SUSY Models

Standard Model (SM) – 18 (+xν) free parameters

Minimal Super Symmetry Model (MSSM) – 105 (+45) additional free parameters

First important choice: mechanism of symmetry breaking

Assume "hidden sector" – neutral w.r.t. SM gauge groups

SUSY breaking occurs in the hidden sector;

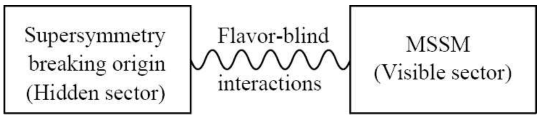
It is transmitted to visible MSSM particles by some "messenger particles"

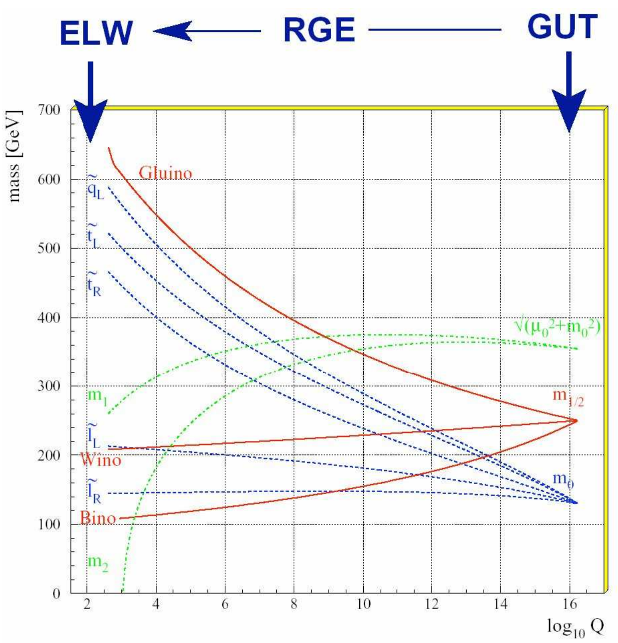
- Gravity Mediated Supersymmetry Breaking (mSUGRA)
- Gauge Mediated Supersymmetry Breaking (GMSB)
- Anomaly Mediated Supersymmetry Breaking (AMSB), . . .

For phenomenology: make some "reasonable assumptions" and use ~5–6 parameters only.

mSUGRA

SUSY is broken by gravity





Assume universal masses at GUT scale:

m_0 – common mass of scalars (squarks, sleptons, Higgs bosons)

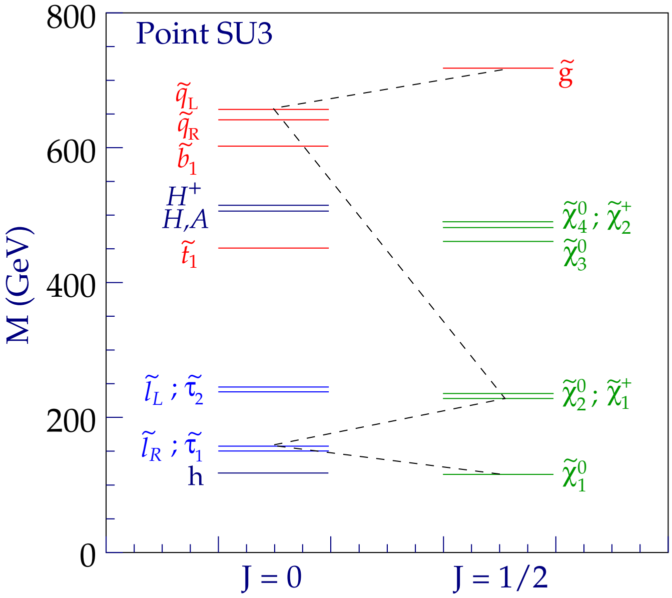
$m_{1/2}$ – common mass of gauginos and higgsinos

A_0 – common trilinear coupling

$\tan\beta$ – ratio of Higgs vacuum expectation values

$\mathrm{sign}\,\mu = \pm 1$ – sign of μ SUSY conserving Higgsino mass parameter

Typical mSUGRA Spectrum



R-Parity

MSSM allows a rapid proton decay: $p \to e^+ \pi^0$
Current experimental limit: $\tau_p > 1.6 \cdot 10^{33}$ years.

Solution: conservation of R-Parity (Matter Parity):

$$R = (-1)^{2S+3B+L}$$

S – spin, B – baryon number, L – lepton number

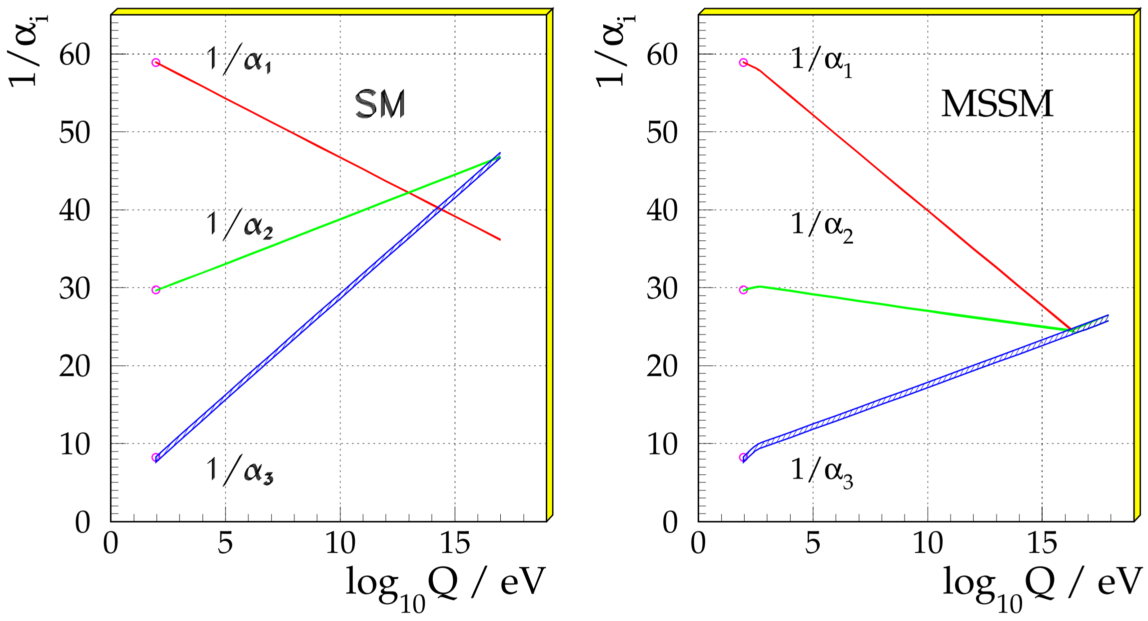
For all SM particles: $R = 1$ For all superpartners: $R = -1$

Consequences:

- Eliminates 45 free parameters (105 remain)
- Baryon and lepton numbers are very well conserved
- Superpartners are always produced in pairs
- The lightest supersymmetric partner (LSP) is stable

LSPs can be dark matter! Should be neutral and not strongly interacting
$\Longrightarrow$ Neutralino

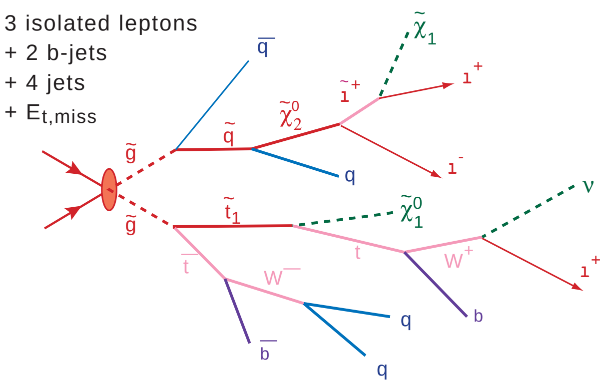
Grand Unification Theory (GUT)



- SUSY can help gauge coupling unification!

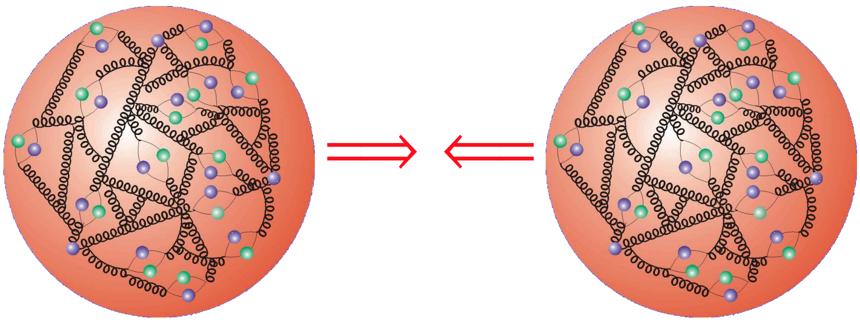
SUSY Production at LHC

- In most cases new particles are short-lived.
  We don't "see" them directly in detector
  but reconstruct from hadron jets, leptons, photons
- Everything is produced at once in long decay chains.
  Dominant backgrounds are combinatorial from SUSY itself.
  $\Longrightarrow$ Cannot study the production of one sparticle in isolation.
  $\Longrightarrow$ Must use a consistent model for simulation.



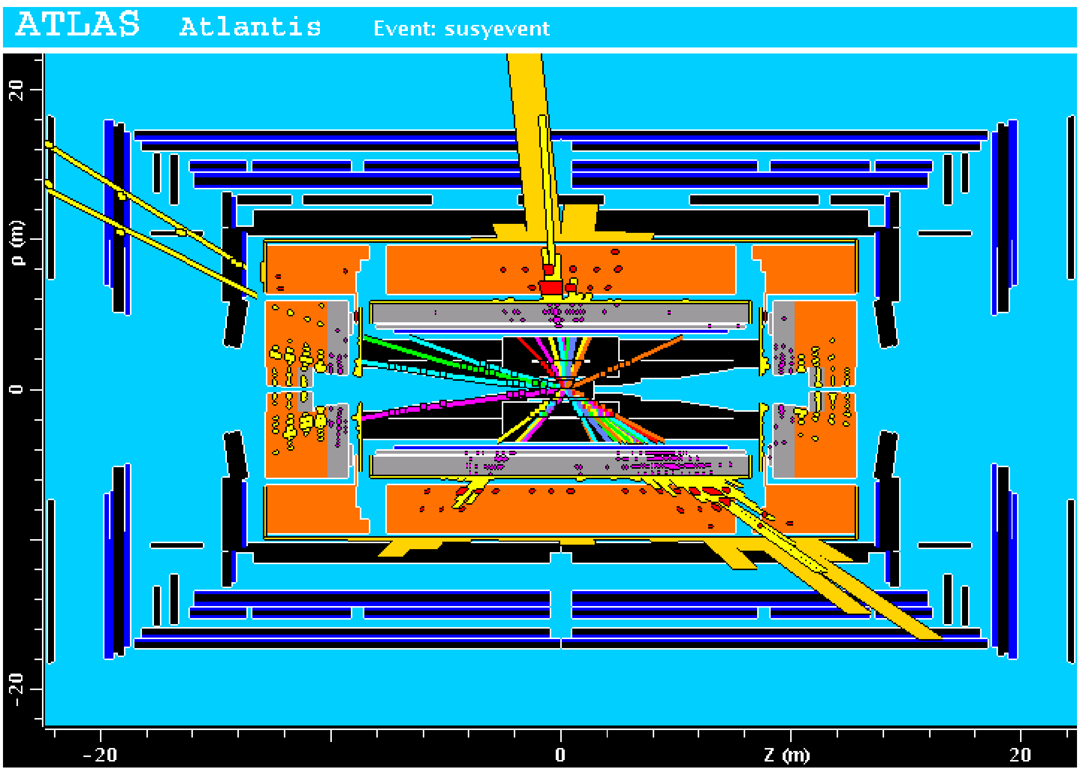
Missing E_T

- 2 LSPs at the end of decay chains $\Longrightarrow$ missing energy
- Parton-parton interactions: $p_1 = x_1 P,\ p_2 = x_2 P$
  $\Longrightarrow$ centre-of-mass is always boosted
  No information from longitudinal momentum component



- Missing transverse momentum is the signature
- Masses are neglected $\Longrightarrow$ missing "transverse energy" E_T

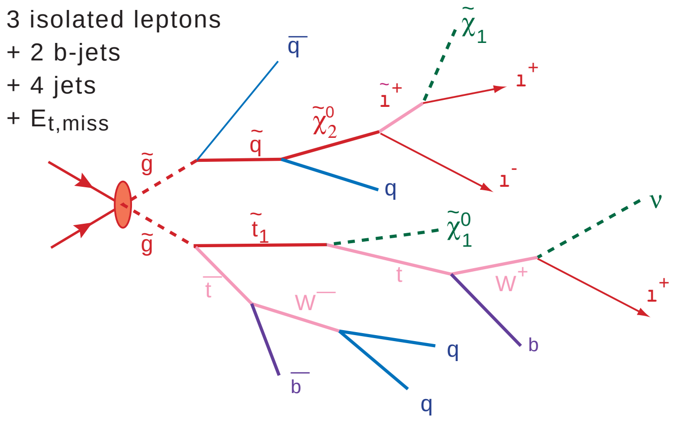
Simulation: SUSY Event in ATLAS



SUSY Signatures at the LHC

Decay cascades down to LSPs. Features:

- Large Missing E_T
- High E_T jets
- Many b quarks
- Many isolated leptons

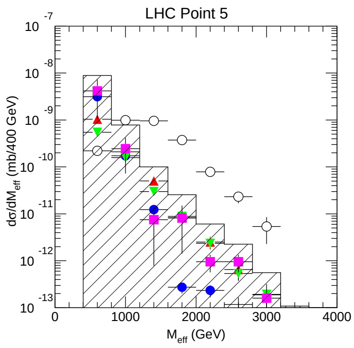


Discovery is "easy" in inclusive measurements

Discovery Potential – Example mSUGRA

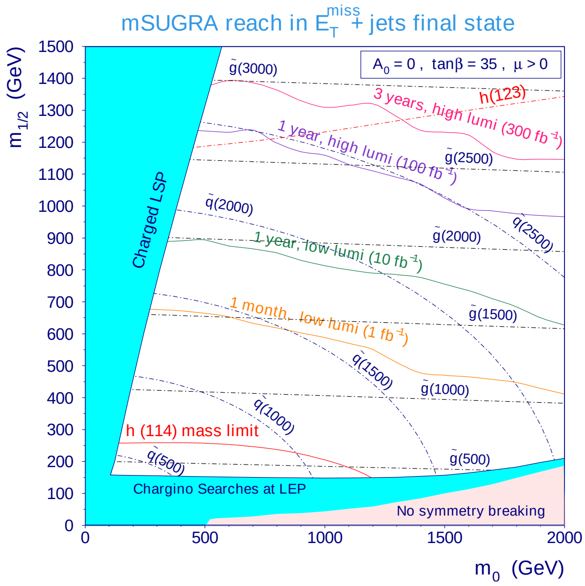
- Select ≥ 4 jets and $E_{T,\text{miss}}$
- Reconstruct effective mass

$$M_{\text{eff}} = \sum_{i=1}^{4} |P_{T,i}| + |E_{T,\text{miss}}|$$



At high M_{eff} SUSY rises above SM

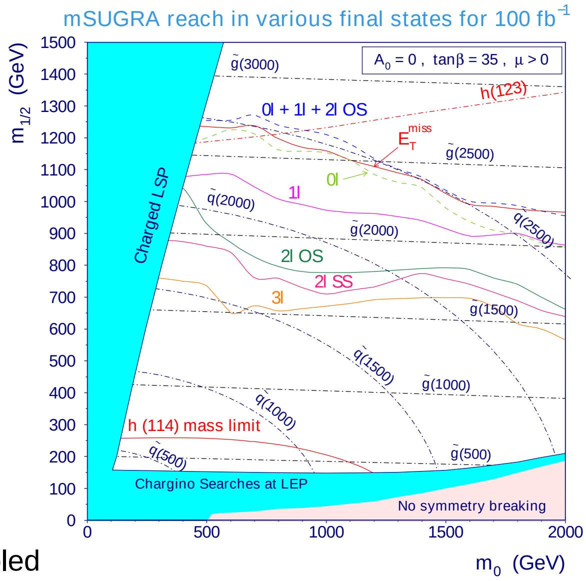
- Inclusive signatures provide evidence up to 2.5 TeV for squarks and gluinos



- Energy of LHC is most crucial.
  Reach increases slowly with luminosity.

Discovery Potential – Adding Leptons

- Monte Carlo may underestimate SM backgrounds from multi-jet final states (Problems: NLO ME+PS . . .)
- Select ≥ 2 jets + $E_{T,\text{miss}}$ + $0l$ (l veto), $1l$, $2l$ opposite sign, $2l$ same sign, 3l
- Cumulative reach can be even better than inclusive



Accessible SUSY mass range:

Collider	Weakly coupled	Strongly coupled
LEP	100 GeV	100 GeV
Tevatron	100 GeV	300 GeV
LHC	500 GeV	2500 GeV

SUSY Particle Mass Reconstruction

Using edges, thresholds and endpoints in invariant mass distributions

Example GMSB: LSP is gravitino $\tilde{G}$ with $m_{\tilde{G}} \sim \text{eV} - \text{keV}$.
Different GMSB models depending on Next-to-Lightest Supersymmetric Particle (NLSP)
Consider here NLSP to be short-lived neutralino $\tilde{\chi}_1^0$

$$\left.\begin{array}{l}\tilde{\chi}_2^0 \to \tilde{l}^\pm\, l^\mp \\ \quad\hookrightarrow \tilde{\chi}_1^0\, l^\pm \\ \qquad\hookrightarrow \tilde{G}\,\gamma\end{array}\right\}$$

chain of three 2-body decays

$m_{\tilde{\chi}_2^0}$, $m_{\tilde{\chi}_1^0}$, $m_{\tilde{l}}$ unknown, $m_{\tilde{G}}$ neglected

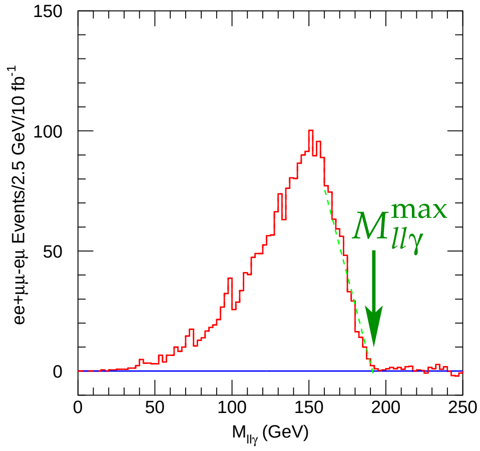
2 $\tilde{\chi}_1^0$ in event. Selection:

- 2 hard isolated photons **make SM background negligible**
- At least 2 leptons
- Missing E_T from gravitinos and possibly neutrinos
- Large M_{eff} (possibly jets . . .)

SUSY Particle Mass Reconstruction

Using edges, thresholds and endpoints in invariant mass distributions

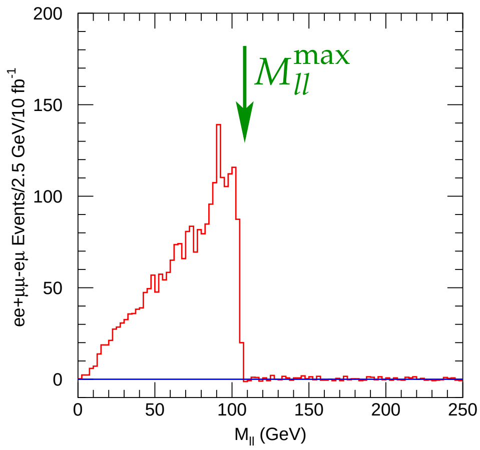
- Plot $e^+e^- + \mu^+\mu^- - e^\pm\mu^\mp$ to subtract SUSY and small SM background
- Select γ with the smaller $M_{ll\gamma}$

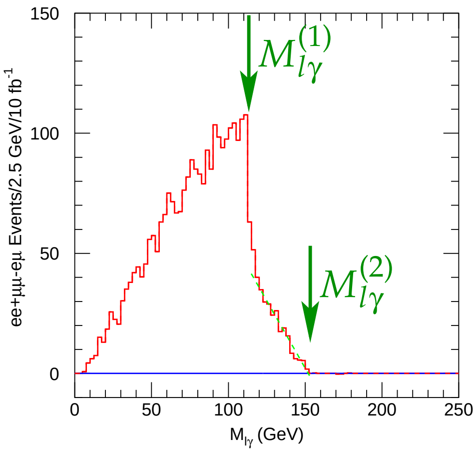


$$M_{ll\gamma}^{max} = \sqrt{m_{\tilde{\chi}_2^0}^2 - m_{\tilde{\chi}_1^0}^2}$$ with $0.2 - 0.5\,\text{GeV}$ precision

SUSY Particle Mass Reconstruction

Using edges, thresholds and endpoints in invariant mass distributions





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

$$M_{l\gamma}^{(1)} = \sqrt{m_{\tilde{l}_R}^2 - m_{\tilde{\chi}_1^0}^2}$$ – "adjacent" $l\gamma$ pair

$$M_{l\gamma}^{(2)} = \sqrt{m_{\tilde{\chi}_2^0}^2 - m_{\tilde{l}_R}^2}$$ – "further" $l\gamma$ pair

► $m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_1^0}, m_{\tilde{l}}$ are found from M_{ll}^{max}, $M_{l\gamma}^{(1)}$, $M_{l\gamma}^{(2)}$

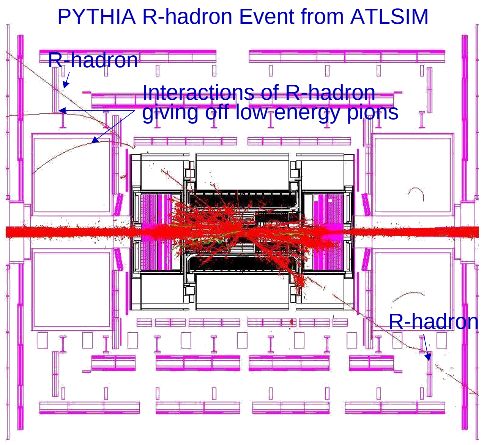
(Quasi-)Stable Coloured Hadrons: R-Hadrons

- LSP is gluino (in Split-SUSY)
- Long-lived squark ($\tilde{t}$ in GMSB or SUSY-5D)

hadronise into heavy ($m_R \gtrsim 100\,\mathrm{GeV}$) bound states: R-hadrons ($\tilde{g}g$, $\tilde{g}q\bar{q}$, $\tilde{g}qqq$, $\tilde{q}\bar{q}$, $\tilde{q}qq$)

Heavy almost non-interacting core surrounded by cloud of light quarks

- "Cannon ball"
- Low energy particles are produced on the way
- Exchanges charge e.g. $R^+ + n \to R^- + p + \pi^+$



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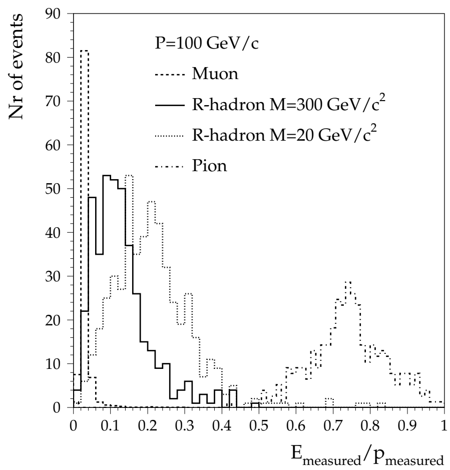
Heavy almost non-interacting core surrounded by cloud of light quarks

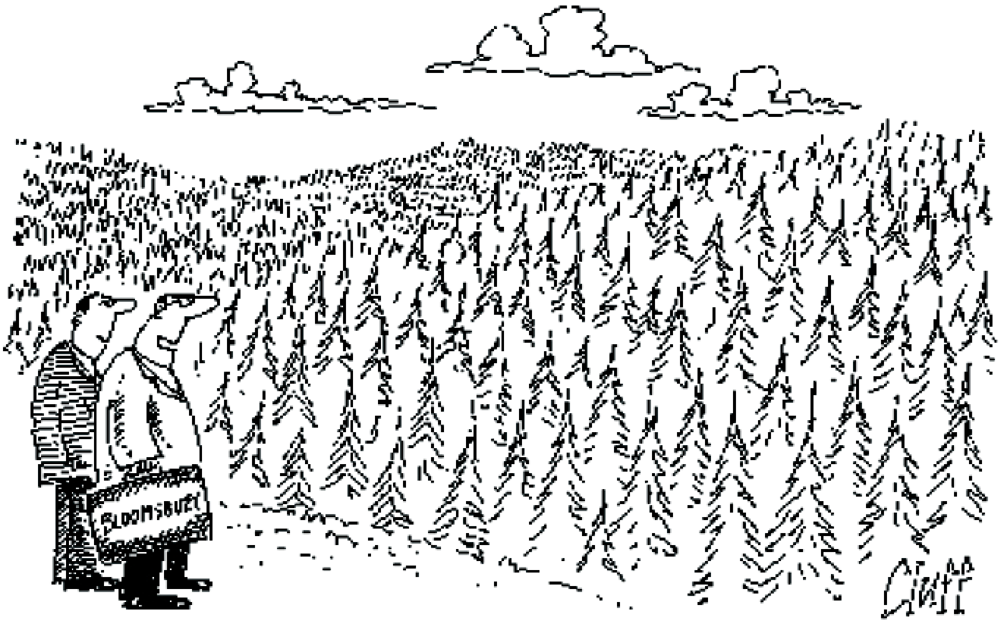
- "Cannon ball"
- Low energy particles are produced on the way
- Exchanges charge e.g. $R^+ + n \to R^- + p + \pi^+$

Signatures

- Large ionisation in tracker (Bethe-Bloch)
- Time-of-Flight in μ systems
- Specific E/p – calo energy / track momentum
- Specific shower shapes
- Charge flips between tracker and μ-system

can be used to find particle type





"One day, all of these will be supersymmetric phenomenology papers."

Arguments for SUSY

- Rich, calculable, self-consistent beyond-the-SM theory
- “Obvious” symmetry extension
- Gauge coupling unification
- Can solve gauge hierarchy problem
- Source of dark matter (R-parity)
- String theory seems to like it

Challenges for Low Energy SUSY

"Throw a dart into Minimal SUSY parameter space,
And what do you get?

Observable predictions would be incompatible with experiment."

- Proton decay (at higher orders also with conserved R-parity)
- Flavor Changing Neutral Currents
- Many new sources for CP Violation
- Full calculation of Higgs mass

$\Longrightarrow$ Suggest high masses for scalars: Several TeV – PeV

- Gauge coupling unification
- Cold dark matter

$\Longrightarrow$ ...-inos are lighter: $\sim 100\,\mathrm{GeV} - 2.5\,\mathrm{TeV}$

"Naturalness" strained?

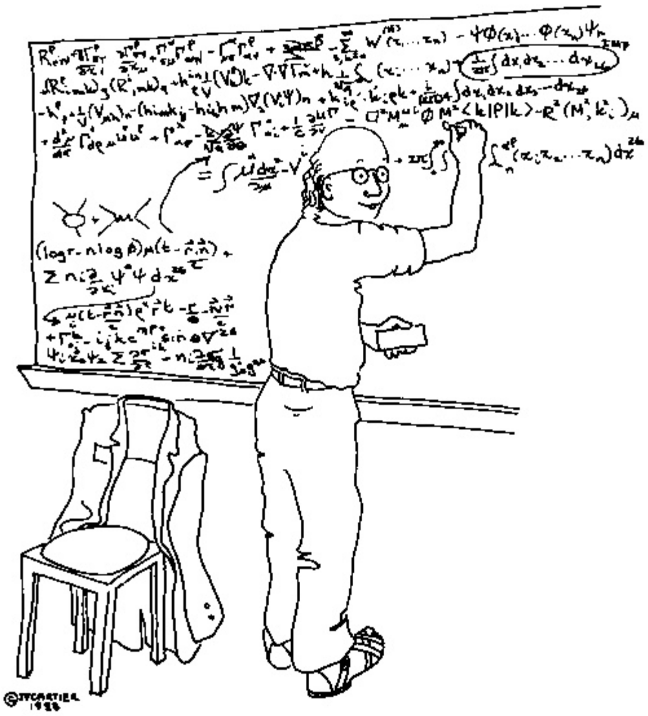
Scenarios for SUSY at the LHC

☟ Pessimistic scenarios:

- SUSY does not exist.
- SUSY can be out of reach (if $M_{\mathrm{LSP}} \gtrsim 2\,\mathrm{TeV}$).
- SUSY can be there but only in very challenging signatures.

☝ Optimistic scenarios:

- SUSY will be found and clearly recognised.
- Something looking like SUSY will be found.
  International Linear e^+e^- Collider (ILC) will give the final answer.

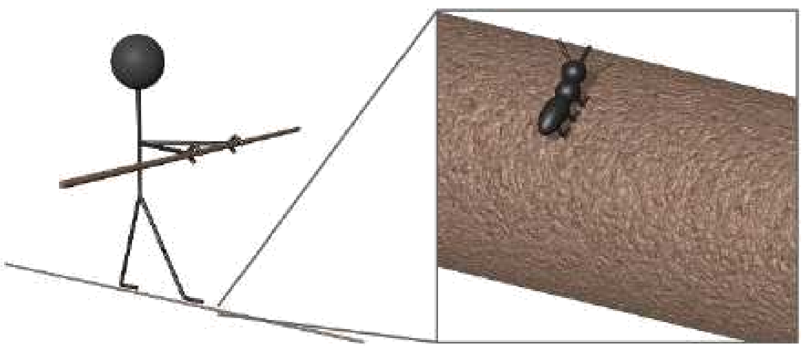


"At this point we notice that this equation is beautifully simplified if we assume that space–time has 92 dimensions."

Compactified Extra Dimensions

Planck scale can be just around the corner $\sim 1\text{TeV}$
$\Rightarrow$ No need to go far away in energy with SM

This can be accomplished by means of Extra Dimensions



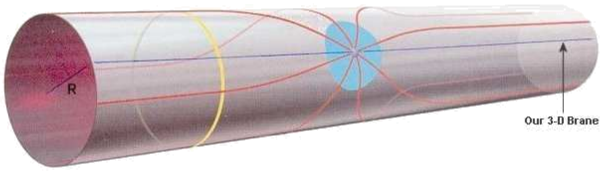
First considered by Nordström (1914), Kaluza (1921) and Klein (1926)
to unify gravity and e.m. force. Later revival in string theory

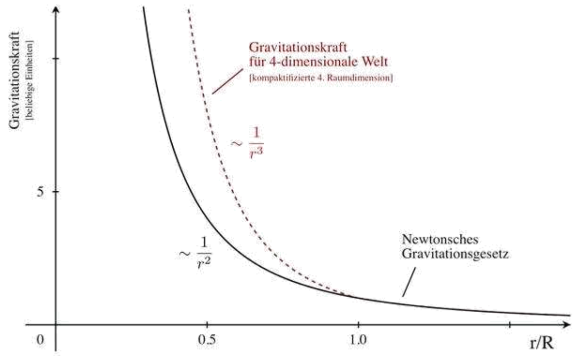
Large Extra Dimensions

ADD approach — Antoniadis, Arkani-Hamed, Dimopoulos, Dvali: hep-ph/9803315, 9804398, 9807344

There are n compactified extra dimensions

Only gravity can propagate in extra dimensions





Using Gauss law

$$F \propto \frac{G}{r^2} \longrightarrow F \propto \frac{G'}{r^{2+n}}$$

For $r \gg R_C$: $F \propto \dfrac{G'}{r^2 R_C^n}$

For a smooth transition

$$G' \sim G R_C^n$$

New Fundamental Planck Scale

"Visible" 4-dim. Planck scale

$$M_{\rm Pl} = \sqrt{\frac{\hbar c}{G}} \quad \Longleftrightarrow \quad G = \frac{\hbar c}{M_{\rm Pl}^2}$$

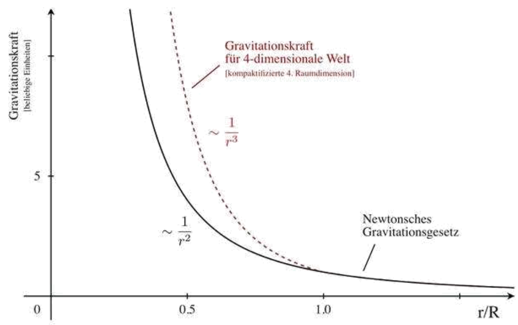
"Real" D-dim. Planck scale ($D = 4 + n$)

where gravity gets strong

$$M_D \propto \sqrt[n+2]{\frac{\hbar c}{G'}} \quad \Longleftrightarrow \quad G' = \frac{\hbar c}{M_D^{2+n}}$$

From that follows

$$G' \sim G R_C^n \quad \Longleftrightarrow \quad M_{\rm Pl}^2 \sim M_D^{n+2} R_C^n$$



Size of extra dimension

$$R_C \sim \frac{1}{M_D} \left(\frac{M_{\rm Pl}}{M_D} \right)^{\frac{2}{n}} \quad \longrightarrow \quad \text{Large } R_C \Longleftrightarrow \text{Small } M_D$$

Possible Sizes of Extra Dimensions

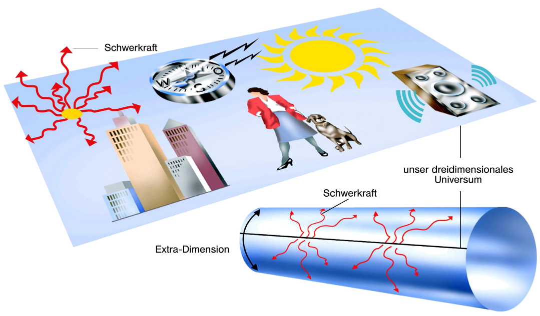
Set $M_D = 1\,\mathrm{TeV}$ to solve the hierarchy problem.
No need for fine tuning any more!

Size for $M_D = 1\,\mathrm{TeV}$:

n	1	2	3	...	7
R_C	$10^{10}\,\mathrm{km}$	$1\,\mathrm{mm}$	$1\,\mathrm{nm}$	...	$1\,\mathrm{fm}$

↑ $\mathcal{O}$(Solar system) (for $n = 1$)

↖ ↑ ↗ "large" compared to HEP scales (for $n = 2, 3, \ldots$)

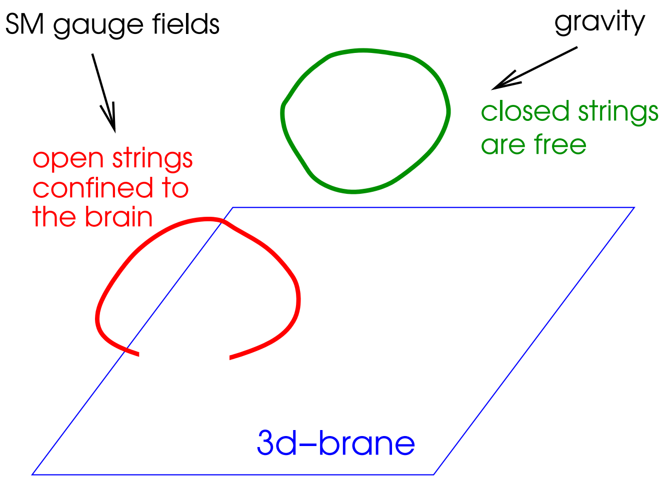


SM gauge fields cannot go to extra dimensions at such scales.
This is ruled out by HEP experiments. But gravity can!

At present, Newton's gravity law is tested down to $\sim 50\,\mu\mathrm{m}$ [hep-ph/0611184]

Motivation by the String Theory

- String theory

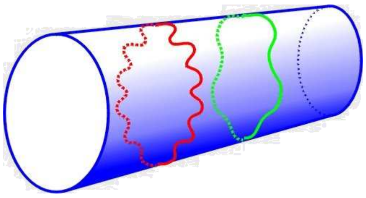


String theories require 6 or 7 extra dimensions, but not necessary of the same size

- Why gravity? Because it couples to energy/momentum.
  If gravity cannot go to extra dimensions, then also no other force can.

Kaluza–Klein Gravitons in ADD

- Winding modes

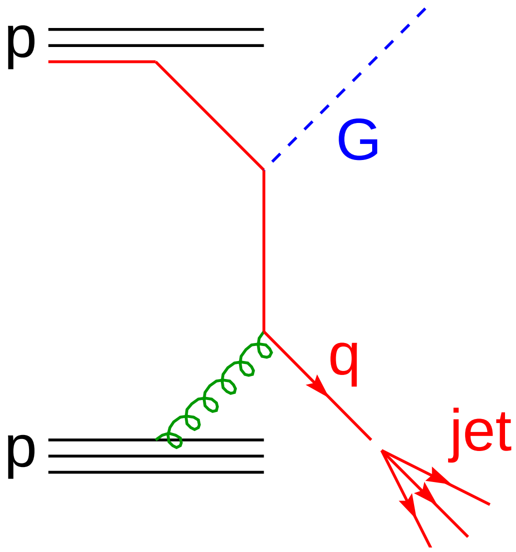


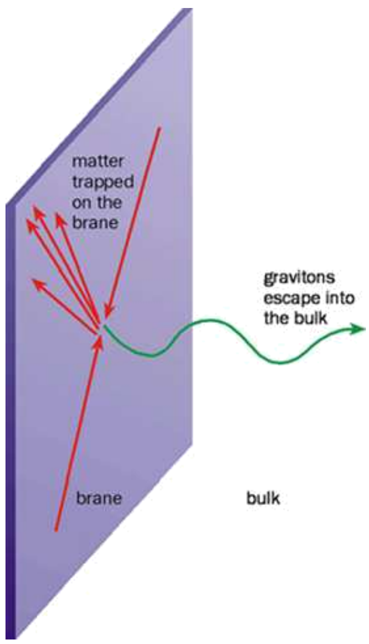
- Energy spacing $\sim 1/R_C \sim 1\,\mathrm{meV} - 100\,\mathrm{MeV}$ (large ED)
  Appear as continuous spectrum in experiment
  Mass: $m^2 = E^2 - \sum_{i=1}^{D} p_i^2 = 0$.
  Effective mass: $m^2 = E^2 - \sum_{i=1}^{3} p_i^2$

- Search for production of
  - real gravitons → monojets, monophotons
  - virtual gravitons → e^+e^-, $\mu^+\mu^-$, $\gamma\gamma$

Monojets

Real graviton production

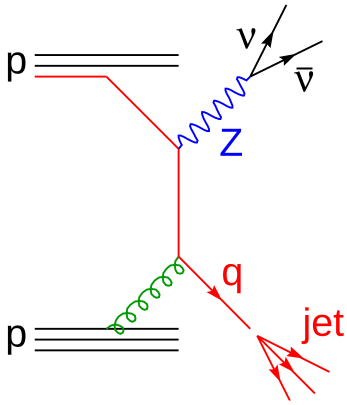


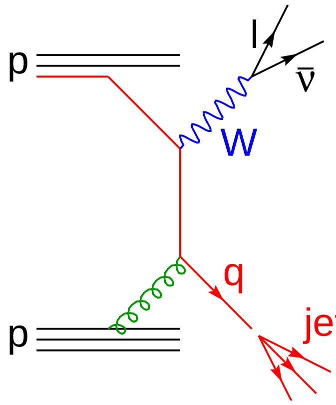


Signal: high E_T jet + missing E_T

Monojets – Standard Model Backgrounds

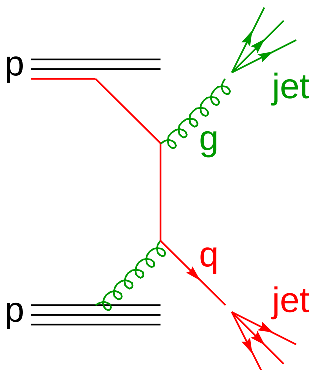
- Jet + $Z \to \nu\bar{\nu}$
- Jet + $W \to \nu e, \nu\mu, \nu\tau$ with lepton lost
  (lepton with low energy, lepton in dead region)

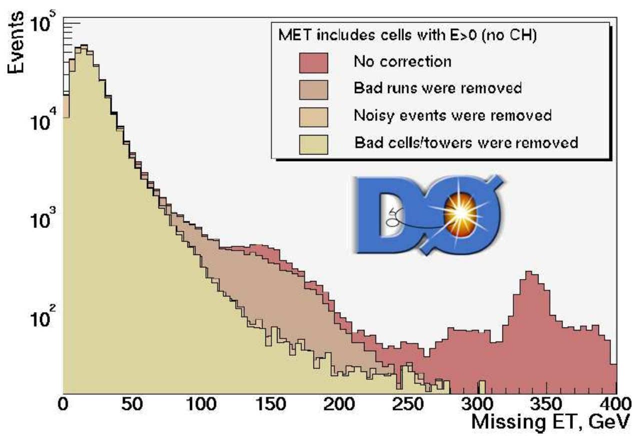




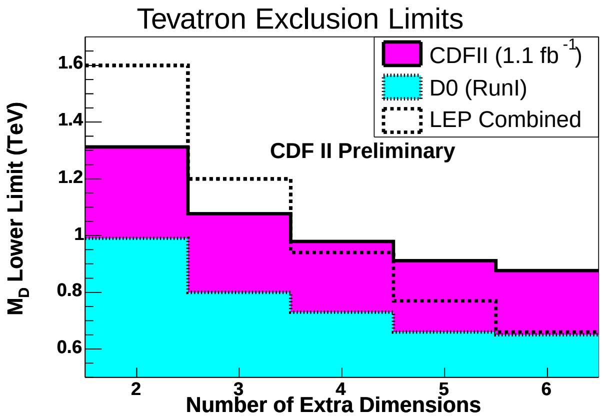
Monojets – Standard Model Backgrounds

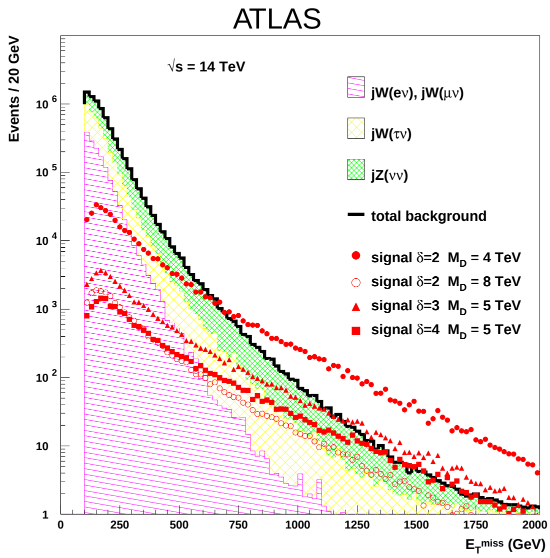
- Instrumentation + QCD
  - QCD dijets with one jet lost in dead region, or due to energy fluctuations, or multijets
  - Calorimeter noise
  - Beam induced signals
  - Cosmics





Monojets @ Tevatron and LHC



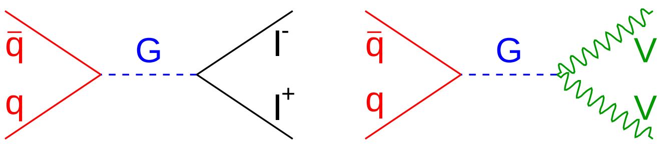


Expected exclusion limits for $100\,\mathrm{fb}^{-1}$:

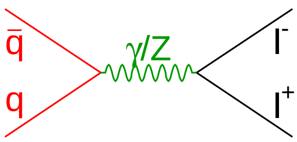
n	2	3	4
M_D / TeV	9	7	6

Virtual Graviton Exchange in ADD

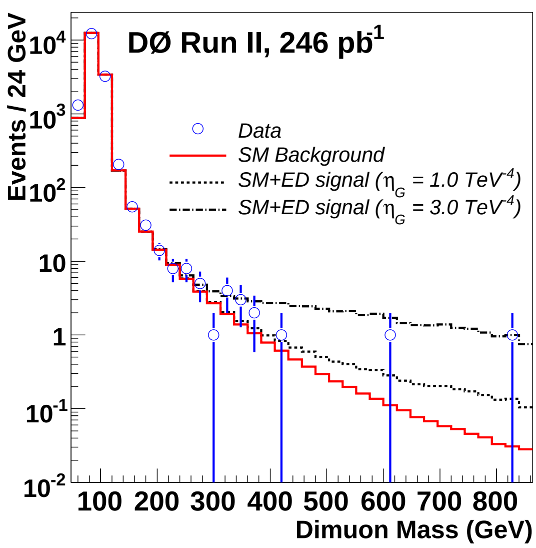
- e^+e^- and $\gamma\gamma$ from calorimeter measurements
- $\mu^+\mu^-$ momentum reconstruction in central and muon chambers



Look for deviations from SM
in Drell-Yan scattering for e^+e^- and $\mu^+\mu^-$

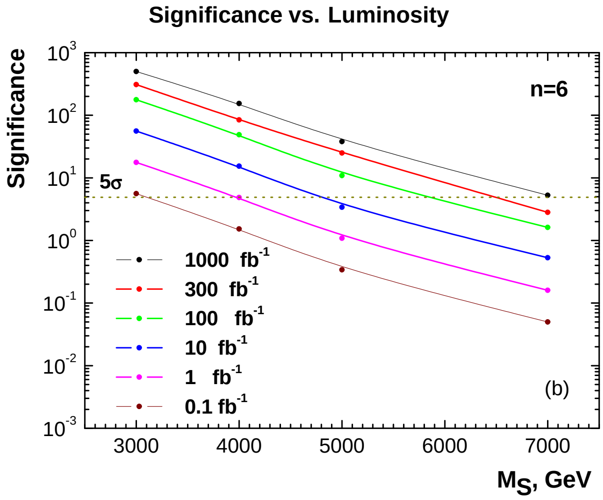


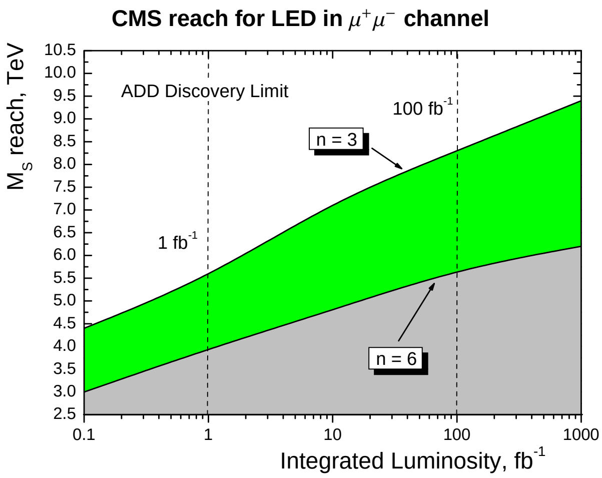
Deviations expected at high invariant masses
as KK gravitons appear “massive”
No deviations observed



Virtual Graviton Exchange in ADD @ LHC

Bounds $M_D > 5 - 10\,\mathrm{TeV}$ depending on luminosity are expected at LHC





Quick discovery is possible with 1st data

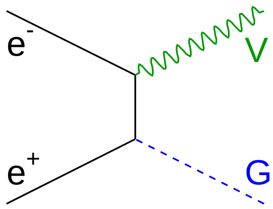
Belotelov et al.: CMS NOTE 2006-076

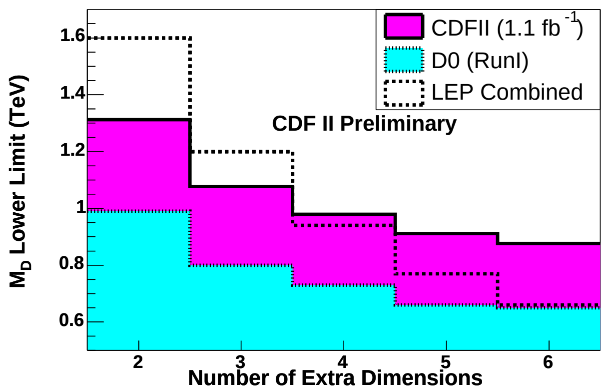
Large Extra Dimensions at LEP

Studied by all LEP experiments (ALEPH, DELPHI, OPAL, L3)

- Real graviton production

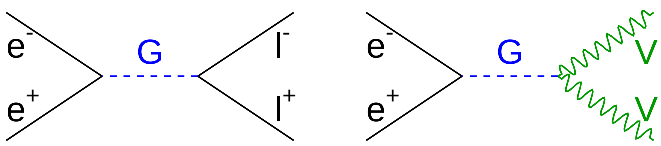
$e^+e^- \to \gamma G\ ,\ ZG$





- Virtual graviton exchange

$e^+e^- \to l^+l^-\ ,\ q\bar{q}\ ,\ VV$



Black Holes

- Black Holes are predicted in general relativity theory (1915)
- Karl Schwarzschild solution (1916) for static non-spinning massive object – metric with singularity at Schwarzschild radius

$$R_S = \frac{2M_{\rm BH}G}{c^2} \propto \frac{1}{M_{\rm Pl}}\frac{M_{\rm BH}}{M_{\rm Pl}}$$

  If the radius of the object is $< R_S$, black hole with event horizon at R_S is formed

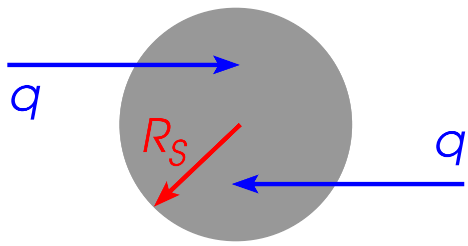
- The term “black hole” was introduced only around 1967 by John Wheeler
- Generalisation by Myers and Perry (1986) for $D = 4 + n$ dimensions

$$R_S \propto \frac{1}{M_D}\left(\frac{M_{\rm BH}}{M_D}\right)^{\frac{1}{n+1}}$$

  For small M_D: R_S is large

Black Hole Formation @ Hadron Colliders

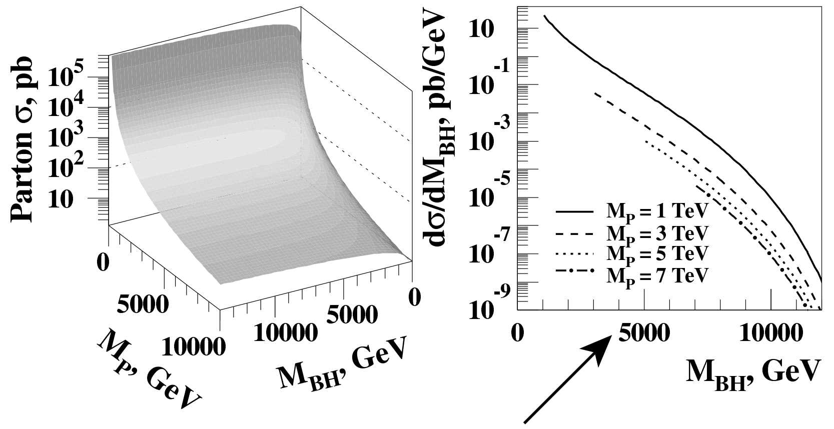
- Big energies $\Longleftrightarrow$ small distances.
  BH forms if partons come closer than $2R_S$
- BH mass $M_{\rm BH}^2 = \hat{s} = (p_1 + p_2)^2 = x_1 x_2 s$
  Continuous mass spectrum starting at some $M \gtrsim M_D$
- Exact cross section needs quantum gravity theory.
  Use quasi-classical “black disc” approximation:
  $\hat{\sigma} = f\pi R^2$ with formation factor $f \sim 1$
  Valid for $M_{\rm BH} \gg M_D$
- Possible for any combination of quarks and gluons.
  All gauge and spin quantum numbers are allowed
- Large $M_{\rm BH} \Longleftrightarrow$ large Bjorken x_1, x_2
  Quark-quark scattering dominates.
  BH are charged and coloured $(B \neq 0)$



R_S – Schwarzschild radius

Black Hole Production @ LHC

- Cross section $\sigma \approx f\pi R_S^2 \propto M_{\rm BH}^2 = \hat{s}$ – Non-perturbative process
  parton-parton σ grows with energy



Of course, it decreases if folded with PDFs

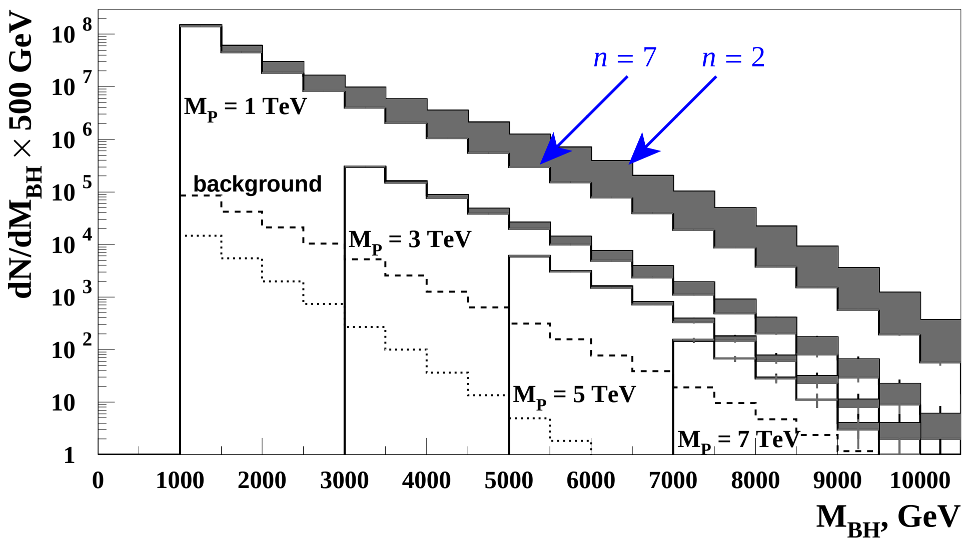
- Hard perturbative processes are suppressed
  Event horizon forms before particles have causal contact
  "The end of short distance physics"

Black Hole Factory

Cross section $\sigma \sim \pi R_S^2 \sim 1\,\mathrm{TeV}^{-2} \sim 10^{-38}\,\mathrm{m}^2 \sim 100\,\mathrm{pb}$

Rate may be very high, e.g. for $M_D = 1\,\mathrm{TeV}$, $M_{\rm BH} > 5\,\mathrm{TeV}$, $n = 10$: rate $\sim 1\,\mathrm{Hz}$

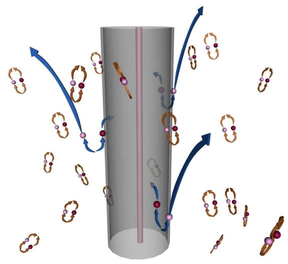
LHC would be "black hole factory"



Spectrum of BH at LHC decaying into final states with electron or photon

Hawking Radiation

- Steven Hawking showed (1975) that black hole can evaporate by emitting pairs of virtual photons at event horizon, with one of photon escaping the BH gravity
- Photons have perfect black body spectrum with temperature



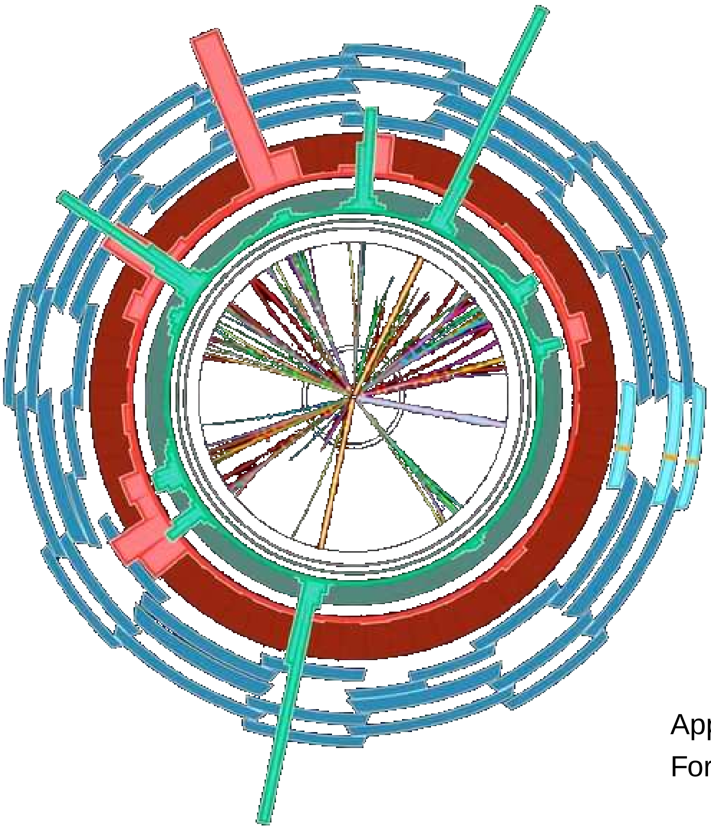
$$T_H = \frac{\hbar c}{4\pi k_B R_S} = \frac{1}{4\pi R_S} \propto M_{\rm Pl} \frac{M_{\rm Pl}}{M_{\rm BH}}$$

- No chance to discover Hawking radiation of astro black holes: sun mass $T_H \sim {\rm nK} \ll T_{\rm CMB} = 2.7\,{\rm K}$; moon mass $T_H \sim T_{\rm CMB}$
- In $D = 4 + n$ dimensions (Myers, Perry, 1986)

$$T_H = \frac{n+1}{4\pi R_S} \propto M_D \left(\frac{M_D}{M_{\rm BH}}\right)^{\frac{1}{n+1}} (n+1)$$

- At high enough T_H massive particles can also be produced
- In MC simulations at the LHC, Hawking radiation is approximated by democrating decay.

Black Hole Event Simulation @ ATLAS



– High multiplicity
– High sphericity

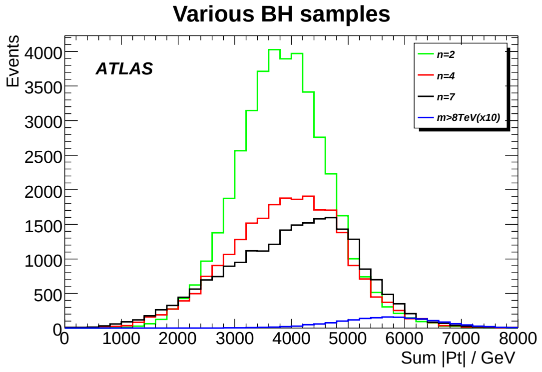
Democratic decay

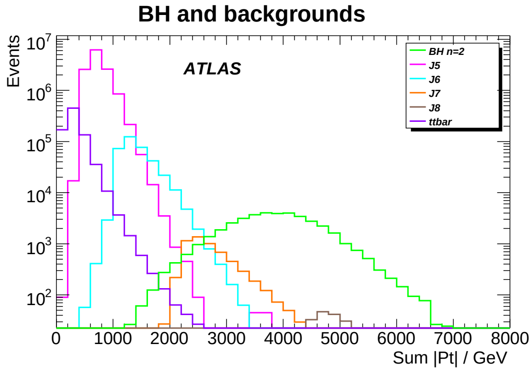
q, g	72%
e, μ, τ	11%
$W^{\pm}, Z$	8%
ν, G	6%
H	2%
γ	1%
h/l activity	5 : 1
h/γ activity	100 : 1

Approximation is valid only for $M_{\rm BH} \gg M_D$.
For $M_{\rm BH} \sim M_D$ quantum gravity is needed.

Black Hole Event Selection

- To reduce QCD background from dijets/multijets, $t\bar{t}$, cut $\sum |p_T| > 2.5\,\mathrm{TeV}$

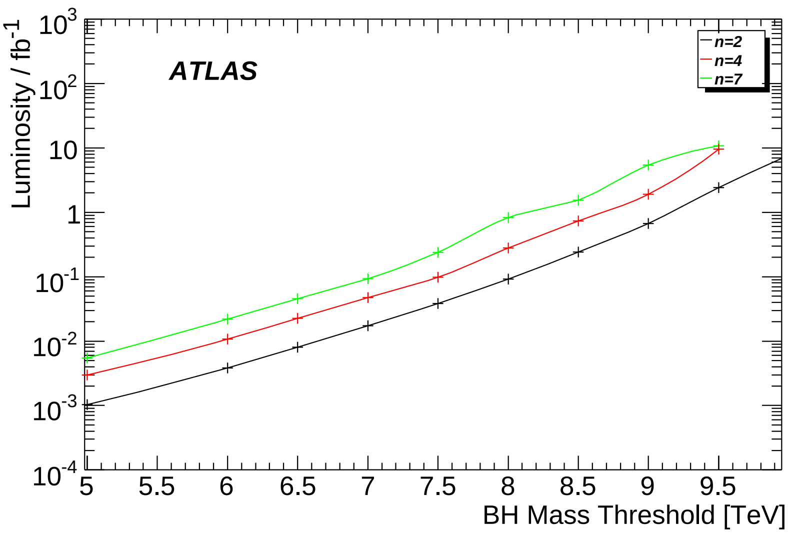




- Require at least one well identified lepton e or μ with $p_T > 50\,\mathrm{GeV}$
  QCD background further reduced by factor ~ 60

Black Hole Discovery Potential

Robust estimation of discovery potential is difficult,
because semi-classical model assumptions are valid only for $M_{BH} \gg M_D$.
Introduce artificial mass cut-off in generated samples $\Longrightarrow$ conservative estimation



Democratic Particle Distribution

Identify BH events

ATLAS

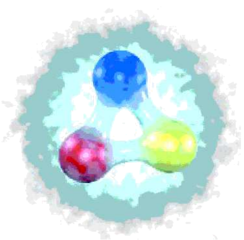
Democratic decay in 120 SM degrees of freedom

emitted particle ratio	**reconstructed**	**generator**
electrons/muons	$\frac{1653\pm149}{1701\pm173} = (97.2 \pm 13.2)\%$	$\frac{1610}{1661} = 96.9\%$
electrons/tops	$\frac{1653\pm149}{6241\pm1631} = (26.5 \pm 7.3)\%$	$\frac{1610}{6234} = 25.8\%$
Z^0/tops	$\frac{1808\pm464}{6241\pm1631} = (29.0 \pm 10.6)\%$	$\frac{1806}{6234} = 29.0\%$
$W^\pm$/tops	$\frac{3112\pm977}{6241\pm1631} = (49.9 \pm 20.4)\%$	$\frac{3118}{6234} = 50.0\%$
$Z^0/W^\pm$	$\frac{1808\pm464}{3112\pm977} = (58.1 \pm 23.6)\%$	$\frac{1806}{3118} = 57.9\%$

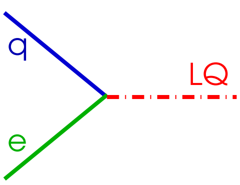
- A significant part of the democratic particle distribution could be reconstructed
- If there are black hole events, we will be able to identify them

Further Alternatives

- Little Higgs
- Compositeness



- Leptoquarks



- Unparticles, hidden world, . . .

More information in the next lecture course + journal club:
Advanced Topics in Particle Physics (WS 2008)