb^{-1}

The *h* can be excluded in all parameter scenarios

Extra Dimensions Searches at the LHC

Let's recall the effect of EDs on processes in High Energy Physics:

- EDs influence cross sections of standard accelerator processes (*e.g.*, $e^+e^- \to \gamma\gamma$)
- EDs allow production of gravitons, *e.g.*, $e^+e^- \to \gamma G$, ZG, and excited KK graviton states

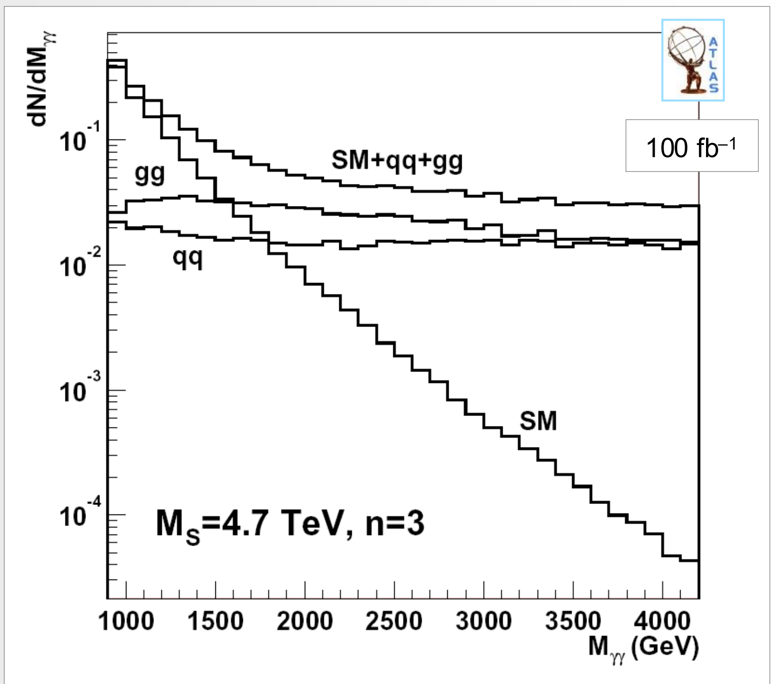
Large Extra Dimensions

- The most direct manifestation of EDs would be the presence of **KK gravitons: G_{KK}**
- Tiny graviton coupling: $\sim 1/M_{Pl}$ compensated by large G_{KK} multiplicity: $\sim (R\sqrt{s})^d$ (in E interval $\sqrt{s}$)
- ➡ (partonic) **cross section**: $\sigma \sim (\sqrt{s} / M_D^2)^d$ **can be macroscopic**

- The produced **gravitons do not interact in detector**
- Signature: **mono-jet or energetic photon + $E_{T,\text{miss}}$, no lepton**

Typical processes are:

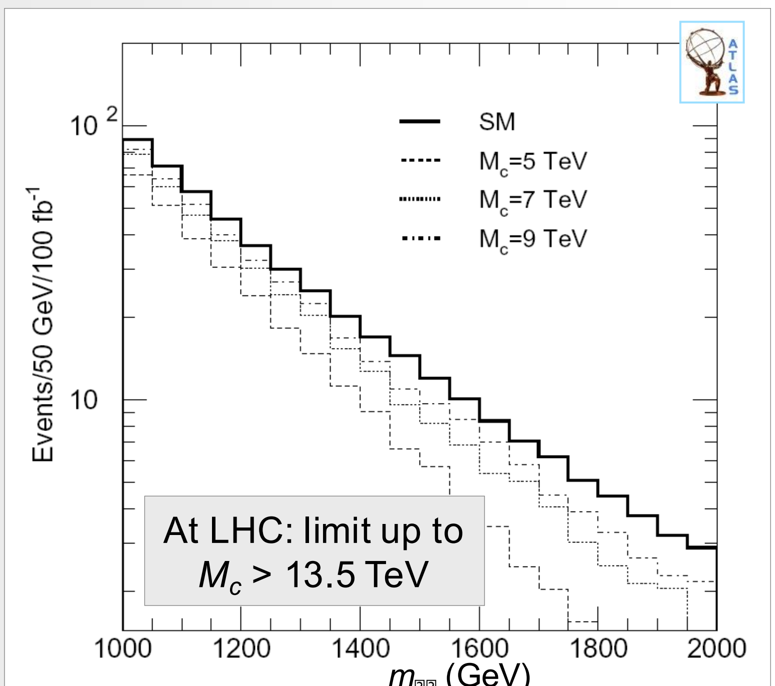
$$q\bar{q} \to (g,\gamma) + G_{KK}$$
$$qg \to q + G_{KK}$$
$$gg \to g + G_{KK}$$



- Graviton contributions to signal for Drell-Yan cross section, and $pp \to \ell^+\ell^-, \gamma\gamma$, leading to large (model-dependent) $\ell^+\ell^-$, $\gamma\gamma$ invariant mass tails
- ➡ For example: $M_D \sim 9$ (6) TeV and $d = 2$ (4) EDs yields compactification radius of $10^{-6}\mu$m;
- Figure shows $m(\gamma\gamma)$ for d=3 and divergency cut-off M_s=4.7 TeV
- ➡ No sensitivity to larger scales or EDs at LHC
- ➡ In case of a discovery, it will be difficult to extract both M_D and d

Small Extra Dimensions

- In the previous example, the SM particles were confined within the SM brane; if they freely propagated into the bulk, KK excitations of γ or Z should be observed, if EDs are large
- One could only confine the fermions, while letting the gauge bosons propagate into the bulk
- The characteristic size of the compact dimensions is then $R \sim 1/M_c \sim 1\ \text{TeV}^{-1}$
- Considering only 1 ED, the EW precision measurements give a lower limit $M_c > 4$ TeV
- The masses of the KK excitations of the gauge bosons are given by: $m_{Vn}^2 = m_V^2 + (n \cdot M_c)^2$

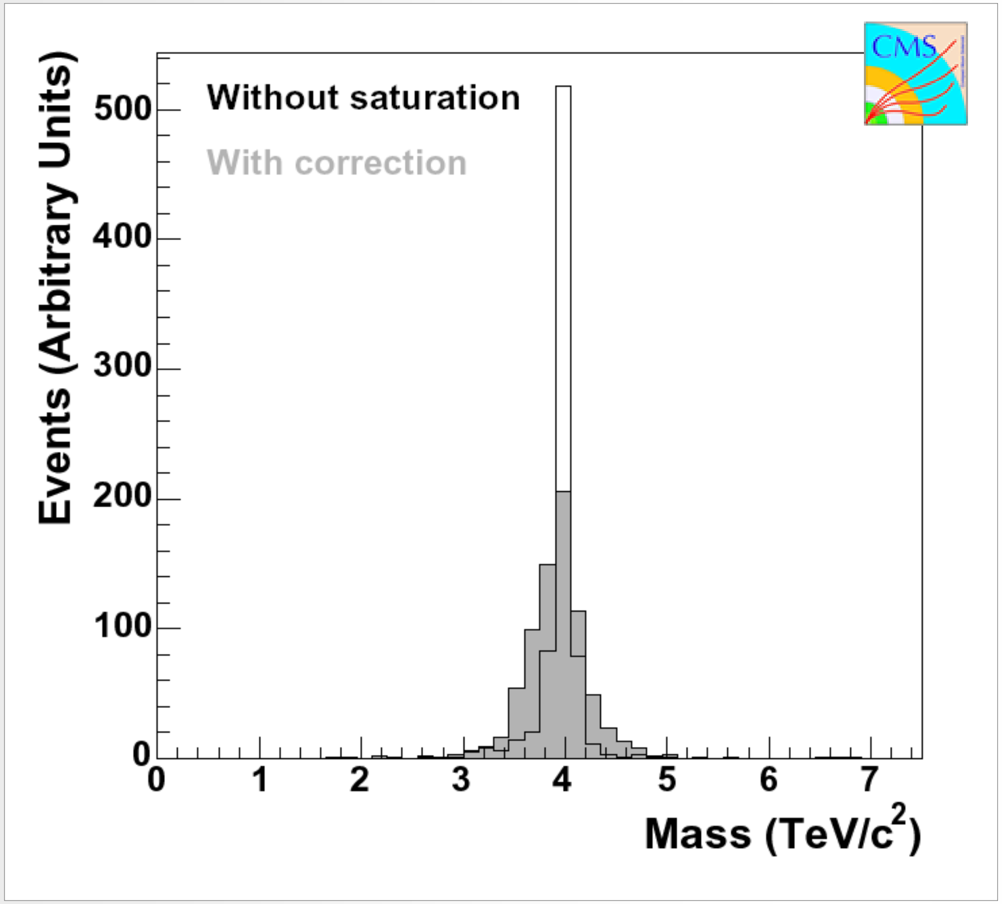


- The peak corresponds to the first KK excitation of Z: Z^1 (Z^1 and γ^1 are ~ degenerated)
- For ATLAS: the excellent resolution of the calorimeter at high p_T, allows to measure the width of the excitation in the mode e^+e^-
- Not as good for the muons

➧ Larger masses than 4 TeV are accessible through interference of the SM di-lepton amplitude with the KK excitations

Warped Extra Dimensions

- At very high p_T, di-electrons have better intrinsic mass resolution than di-muons
- However: the EM calorimeters suffers from saturation of dynamic range (CMS > ATLAS)



- Example for Graviton KK excitation ("tower") G^1 decaying into e^+e^- in Randall-Sundrum Model
- The width of the resonance is small compared to the experimental resolution

Little Higgs Searches at the LHC

Little Higgs

- The breaking of a new SU(5) symmetry leads to new *O*(TeV) particles, among which are **a new quark top (*T*)**, new **gauge fields $W^{\pm}_H$, Z_H, A_H**, and **5 new Higgs bosons**

- Example:
  T signature at the LHC:

T production at LHC:

$$gg, q\bar{q} \rightarrow T\bar{T}$$

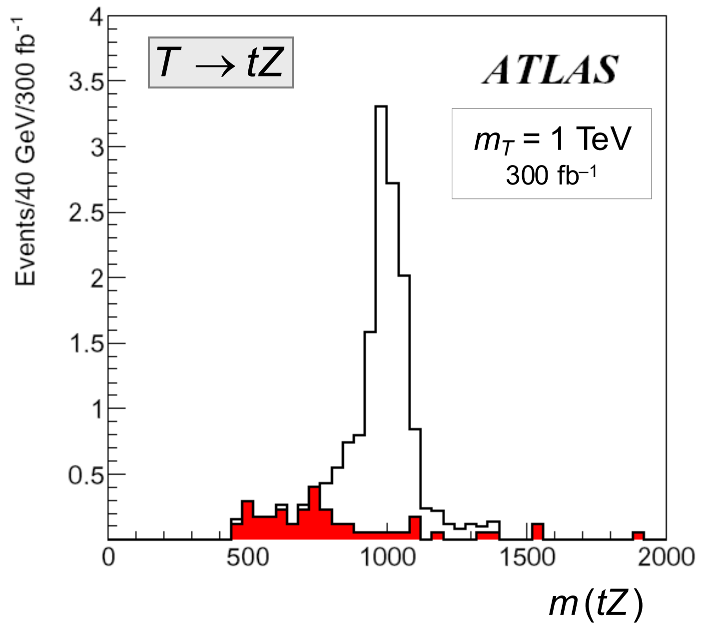
$$qb \rightarrow q'T$$

dominant if $m(T) > 0.7$ TeV

Dominant *T* decays:

$$T \rightarrow tZ, bW$$

$$T \rightarrow tH$$



Little Higgs

- Breaking a new SU(5) symmetry leads to new *O*(TeV) particles, among which are **a new quark top (*T*)**, new **gauge fields $W^{\pm}_H$, Z_H, A_H**, and **5 new Higgs bosons**

- Example:
  new Higgs boson: ϕ^{++}

ϕ^{++} production at LHC:

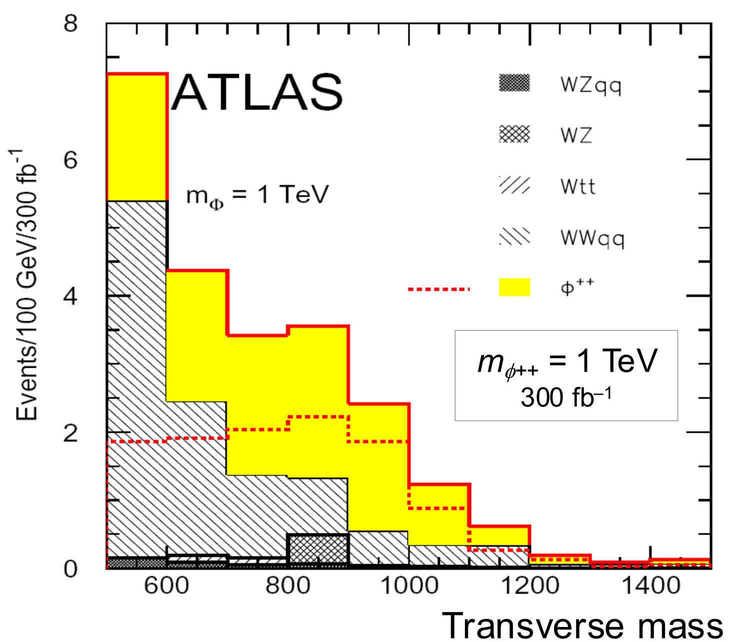
$$q\bar{q} \to \phi^{++}\phi^{--} \to 4l$$

too small cross section for discovery

Vector-boson fusion:

$$uu \to dd\phi^{++} \to ddW^{+}W^{+}$$

signature is 2 leptons with same charge



Conclusions

Conclusions

Most new-physics signatures are ambiguous

Only the combination of observations and precision measurements can guide us to the fundamental theory

Curved extra dimensions:

- Radions

If the Planck scale becomes a … sions, the E_{CM} (LHC) = 14 TeV, will have access to "trans-Pla…

- Could give rise to micro black … O(TeV)
- Fast evaporation would lead … articles in detector

Many more … (Technicolor, C… ersymmetry, Leptoquarks, …)

Appendix: Three Scales ore Finetuning ?

- Let's not forget that we **did not see any obvious new physics effects** in precision physics (we may have missed it of course…)
- Large effects from new physics can be avoided if new strong interactions occur at > ~10 TeV
- We would then need an intermediate weakly interacting new physics model to lead us from the light Higgs to this scale

Three-scale Model structure

Scale Λ

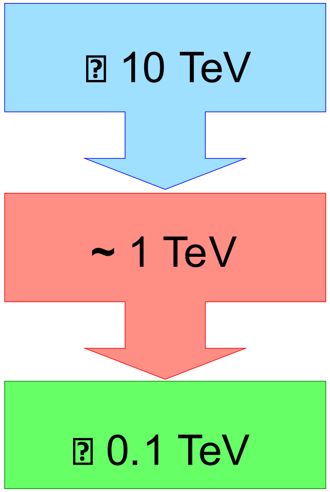
- Strong interactions, dynamical symmetry breaking

Scale *F*

- New weakly interacting particles

Scale *v*

- SM: Higgs, Gauge bosons, fermions



Note that the labels "strong" and "weak" do not refer to the corresponding SM interactions

Three Scales ore Finetuning ?

- Models of SUSY breaking:
  - SUSY partners at scale *F*, dynamical SUSY breaking at scale Λ
  - Λ □ *F* can be achieved (all-order cancellations of the Higgs radiative corrections)
  - Renormalization group running of the masses mixes *F* and *v*
  - *v* □ *F* (no SUSY observed so far) requires some finetuning of the MSSM via flavour-blind SSB model

- Models with TeV-scale extra dimensions:
  - KK excitations at scale *F*, compactification scale $1/\Lambda$
  - *v* □ *F* is no problem, but Λ is not too far away
  - Presence of infinitely many KK excitations limits validity of calculations

- Little Higgs models:
  - New particles realise new global symmetry at scale *F*, dynamical symmetry breaking at scale Λ
  - *v* □ *F* is possible, but Λ is not far away (Higgs rad. corr. cancellation only at leading order)
  - Presence of Λ limits accuracy of calculations