Hadron Collider School - HASCO

Stockholm University

# Supersymmetry and Exotics

HASCO 2012 Göttingen

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# Structure of the SUSY & Exotics Lectures

1. **What questions do we want to answer?** (and that are not answered by SM)
   - The Planck and GUT Scale
   - The hierarchy problem
   - Dark Matter
   - Sakharov's conditions
   - Other Problems with the Standard model

Part I

2. **Suypersymmetry**
   - Construction of supersymmetry
   - Particle spectrum
   - SUSY Particle production and decay
   - R-Parity
   - Some experimental searches

Part II

Part III

3. **Extra-dimensions and other BSM theories**
   1. Extra-dimensions
   2. Experimental signature
   3. Other BSM

Part IV

# SUSY Phenomenology

Experimentally

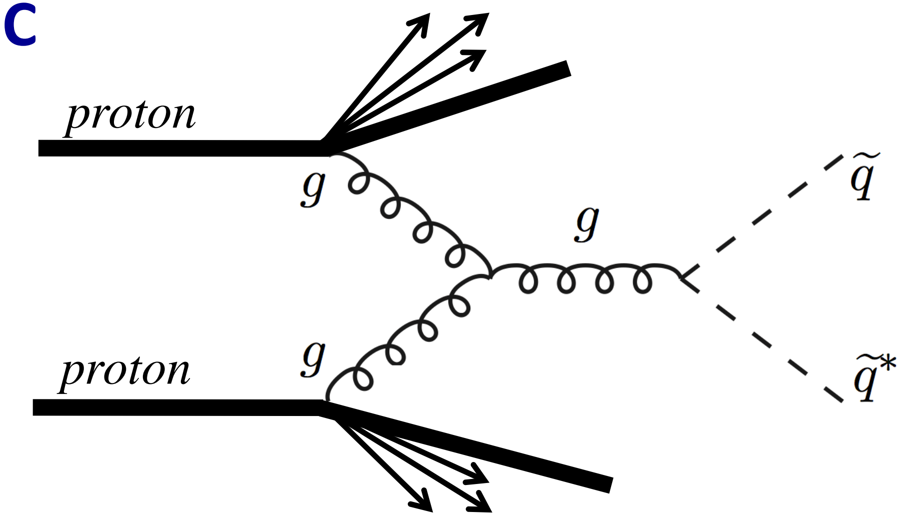
***R-parity Conserving*** and ***R-Parity Violating SUSY***

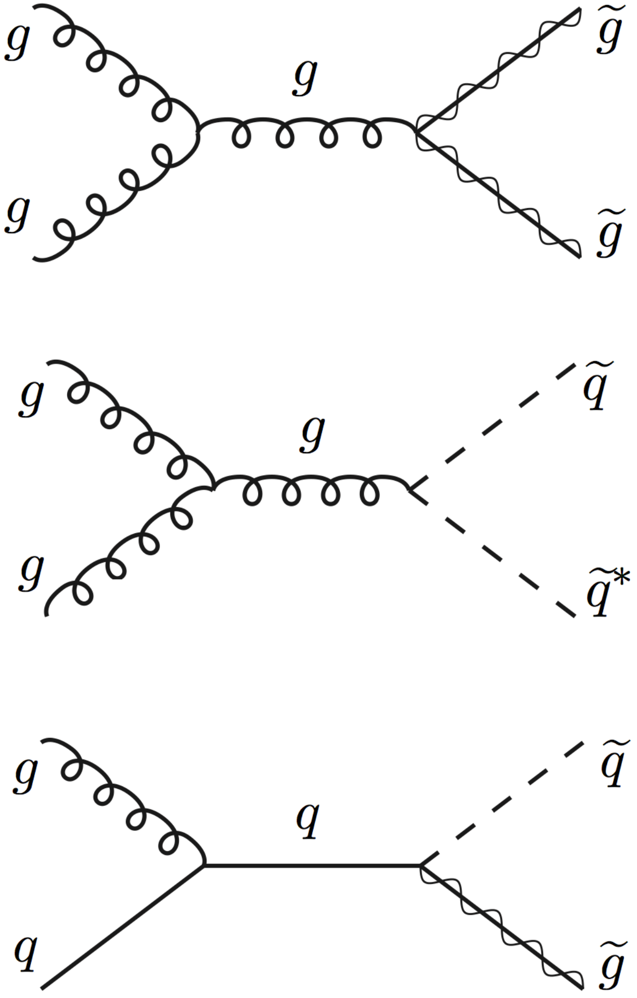
can lead to significantly different phenomenologies

**Treat them separately** when analysing the LHC data.

# Strong SUSY Production at the LHC

## A few diagrams (out of *many*)





**squark pairs, squark-gluino or gluino-gluino**

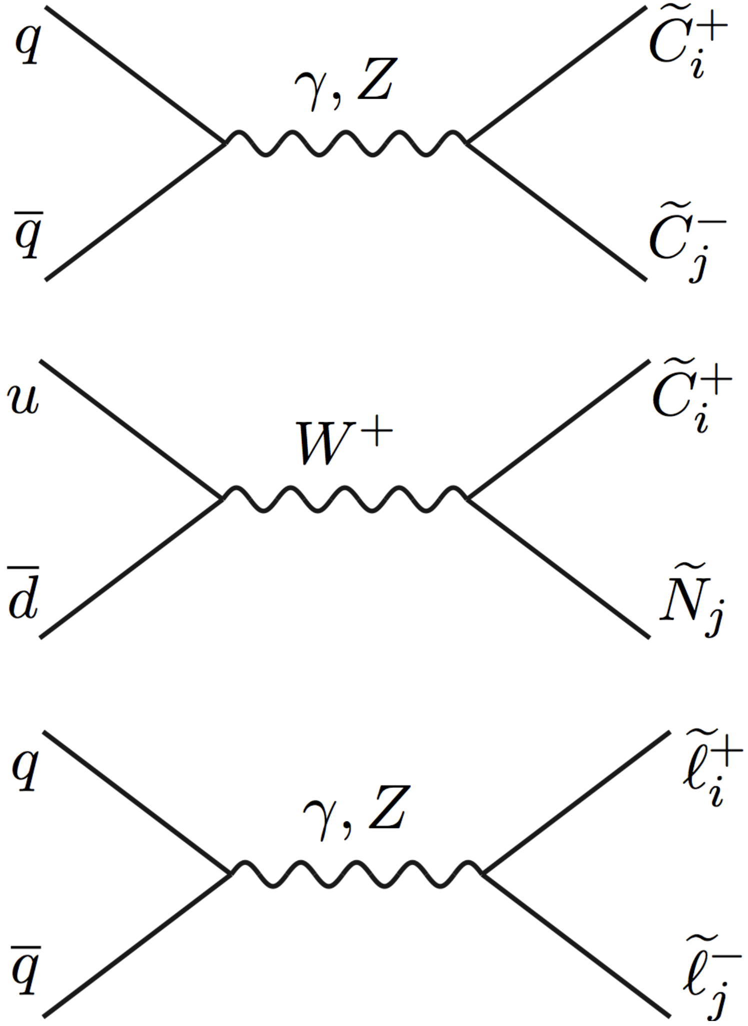
In principle the largest due to the strong interaction

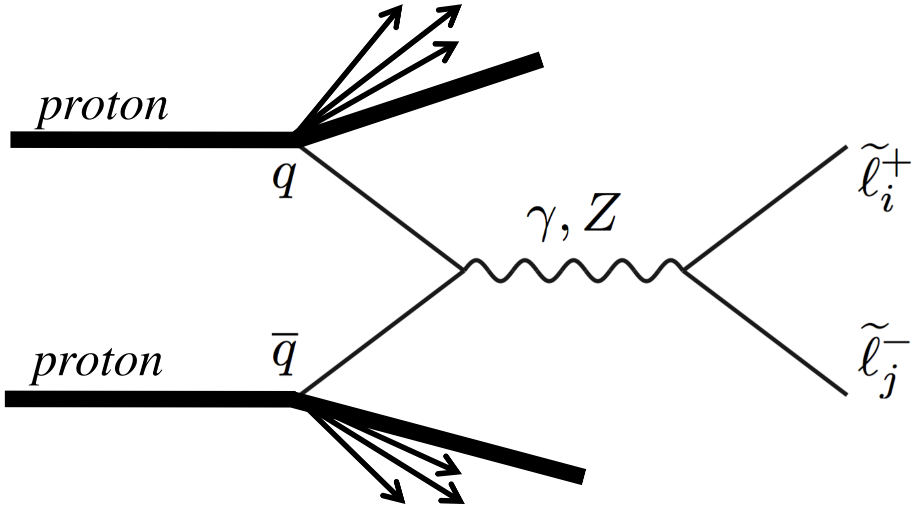
However so far the search has been negative

Remember R-parity conservation:
⇒SUSY Particles are produced in pairs

# Weak SUSY Production at the LHC

## A few diagrams (out of *many*)





**Neutralino-neutralino pairs, neutralino-chargino, chargino-chargino pairs, slepton pairs**

Via the weak interaction, hence lowest cross section

Could be important to discover SUSY if the squarks and gluinos are very heavy.

# Reminder SUSY Particle Spectrum

| Names | Spin | $P_R$ | Gauge Eigenstates | Mass Eigenstates |
|---|---|---|---|---|
| Higgs bosons | 0 | $+1$ | $H_u^0\ H_d^0\ H_u^+\ H_d^-$ | $h^0\ H^0\ A^0\ H^\pm$ |
| squarks | 0 | $-1$ | $\widetilde{u}_L\ \widetilde{u}_R\ \widetilde{d}_L\ \widetilde{d}_R$ | (same) |
| | | | $\widetilde{s}_L\ \widetilde{s}_R\ \widetilde{c}_L\ \widetilde{c}_R$ | (same) |
| | | | $\widetilde{t}_L\ \widetilde{t}_R\ \widetilde{b}_L\ \widetilde{b}_R$ | $\widetilde{t}_1\ \widetilde{t}_2\ \widetilde{b}_1\ \widetilde{b}_2$ |
| sleptons | 0 | $-1$ | $\widetilde{e}_L\ \widetilde{e}_R\ \widetilde{\nu}_e$ | (same) |
| | | | $\widetilde{\mu}_L\ \widetilde{\mu}_R\ \widetilde{\nu}_\mu$ | (same) |
| | | | $\widetilde{\tau}_L\ \widetilde{\tau}_R\ \widetilde{\nu}_\tau$ | $\widetilde{\tau}_1\ \widetilde{\tau}_2\ \widetilde{\nu}_\tau$ |
| neutralinos | 1/2 | $-1$ | $\widetilde{B}^0\ \ \widetilde{W}^0\ \ \widetilde{H}_u^0\ \ \widetilde{H}_d^0$ | $\widetilde{N}_1\ \widetilde{N}_2\ \widetilde{N}_3\ \widetilde{N}_4$ |
| charginos | 1/2 | $-1$ | $\widetilde{W}^\pm\ \ \widetilde{H}_u^+\ \ \widetilde{H}_d^-$ | $\widetilde{C}_1^\pm\ \ \widetilde{C}_2^\pm$ |
| gluino | 1/2 | $-1$ | $\widetilde{g}$ | (same) |
| goldstino<br>(gravitino) | 1/2<br>(3/2) | $-1$ | $\widetilde{G}$ | (same) |

*also often denoted*

$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0,$

$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$

# SUSY Production at LHC

LHC in physics operation for only 2 years.

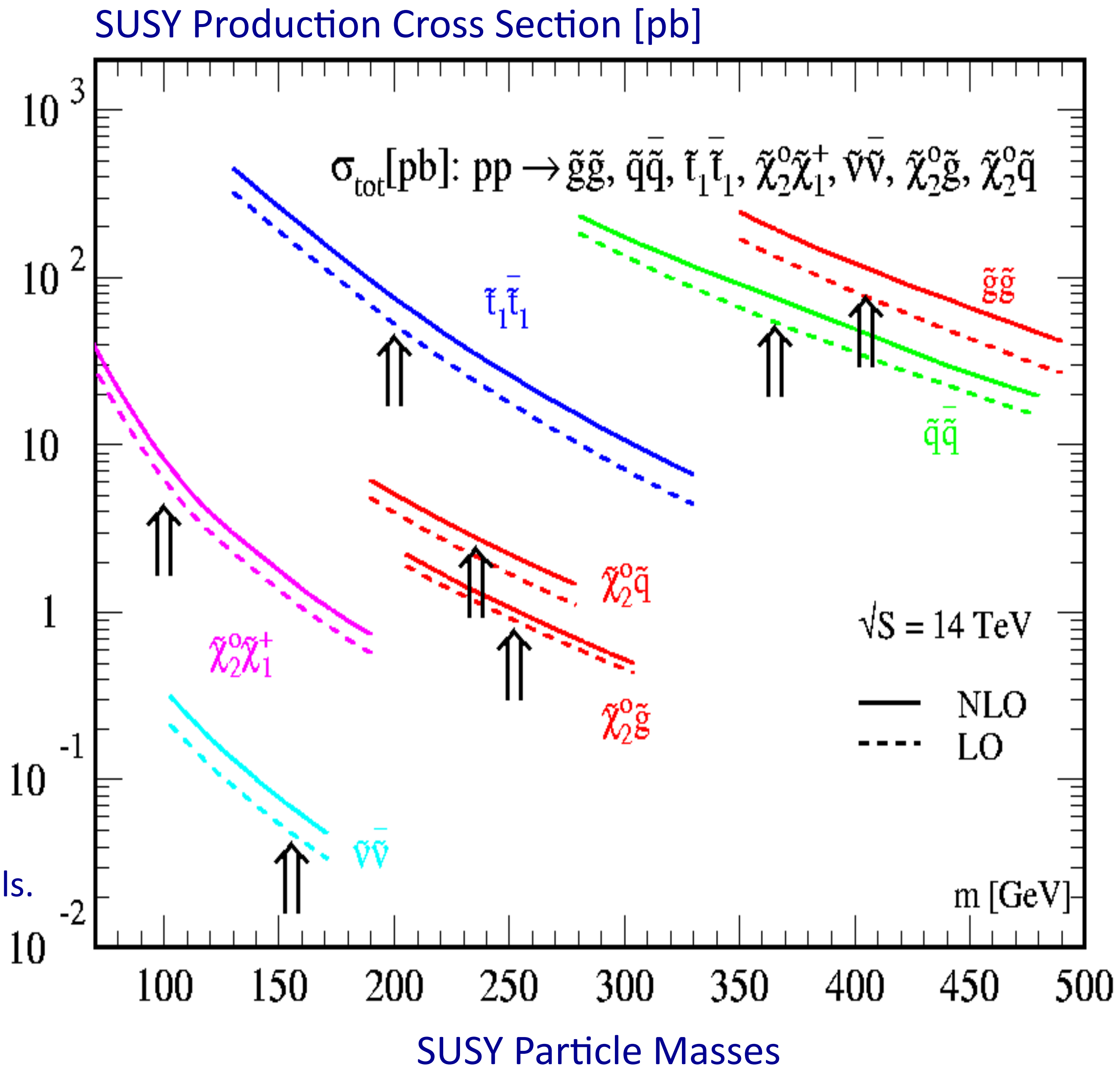
Already see historical evolution of how to approach SUSY search.

Started by searches for strong production.

**Direct stop quark search.**

2012 first search for direct slepton production.

Now LHC experiments cover the whole range of production channels.



Made with Prospino 2
http://www.thphys.uni-heidelberg.de/~plehn/index.php?show=prospino&visible=tools

# Cross Section σ?

*Very brief reminder*

It is related the probability for a interaction to occur, eg. to produce a particle.

The number of collisions $N_{SUSY}$ with of a certain process is proportional to
- Luminosity $L$ of the accelerator (= number of p-p collisions per unit of time)
- How long the accelerator has been operating $\Delta t$
- The cross section for the process $\sigma$.

$$N_{SUSY} = L\Delta t\sigma$$

eg.
Integrated luminosity is $L.\Delta t = 10\ fb^{-1} = 10{,}000\ pb^{-1}$
Cross section for $N_2C_1$ production at 150 GeV is $1\ pb$

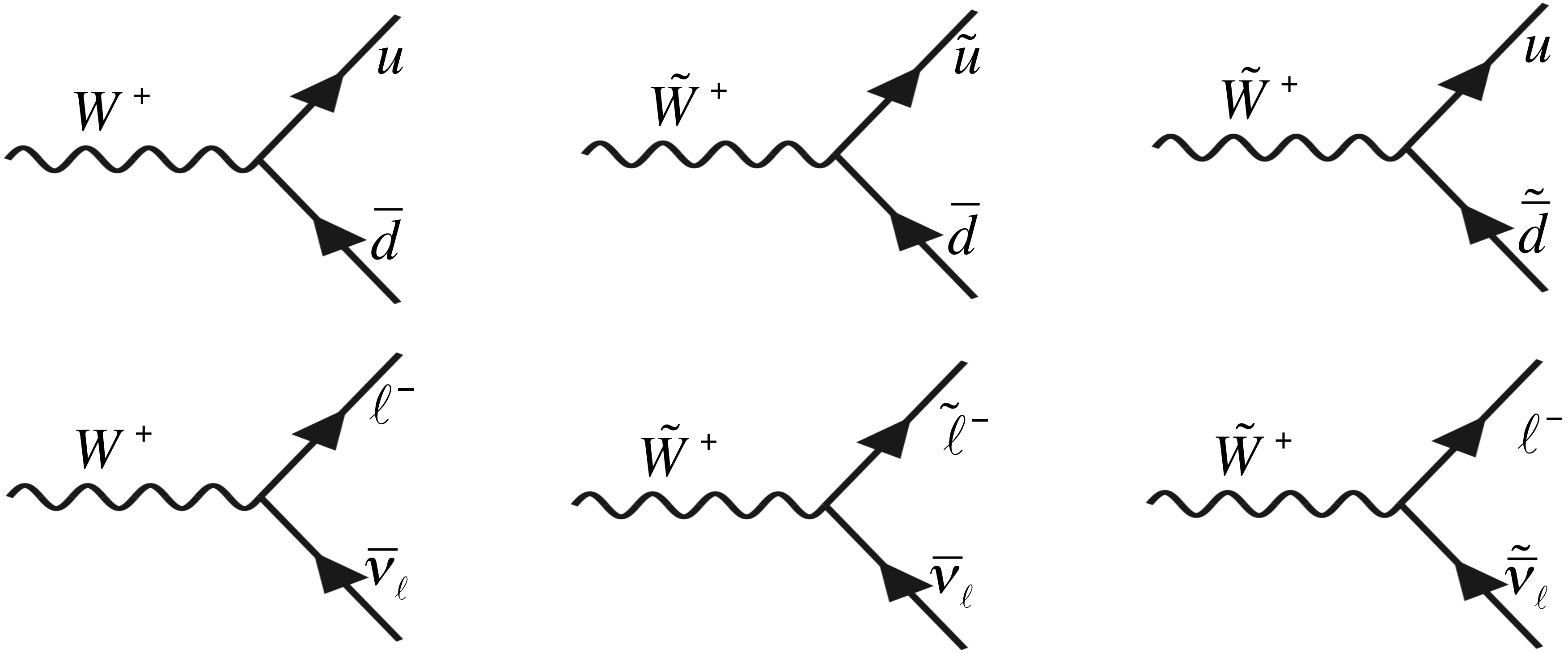
$N_{N2C1} = L.\Delta t.\sigma = 10{,}000$ ***collisions***

# Neutralino and Chargino Decays

Guideline to understand how SUSY particles

1. Remember that a SUSY particle has the same gauge quantum numbers as its SM particle
2. Is a decay kinematically allowed (SUSY particle masses are not known)

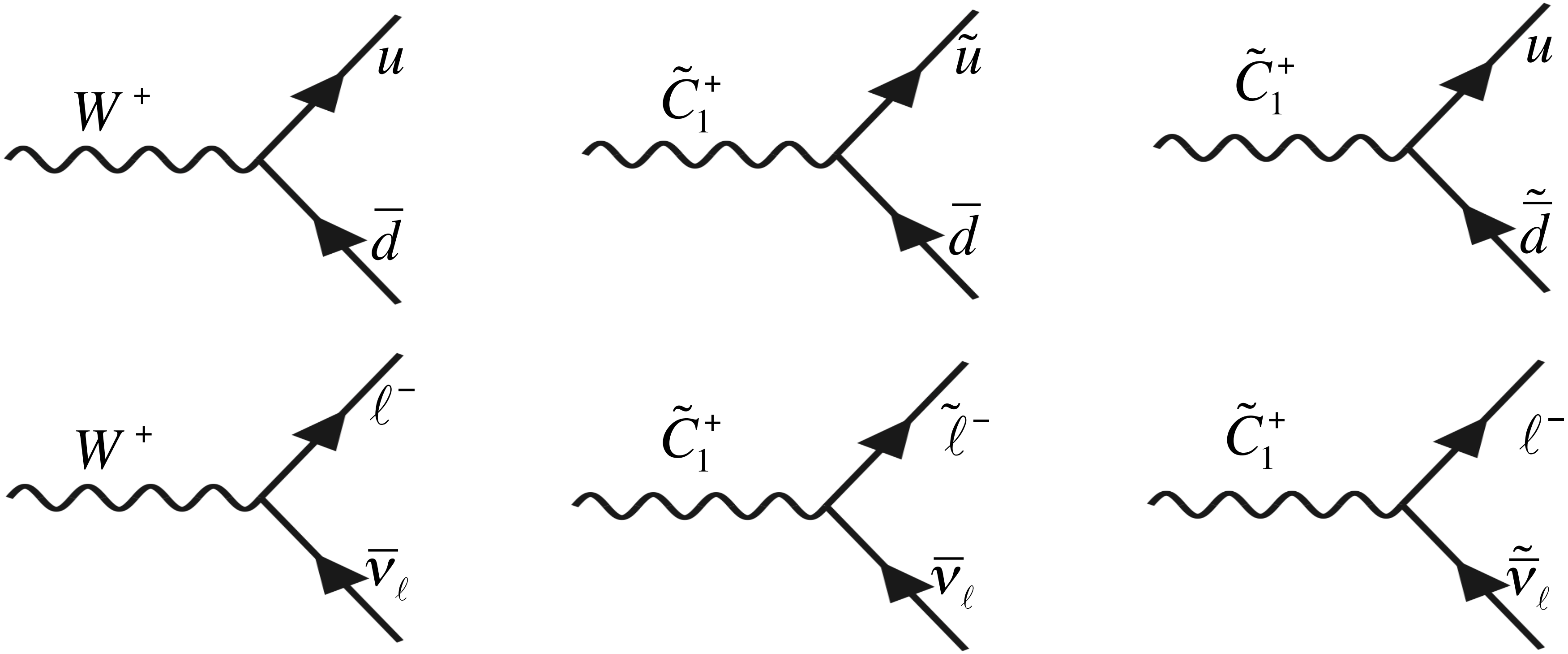
So if a Standard Model Feynman diagram exists, then a similar diagram exists with SM particle transformed into the SUSY partners.



Would also need to consider the Higgs decays to obtain the Higgsino decays

# Neutralino and Chargino Decays

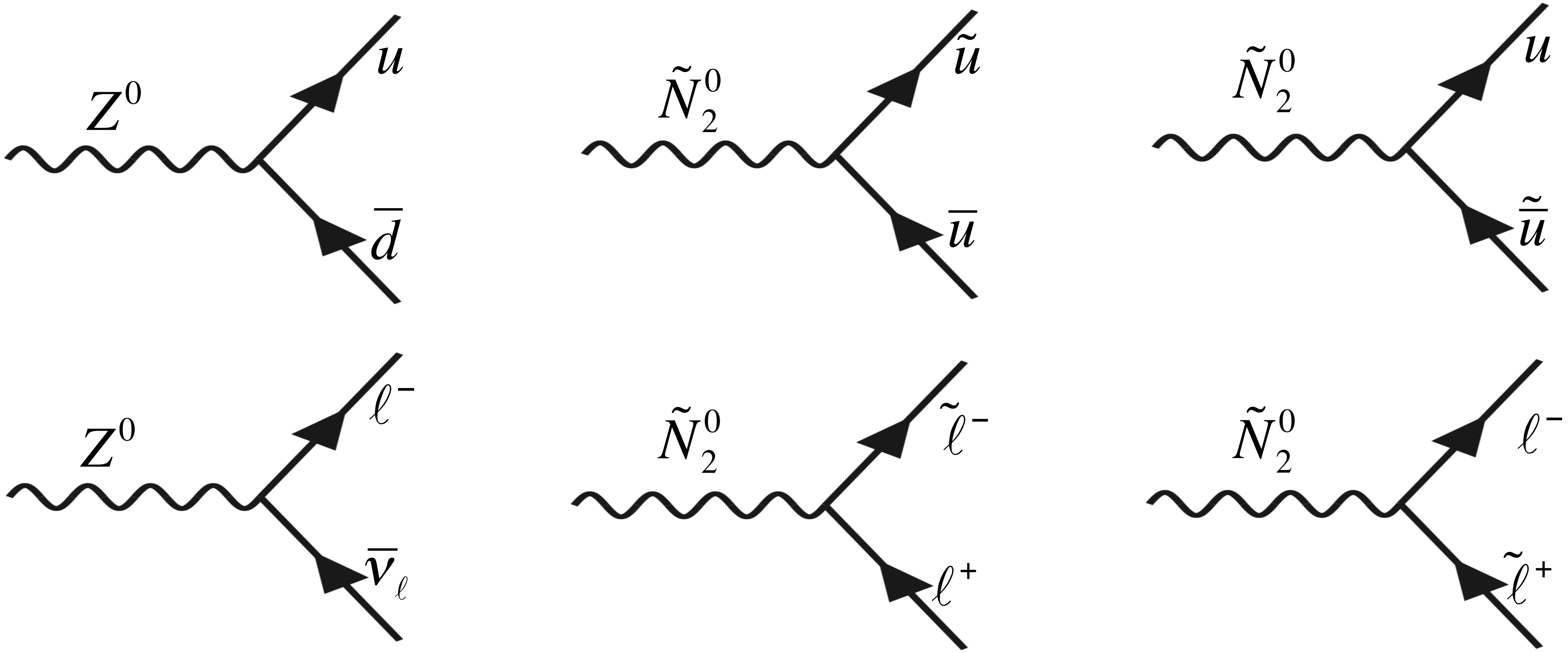
Remember the mass states are: $\begin{pmatrix} C_1^+ \\ C_2^+ \end{pmatrix} = M_{\tilde{C}} \begin{pmatrix} \tilde{H}_u^+ \\ \tilde{W}^+ \end{pmatrix}$



## Neutralino and Chargino Decays

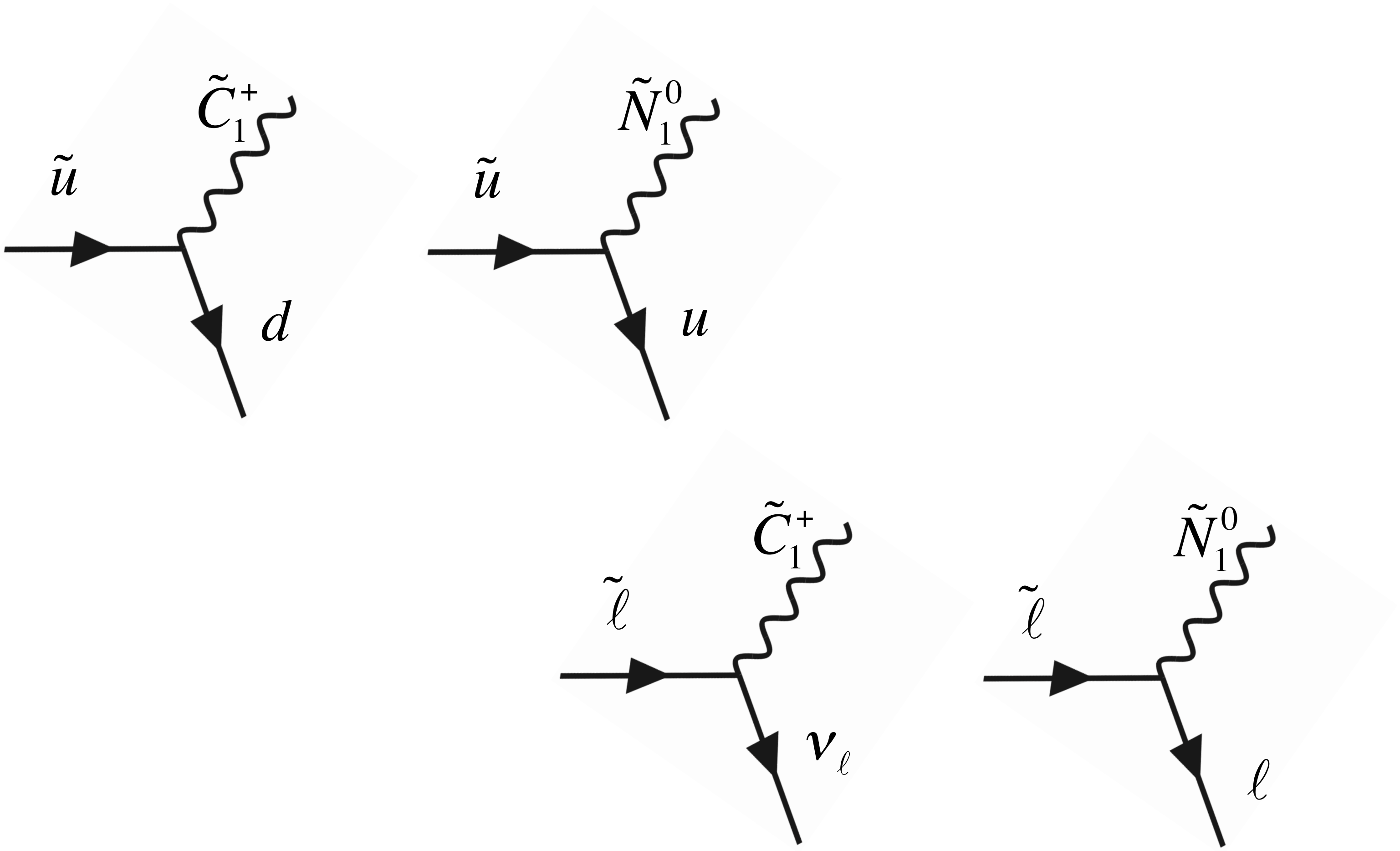
For the neutralinos the mass eigenstates are :

$$\begin{pmatrix} \tilde{N}_1 \\ \tilde{N}_2 \\ \tilde{N}_3 \\ \tilde{N}_4 \end{pmatrix} = M_{\tilde{N}} \begin{pmatrix} \tilde{B}^0 \\ \tilde{W}^0 \\ \tilde{H}_d^0 \\ \tilde{H}_u^0 \end{pmatrix}$$



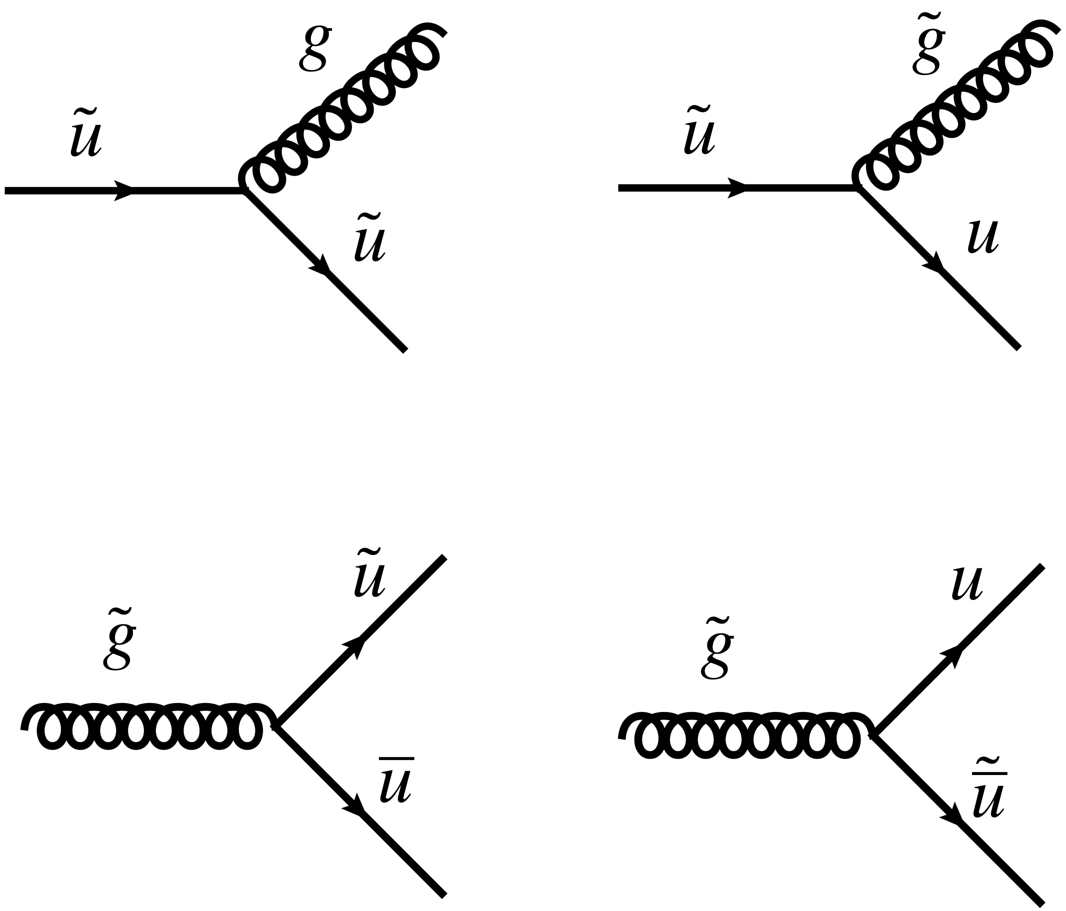
# Squark and Slepton decays

*Can be obtained by rotating the previous diagrams or moving around the “SUSY-ness” “~”*

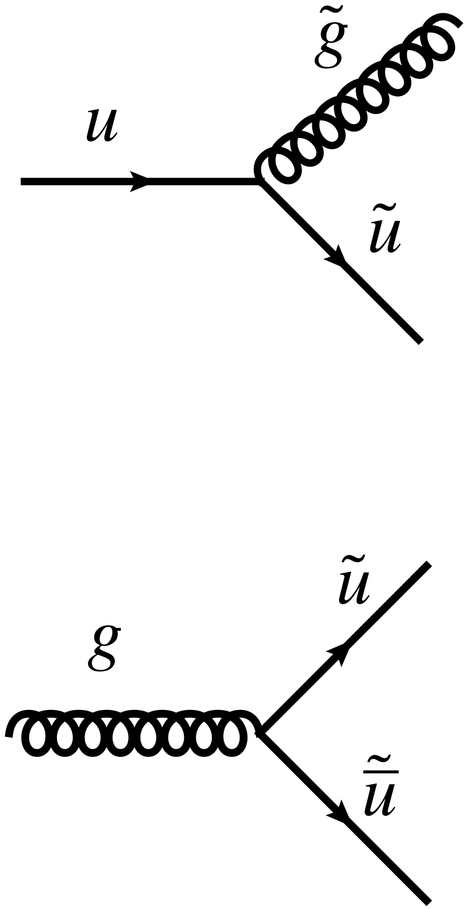


# Gluinos

*quarks and gluons couple with each other… hence squarks and gluinos also couple*

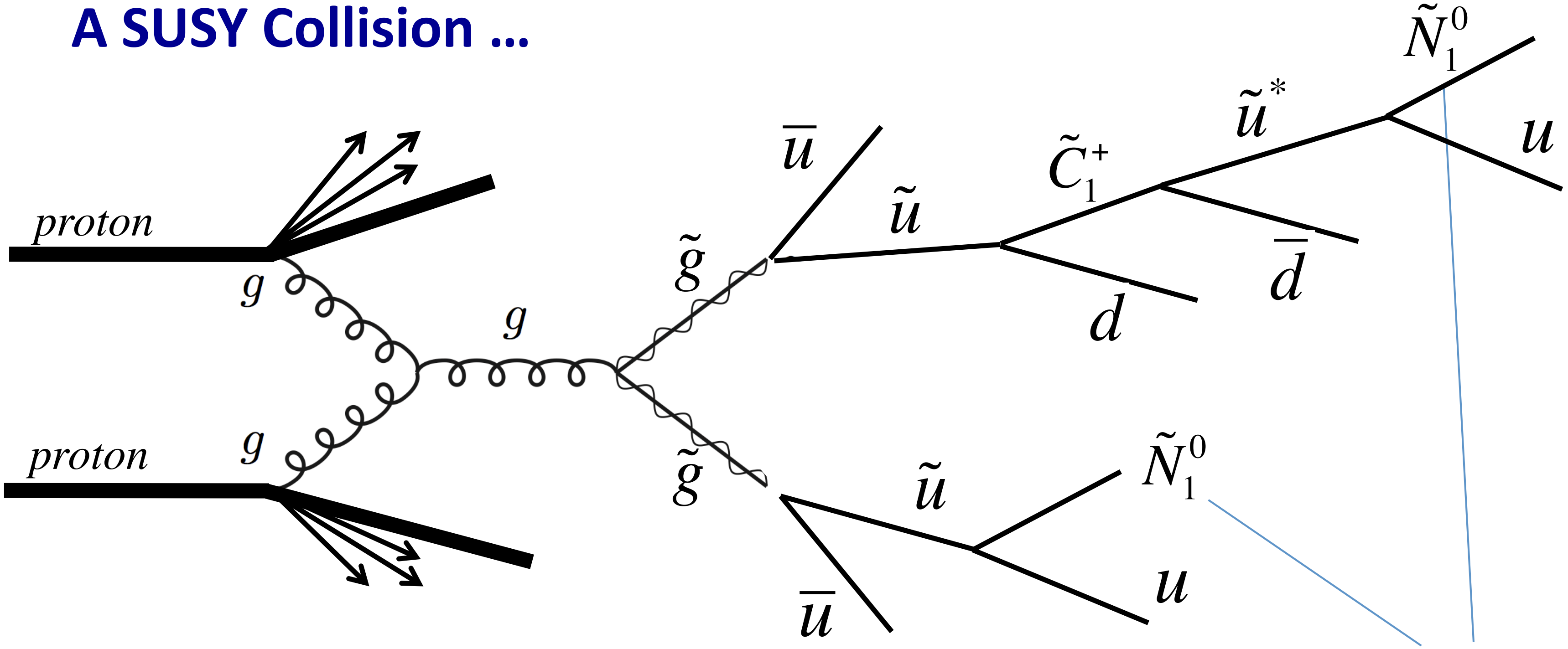


*Squark and gluino decays*



*production of SUSY particles*

# A SUSY Collision …



*these cannot be detected in ATLAS or CMS*

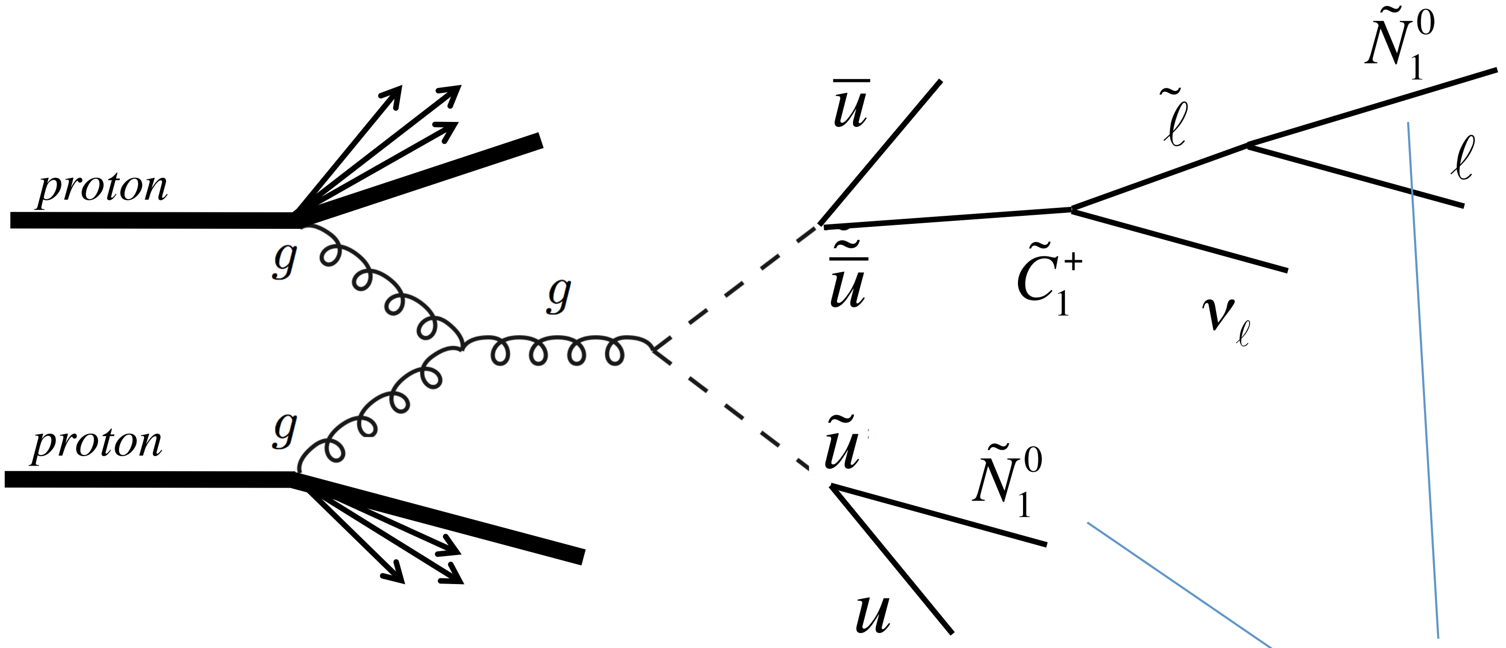
**Final state with**

- 6 quarks -> ~6 hadronic jets
- 2 $\tilde{N}_1^0$ -> Missing energy
- 0 leptons

**Signature = Many Hadronic Jets + Missing Energy**

*This is perhaps the most canonical SUSY signature*

# Another SUSY Collision …



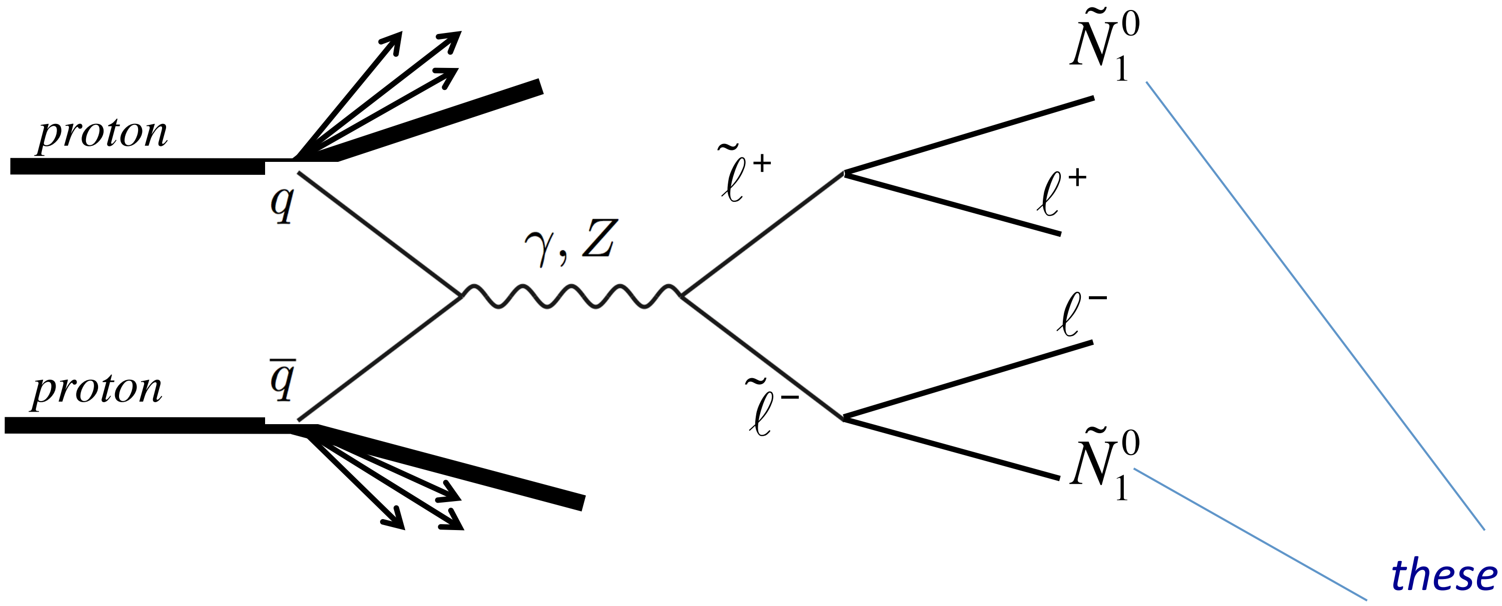
*these cannot be detected in ATLAS or CMS*

**Final state with**

- 2 quarks -> ~2 hadronic jets
- 1 lepton
- 2 $\tilde{N}_1^0$ -> Missing energy
- 1 neutrino -> missing energy

**Signature = Hadronic Jets + N leptons + Missing Energy**

# Another SUSY Collision …



*these cannot be detected directly in ATLAS or CMS*

**Final state with**

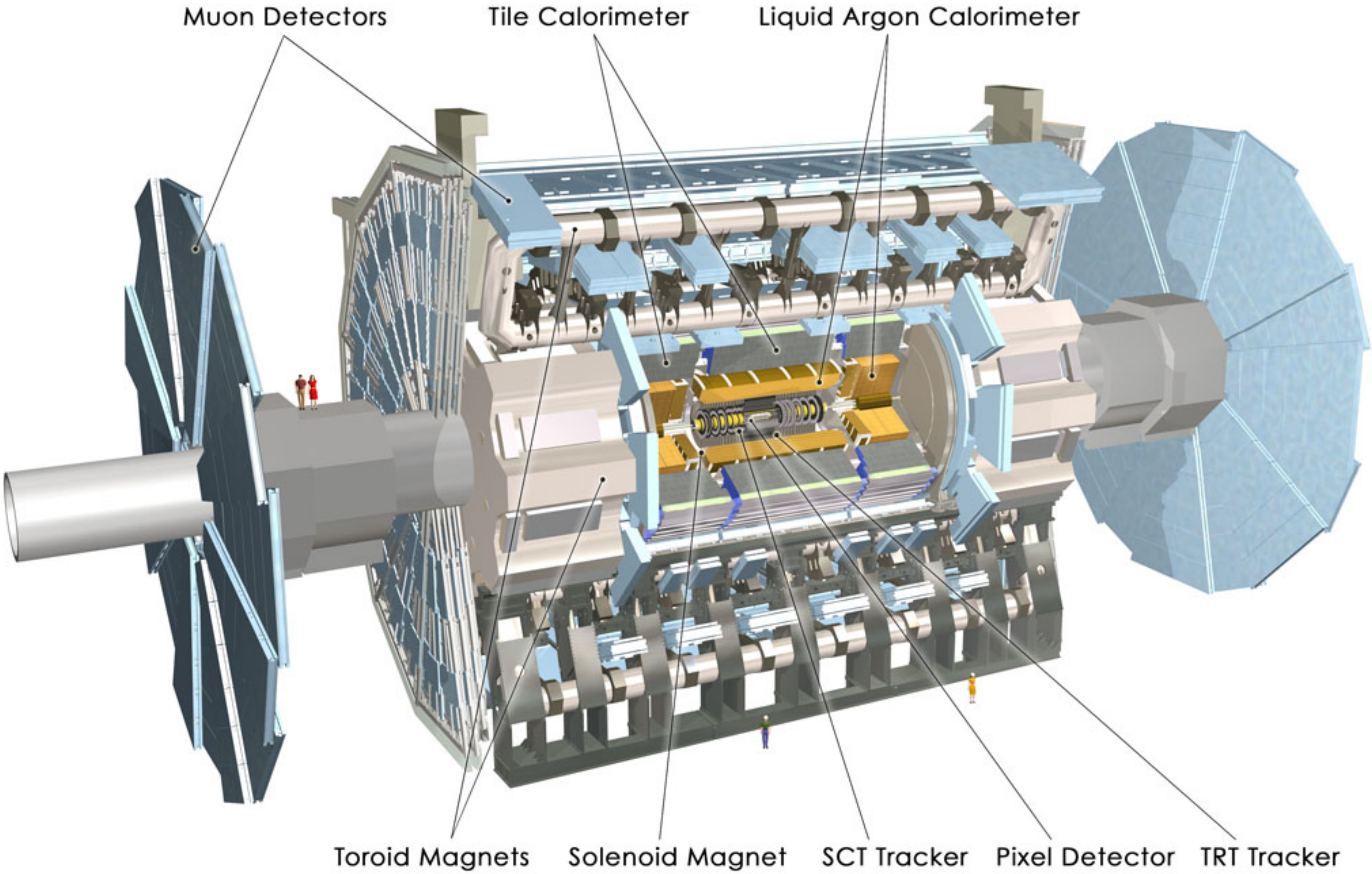
- 2 opposite charge same flavour leptons
- 2 $\tilde{N}_1^0$ -> Missing energy

**Signature = 2 leptons + Missing Energy + No Jets**

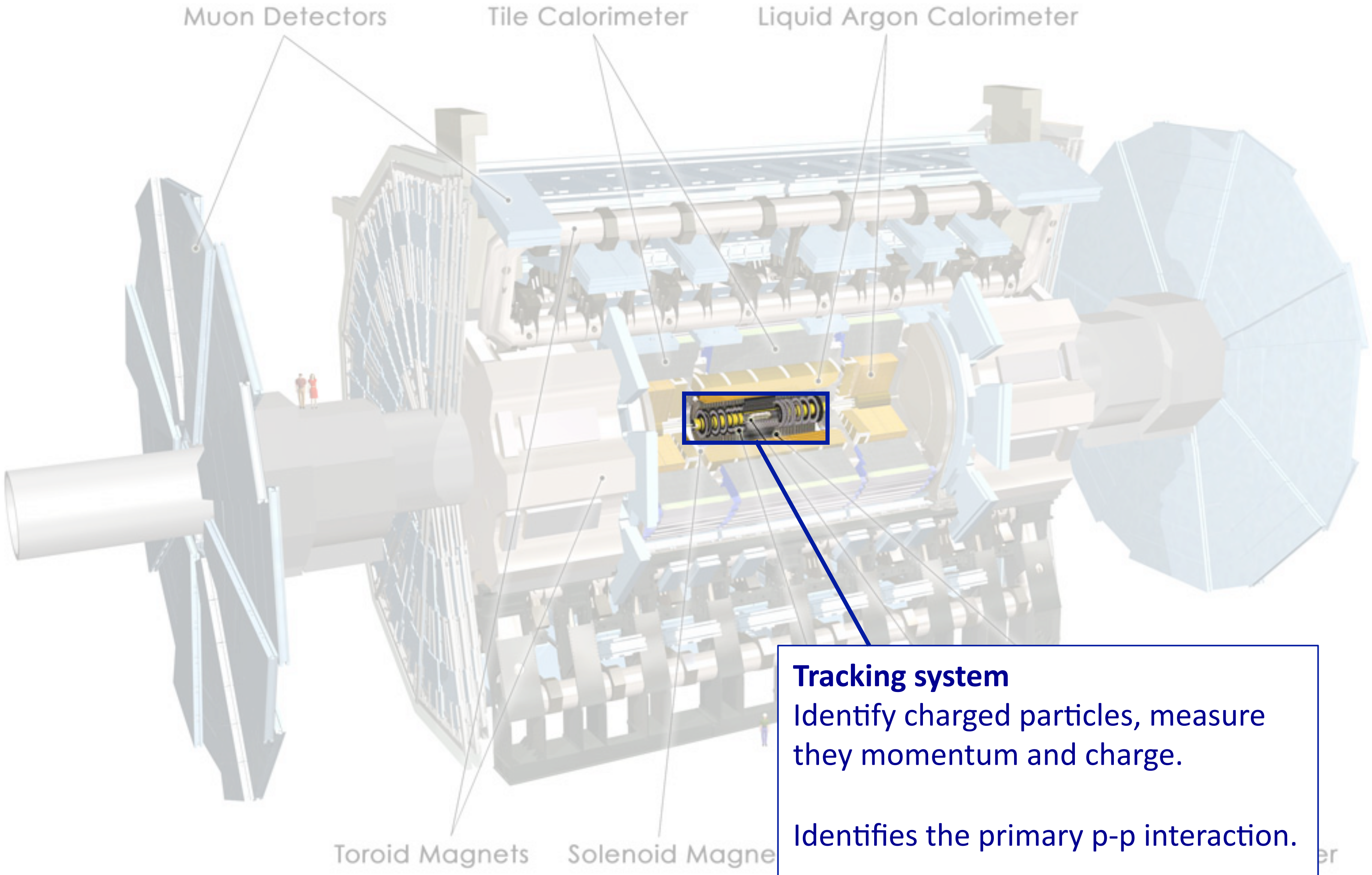
⇒ Rather large variety of possible SUSY final states

⇒ Need first to define what process you are looking for before designing your data selections

# Experimental Observables for Supersymmetry Searches with ATLAS



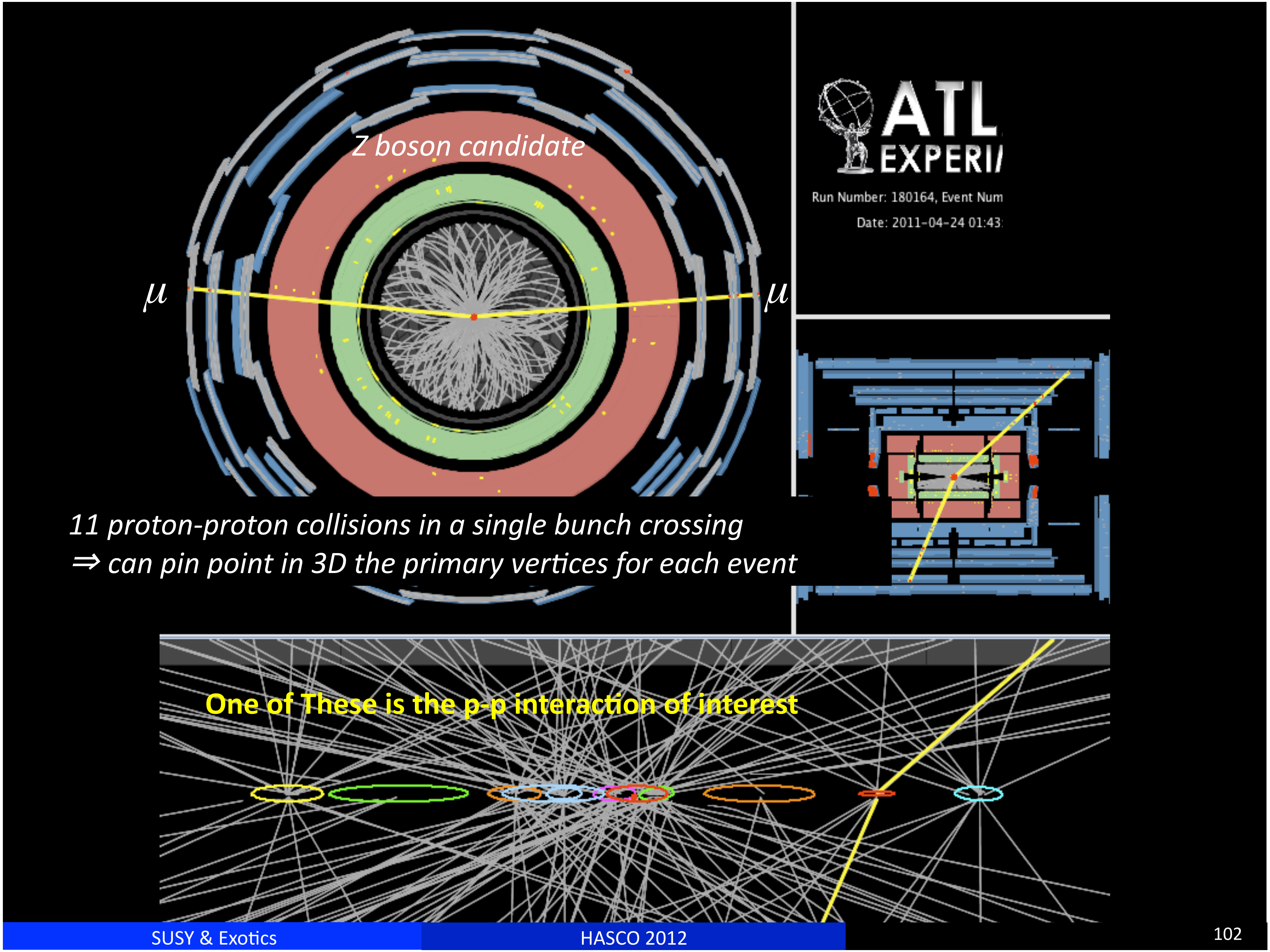
# Experimental Observables for Supersymmetry Searches with ATLAS



**Tracking system**
Identify charged particles, measure they momentum and charge.

Identifies the primary p-p interaction.

Identifify displaced vertices



*11 proton-proton collisions in a single bunch crossing*
*⇒ can pin point in 3D the primary vertices for each event*

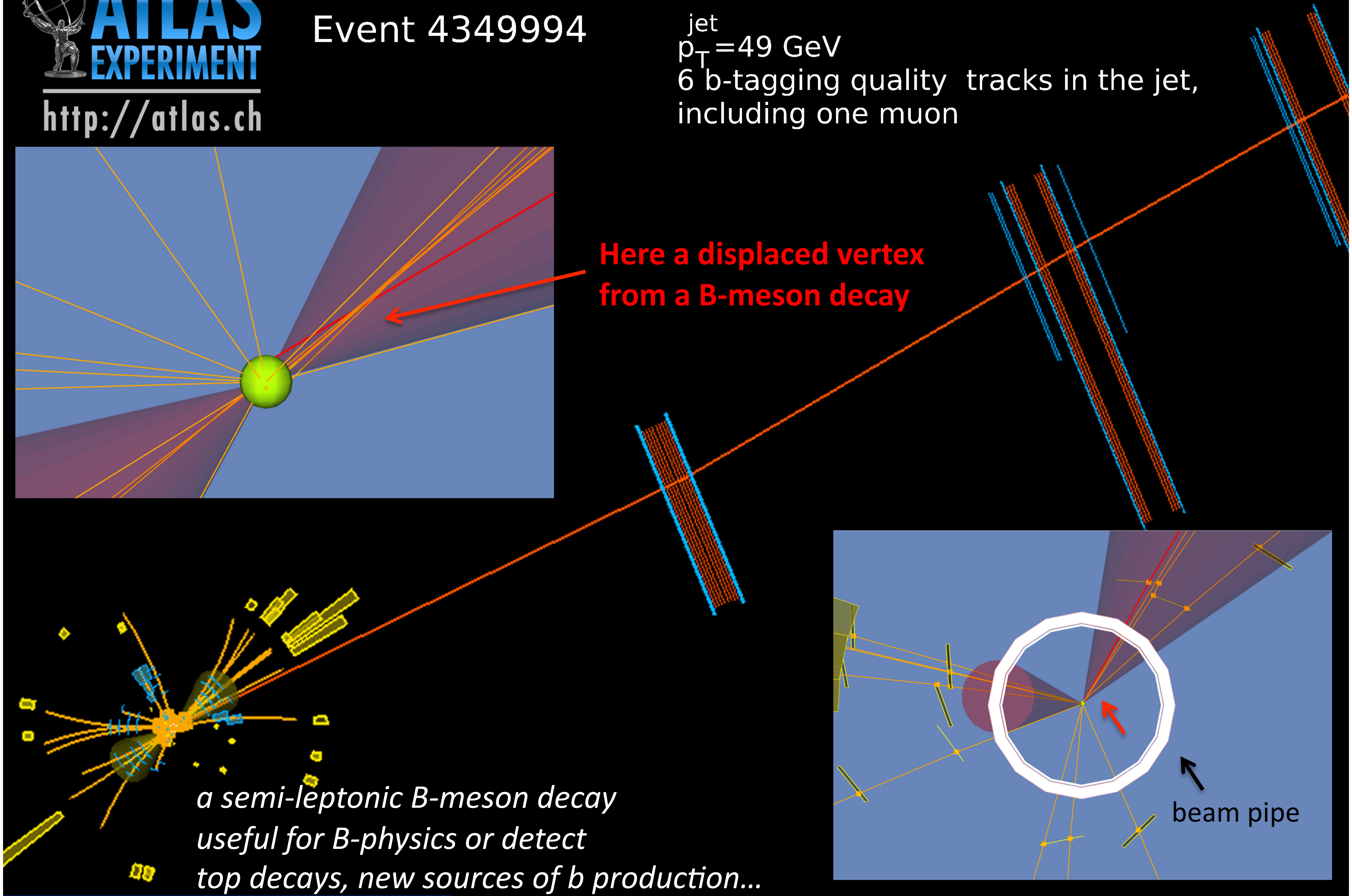
**One of These is the p-p interaction of interest**

ATLAS EXPERIMENT
http://atlas.ch

Run 152409
Event 4349994

# b-tagged jet in 7 TeV collisions

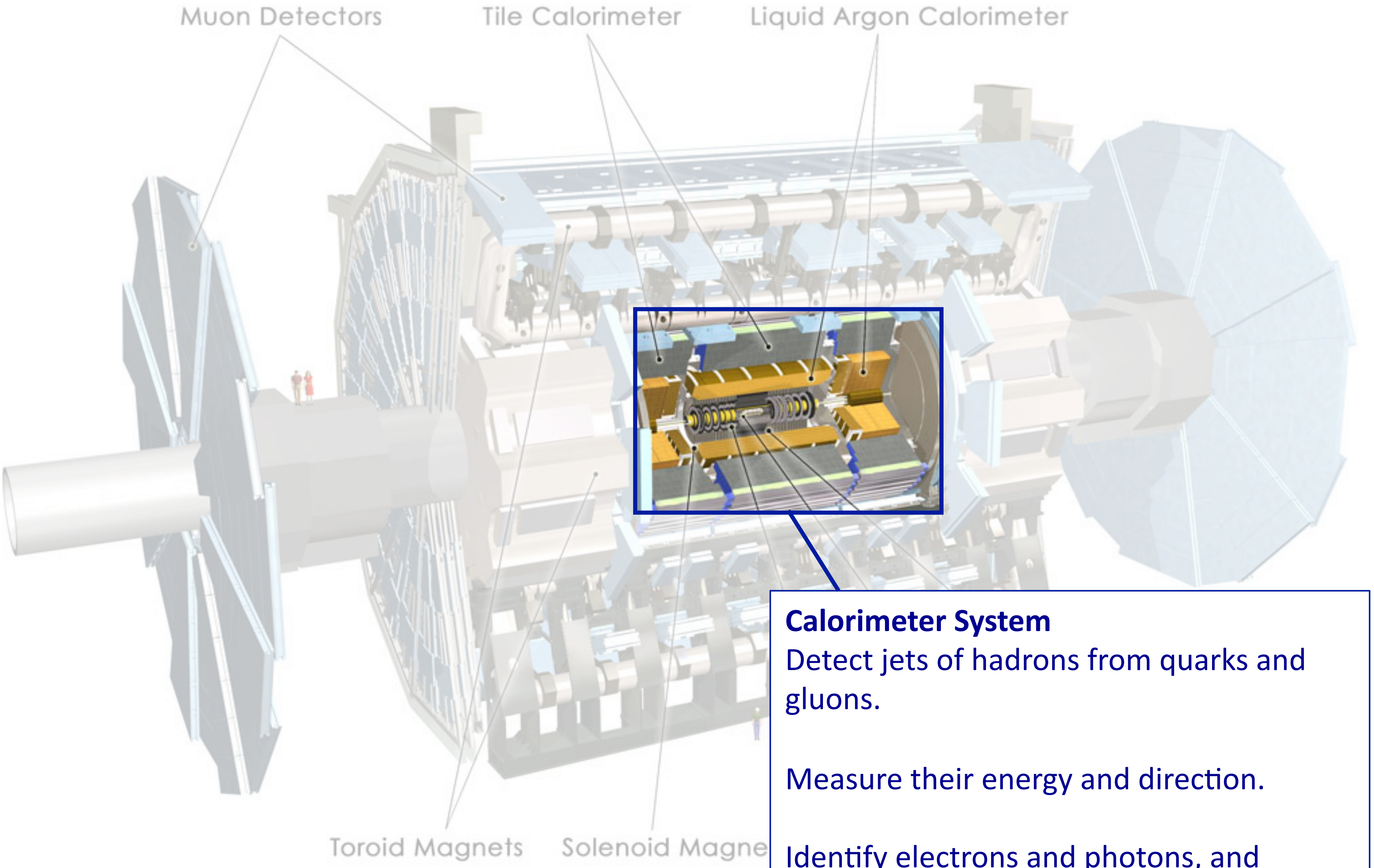
$p_T^{jet}$=49 GeV
6 b-tagging quality tracks in the jet,
including one muon



**Here a displaced vertex from a B-meson decay**

*a semi-leptonic B-meson decay*
*useful for B-physics or detect*
*top decays, new sources of b production…*

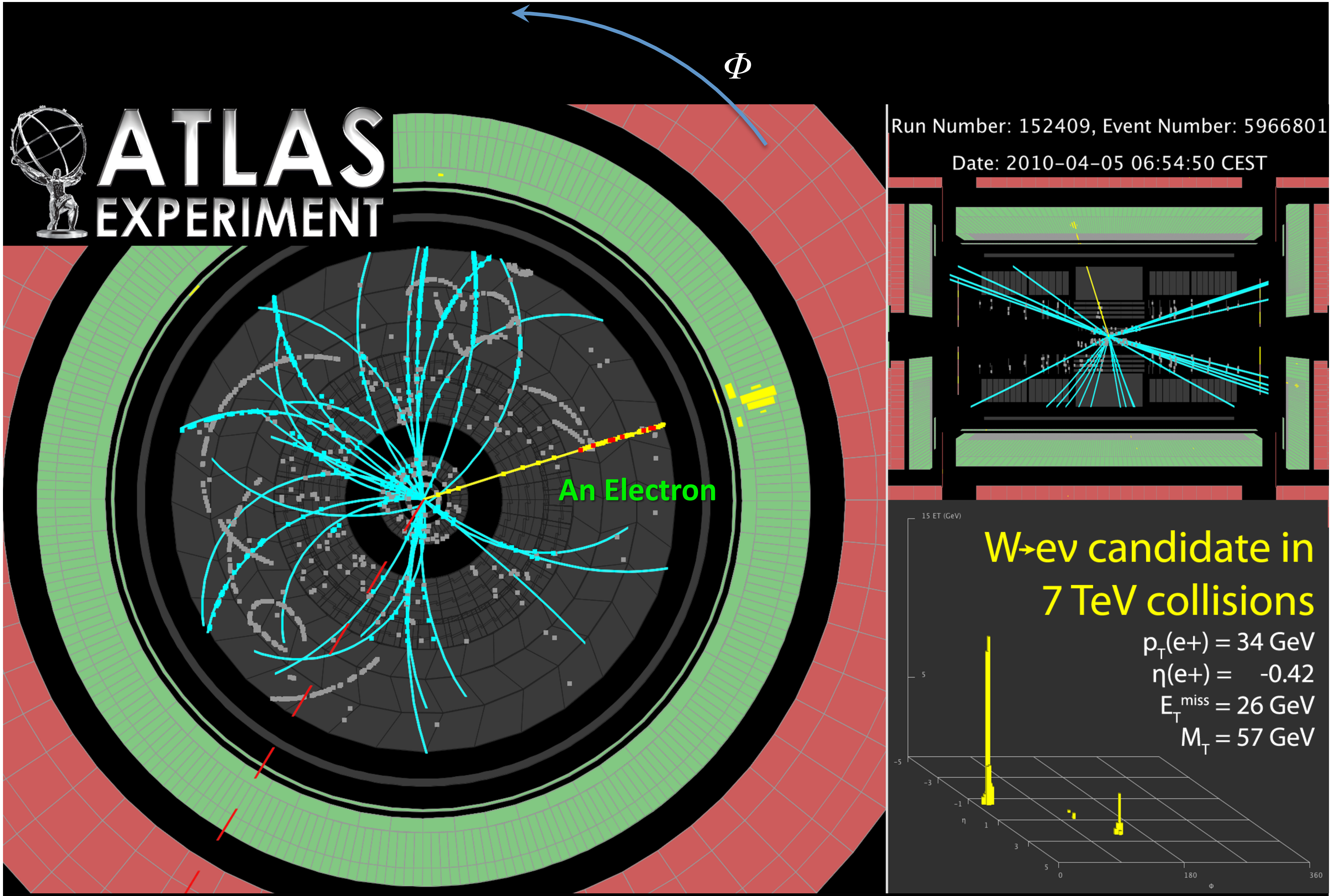
# Experimental Observables for Supersymmetry Searches with ATLAS



**Calorimeter System**
Detect jets of hadrons from quarks and gluons.

Measure their energy and direction.

Identify electrons and photons, and measure their 4-vectors.



W→eν candidate in 7 TeV collisions

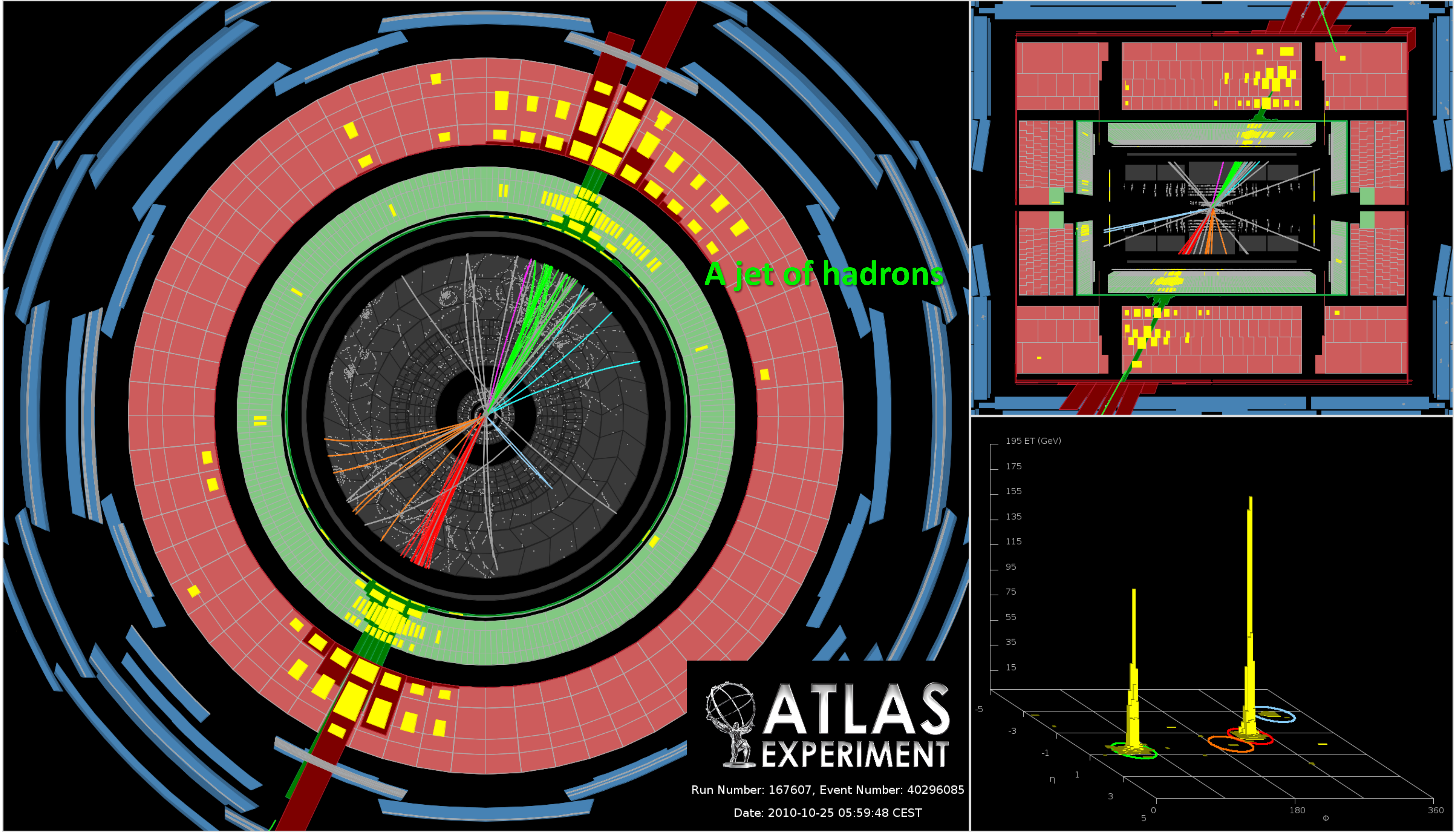
$p_T(e+) = 34$ GeV

$\eta(e+) = -0.42$

$E_T^{miss} = 26$ GeV

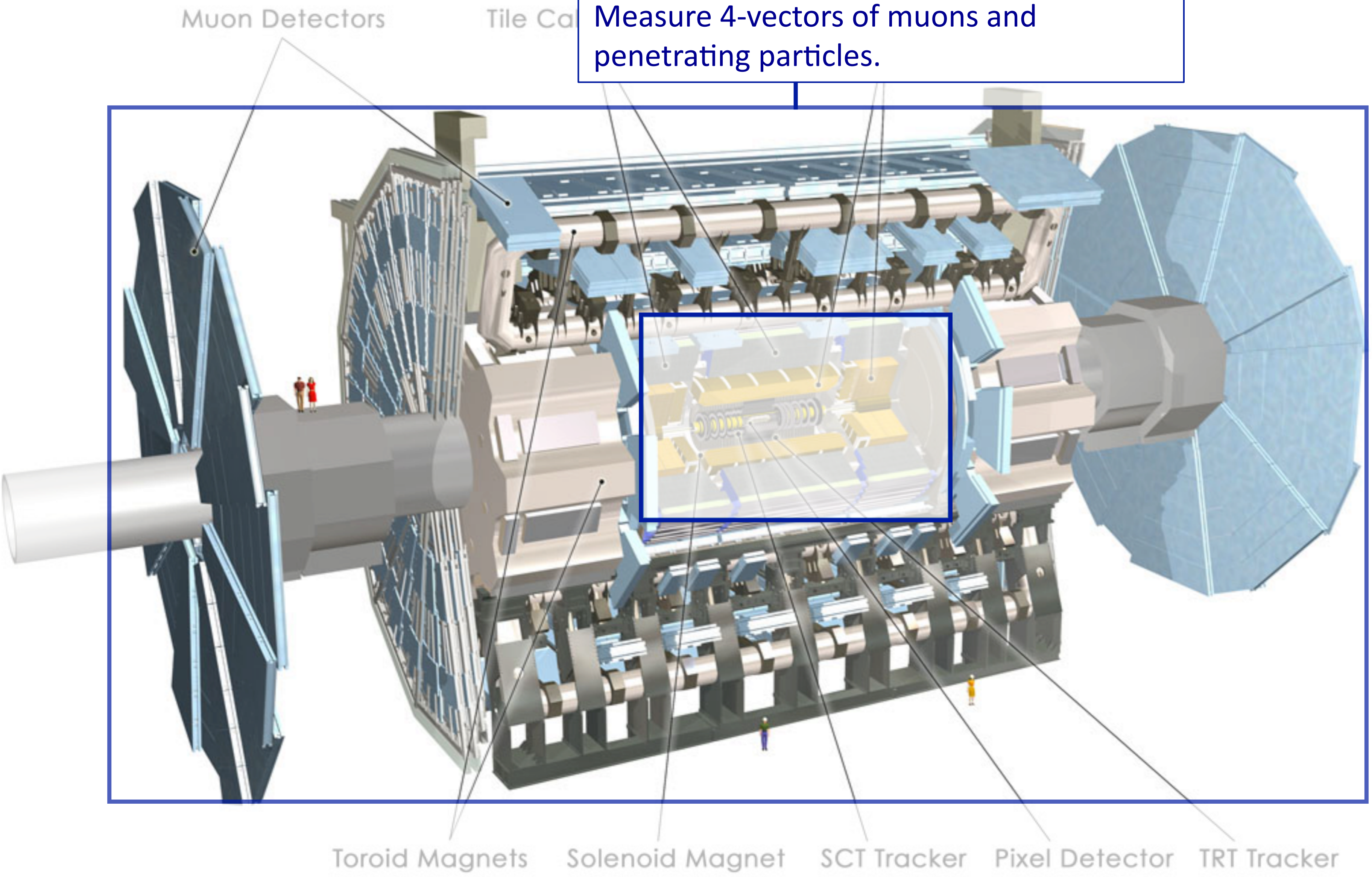
$M_T = 57$ GeV

*Narrow isolated energy deposit in the EM calorimeter+track with $E_T^{miss}$ =26 GeV*

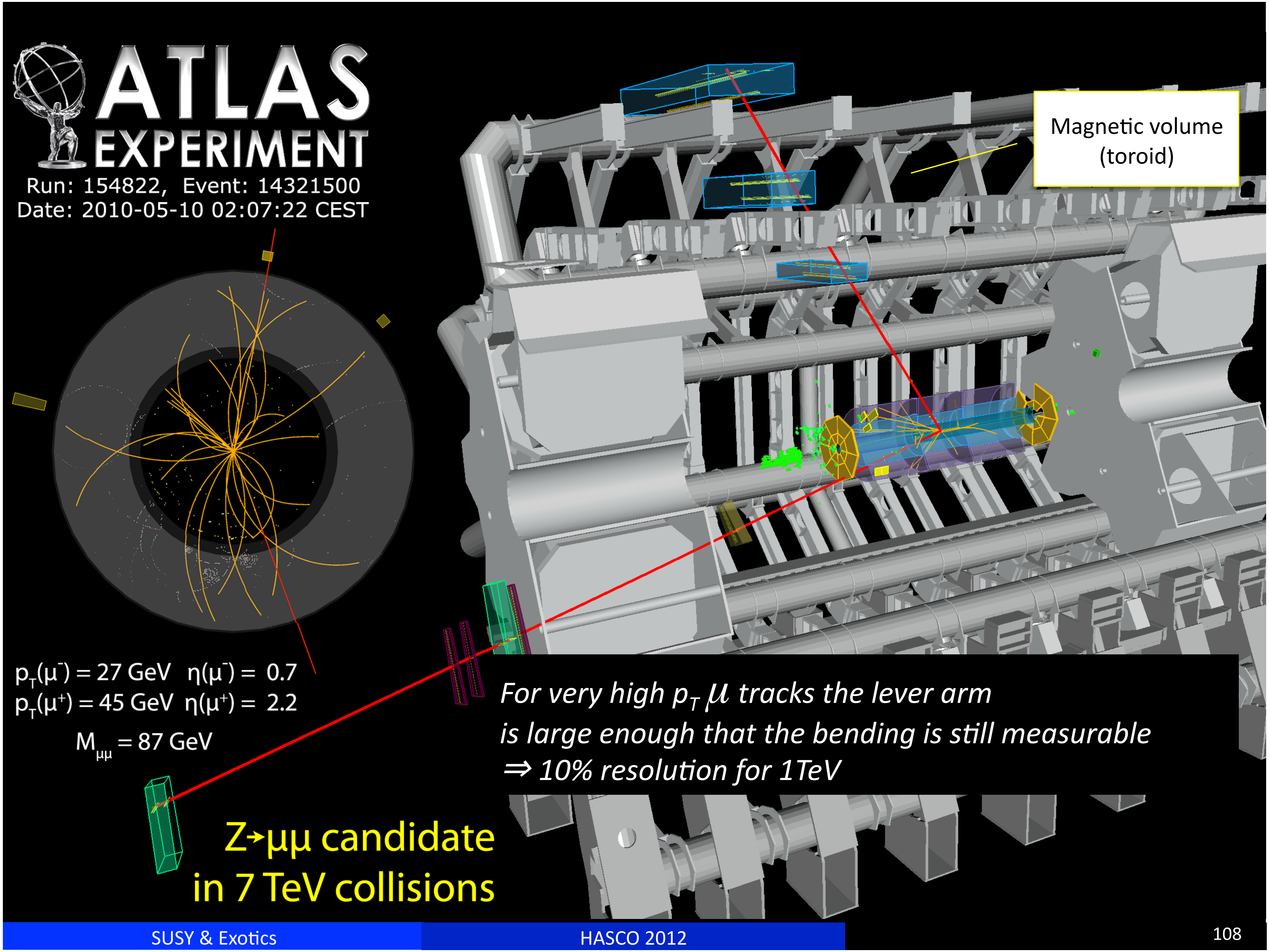


*Highest mass dijet event in 2010, di-jet invariant mass 3.1 TeV,* $E_T^{miss}$ *46 GeV*

# Experimental Observables for Supersymmetry Searches with ATLAS



**Muon System**
Measure 4-vectors of muons and penetrating particles.



Magnetic volume
(toroid)

$p_T(\mu^-) = 27$ GeV $\eta(\mu^-) = 0.7$
$p_T(\mu^+) = 45$ GeV $\eta(\mu^+) = 2.2$
$M_{\mu\mu} = 87$ GeV

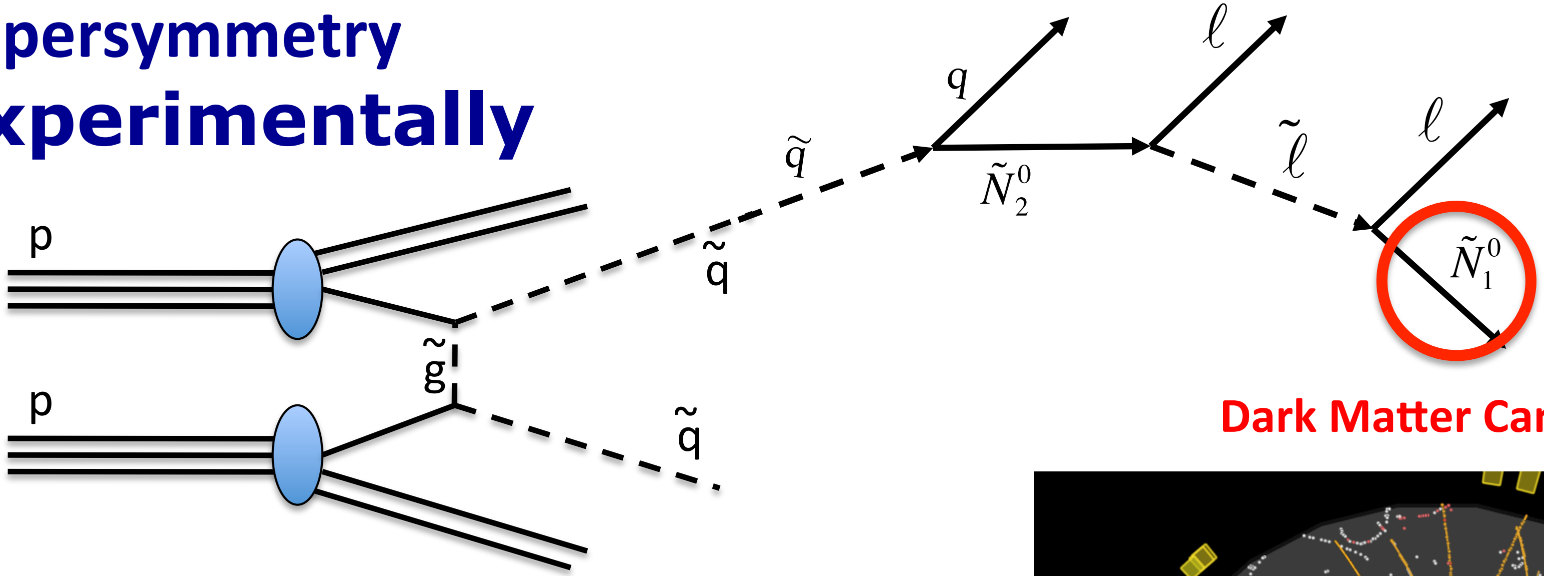
*For very high $p_T$ $\mu$ tracks the lever arm*
*is large enough that the bending is still measurable*
*⇒ 10% resolution for 1TeV*

Z→μμ candidate
in 7 TeV collisions

# Additional SUSY Specific

# Observables

# Supersymmetry
# Experimentally

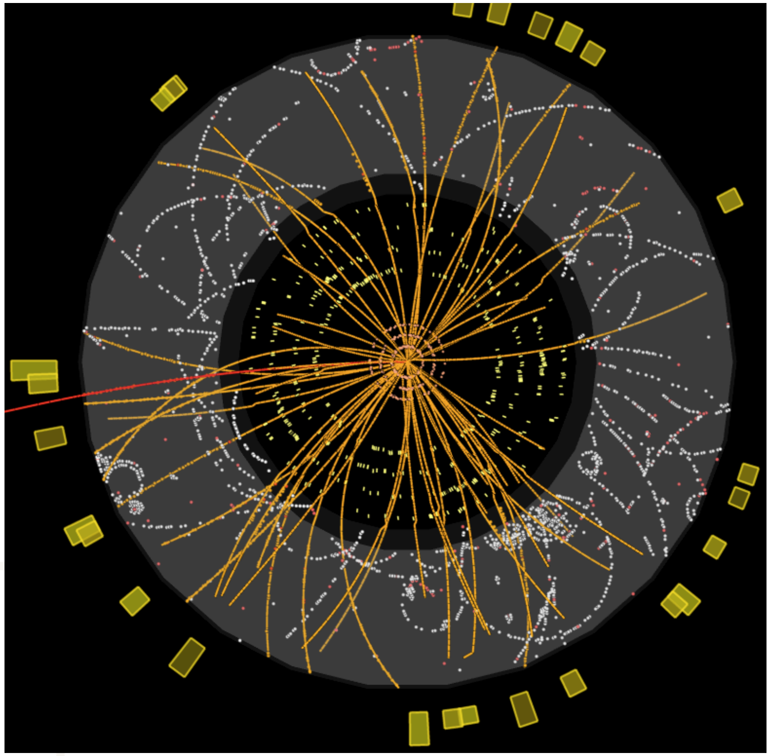


**Dark Matter Candidate**

***Long decay chains*** with many final particles.

***The LSP leaves the detector without trace***
⇒ Missing Energy!

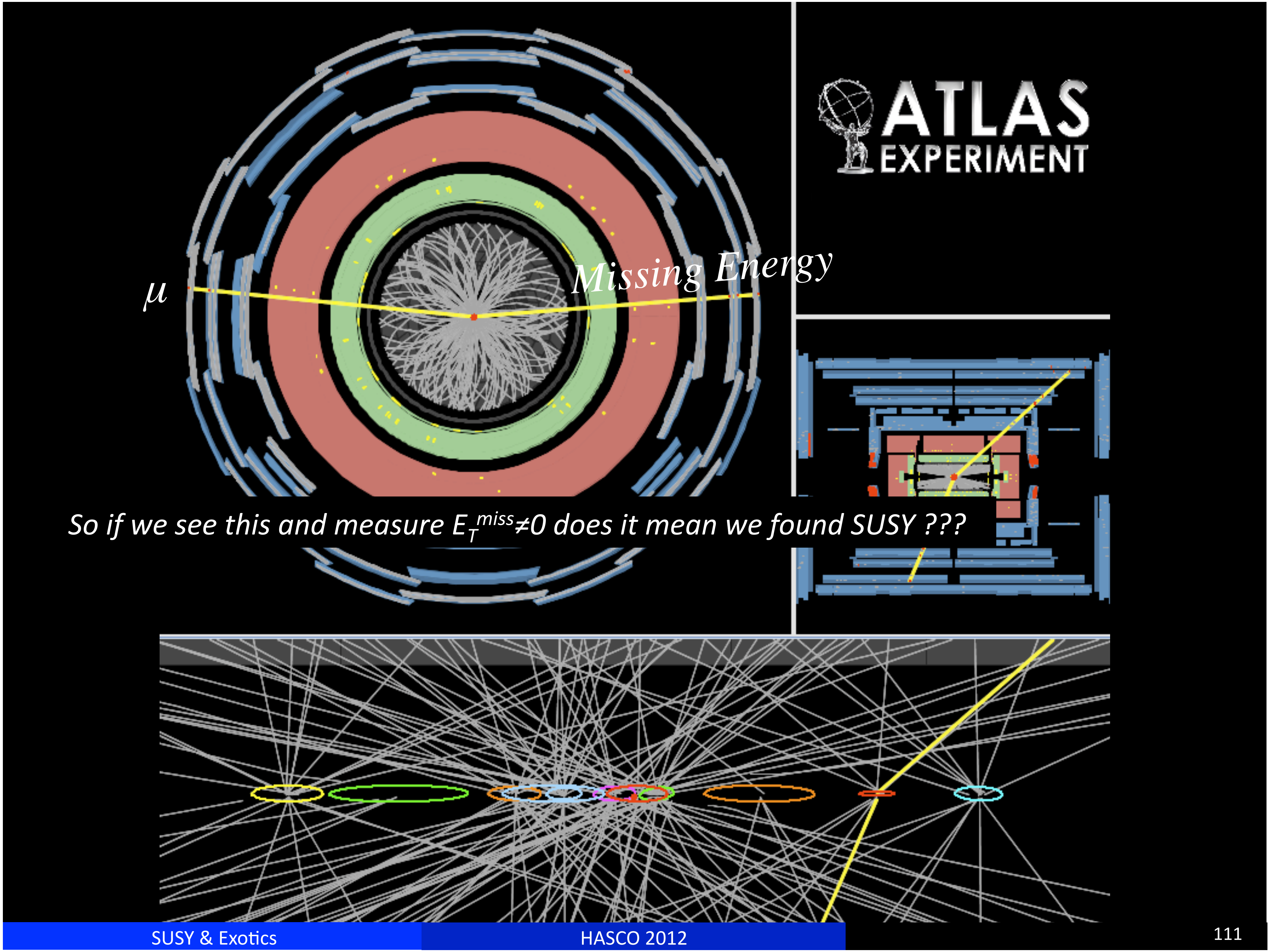
Collisions with SUSY particles mimick non-conservation of momentum.



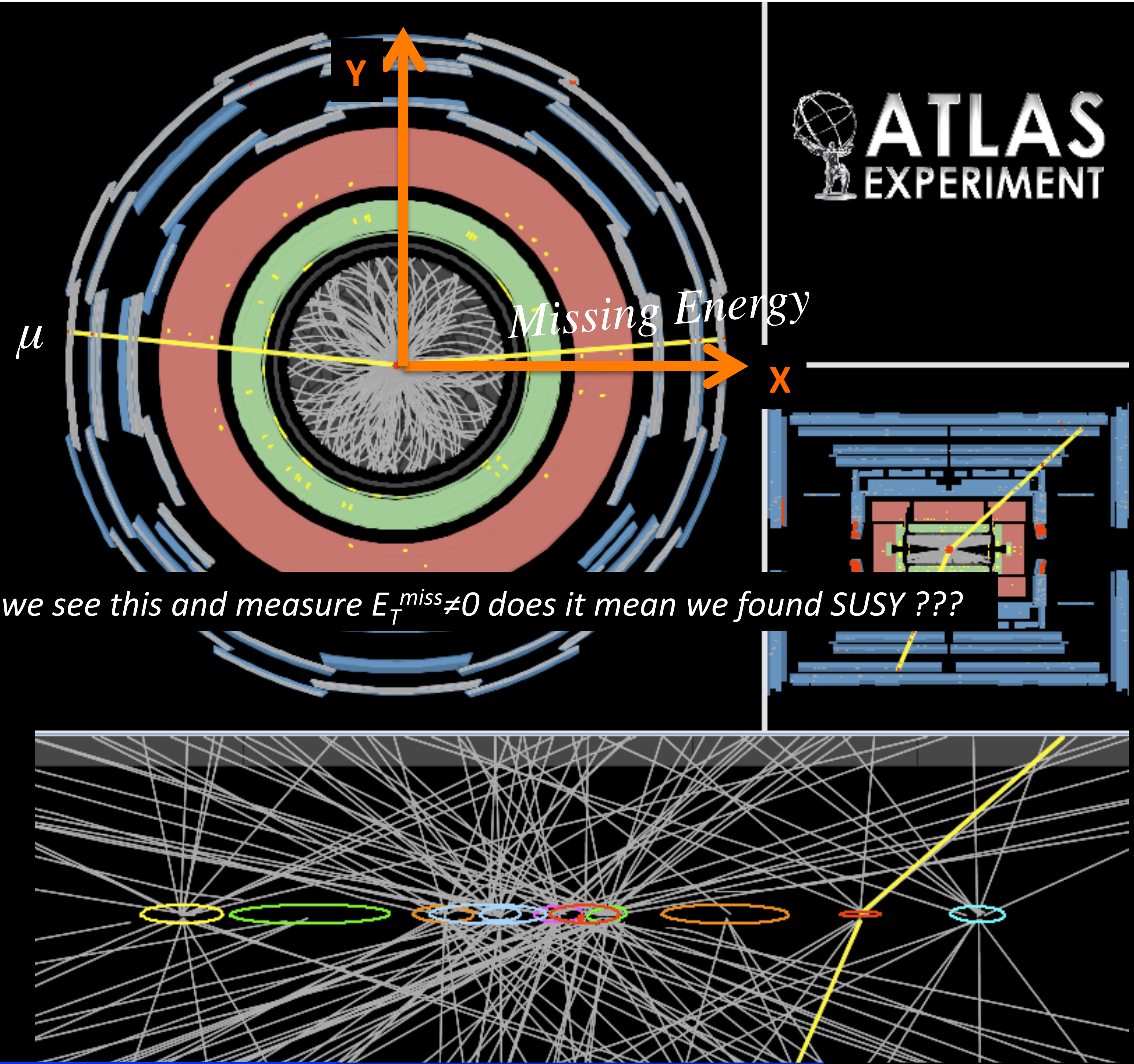
***Missing Transverse Energy***

$E_T^{miss}$ = |Vector sum of all momenta|

Should be zero within the experimental resolutions.
Both SUSY & neutrinos can give rise to high $E_T^{miss}$



*So if we see this and measure* $E_T^{miss} \neq 0$ *does it mean we found SUSY ???*



*So if we see this and measure $E_T^{miss} \neq 0$ does it mean we found SUSY ???*

# Missing Transverse Energy

$$0 = \sum_{k \in particles} p_x^k$$

*conservation of moment in x and y directions*

$$0 = \sum_{k \in visible} p_x^k + \sum_{k \in invisible} p_x^k$$

*split into measurable and non-measurable parts*

$$E_x^{miss} \equiv \sum_{k \in invisible} p_x^k$$

*define **the missing energy** as the momentum sum the experiment cannot measure*

$$E_{x,y}^{miss} = -\sum_{k \in visible} p_{x,y}^k$$

$$E_T^{miss} = \sqrt{(E_x^{miss})^2 + (E_y^{miss})^2}$$

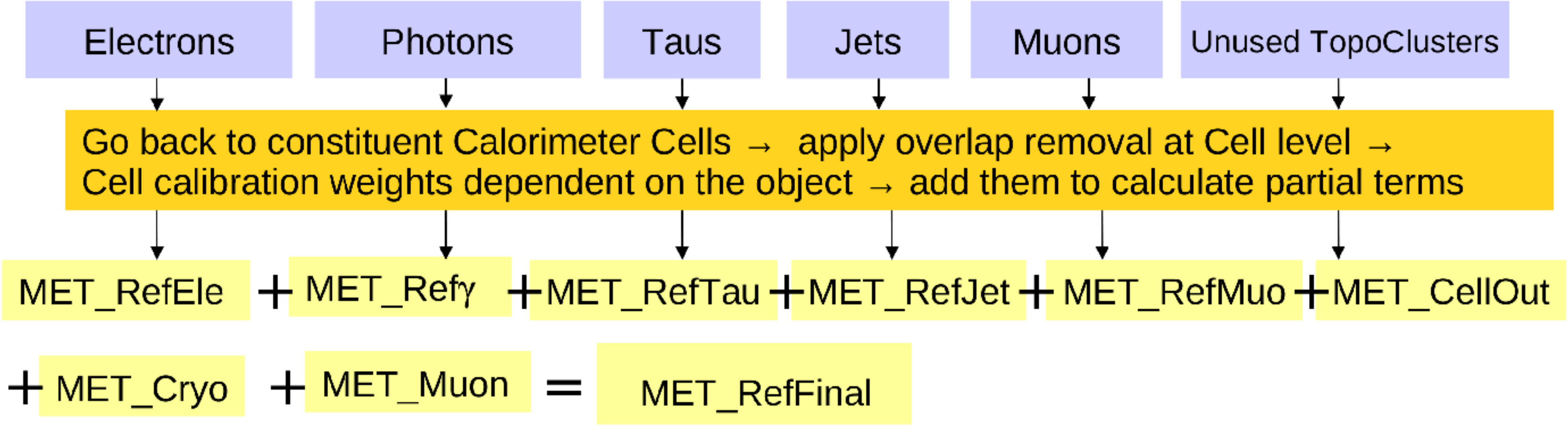
There are as many ways to compute $E_T^{miss}$ as there are ways to compute the sum of momenta of visible particles.

Any detector resolution effect in the measured momenta propagates to the missing energy resolution.

# Missing Transverse Energy

$$-E_{x,y}^{miss} = \sum_{k \in visible} p_{x,y}^{k}$$

$$= \sum_{k \in electrons} p_{x,y}^{k} + \sum_{k \in photons} p_{x,y}^{k} + \sum_{k \in taus} p_{x,y}^{k} + \sum_{k \in jets} p_{x,y}^{k} + \sum_{k \in muons} p_{x,y}^{k} + \sum_{k \in unused\ \ clusters} p_{x,y}^{k}$$



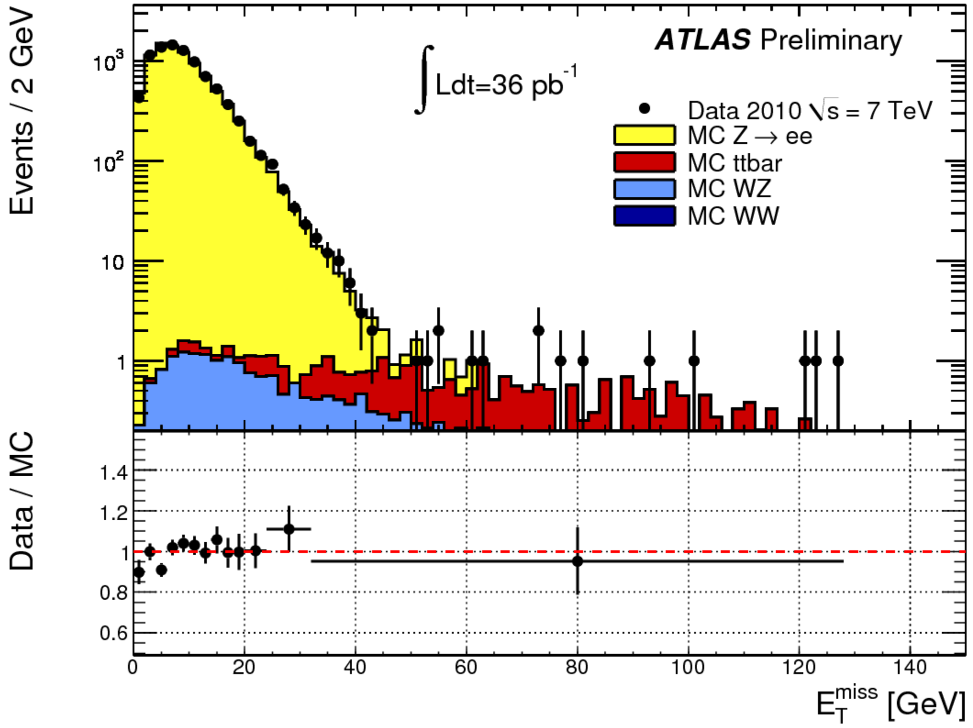
Electrons | Photons | Taus | Jets | Muons | Unused TopoClusters

Go back to constituent Calorimeter Cells → apply overlap removal at Cell level →
Cell calibration weights dependent on the object → add them to calculate partial terms

MET_RefEle + MET_Refγ + MET_RefTau + MET_RefJet + MET_RefMuo + MET_CellOut

+ MET_Cryo + MET_Muon = MET_RefFinal

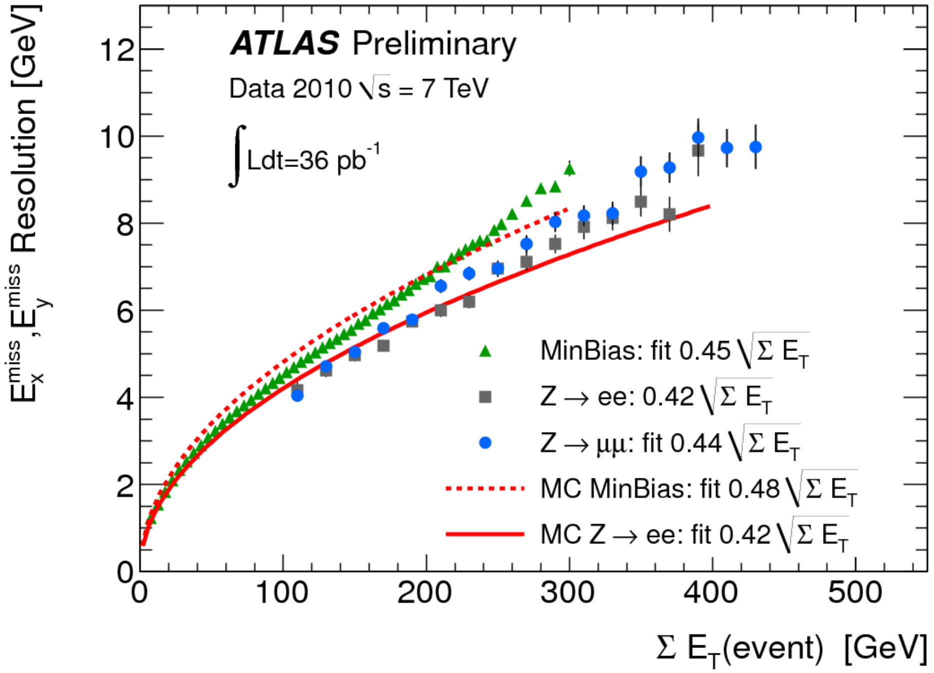
A non zero value of $E_T^{miss}$ must be significantly above resolution effects to indicate a real invisible particles such as a high momentum neutrino or a SUSY Neutralino



*$E_T^{miss}$ in Z→ee*

*Verify that $E_T^{miss}$*
*is well understood in data …*

*$E_{x,y}^{miss}$ resolution in Z→ee*



# Effective Mass ($M_{eff}$)

Originally introduced in the 1990's

Related to the mass of the SUSY particle  produced, eg. gluino or squark.

It is the scalar sum of the 4 leading jet $p_T$  and $E_T^{miss}$!

$$\boxed{M_{\mathrm{eff}} = E_{\mathrm{T}}^{\mathrm{miss}} + p_{\mathrm{T},\,1} + p_{\mathrm{T},\,2} + p_{\mathrm{T},\,3} + p_{\mathrm{T},\,4}}$$

Standard model processes have generally

much lower values of $M_{eff}$.

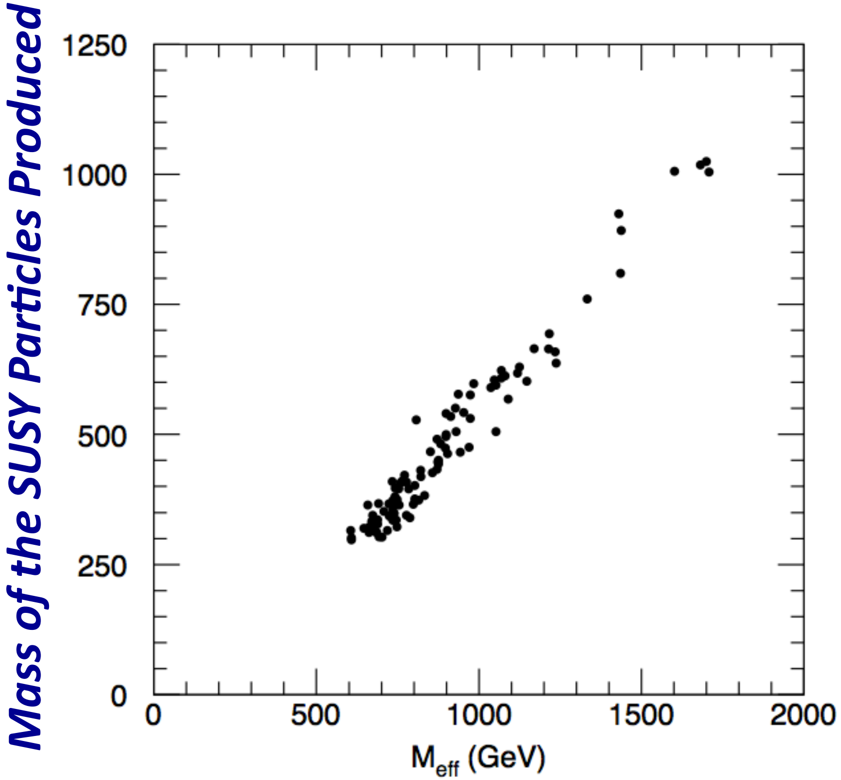
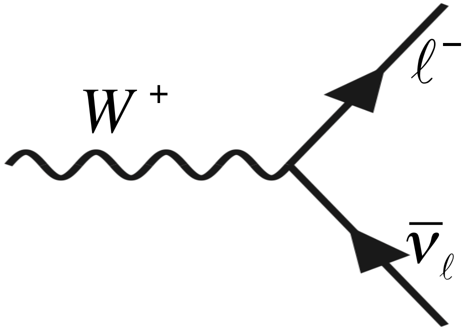


**Figure 20-5** Peak of $M_{\mathrm{eff}}$ distribution as a function of. $M_{\mathrm{SUSY}} = \min(M_{\tilde{g}}, M_{\tilde{u}_R})$ for various models.

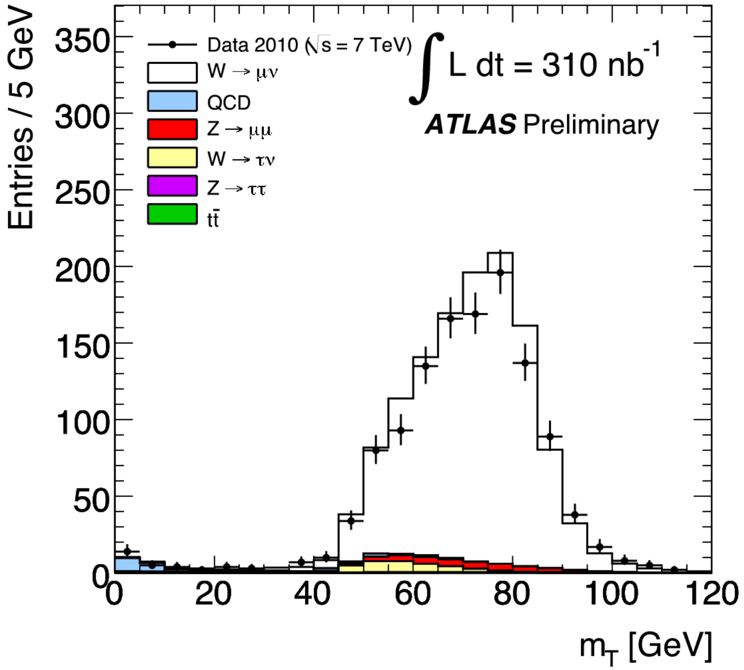
# $m_T$ and $M_{T2}$

The transverse mass variable $m_T$ was introduced

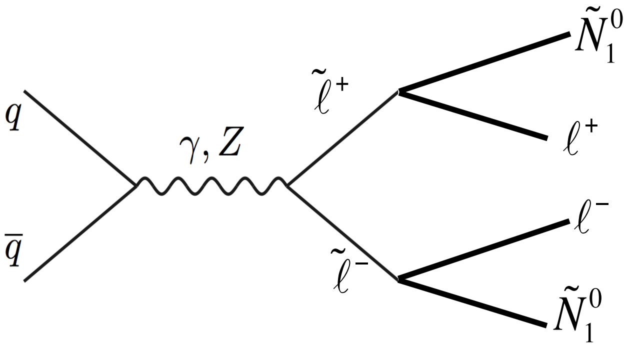
in earlier lectures.

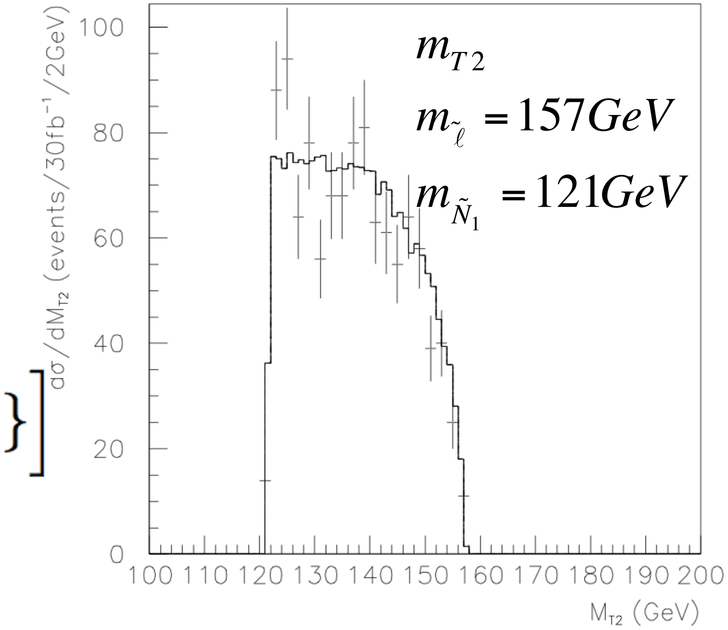


$$\boxed{\begin{aligned} m_T &= p_T^\ell p_T^\nu \quad (1-\cos\phi_{\ell\nu}) \\ &= p_T^\ell E_T^{miss}(1-\cos\phi_{\ell,E_T^{miss}}) \end{aligned}}$$



Now consider the slepton production and decay, there are now **two invisible particles**





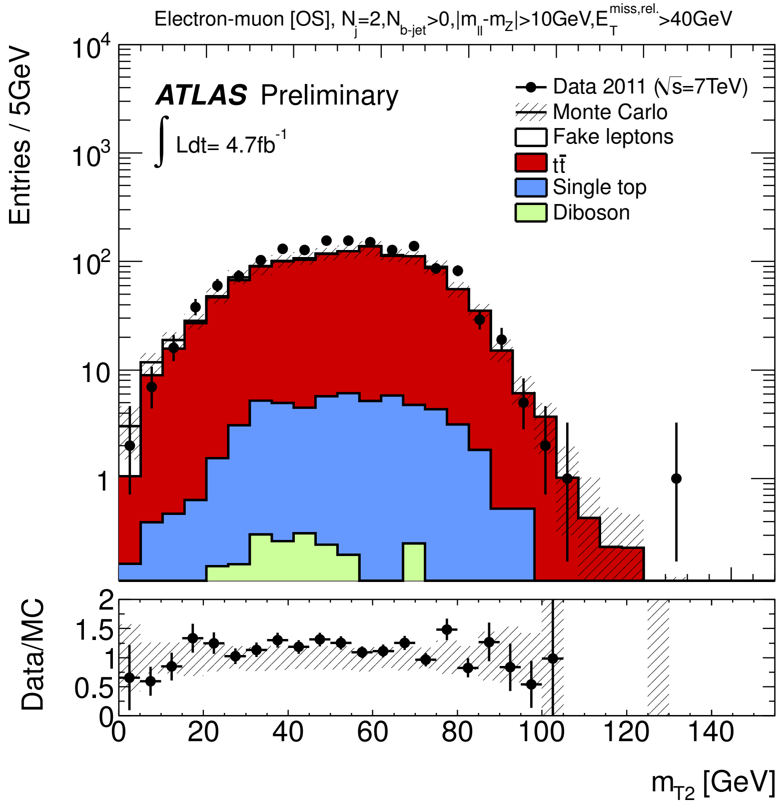
$$M_{T2}^2 \equiv \min_{\not{p}_1 + \not{p}_2 = \not{p}_T} \left[ \max\left\{ m_T^2(\mathbf{p}_{Tl^-}, \not{p}_1), m_T^2(\mathbf{p}_{Tl^+}, \not{p}_2) \right\} \right]$$

See C.G. Lester and D.J. Summers
http://arxiv.org/abs/hep-ph/9906349v1

# Direct Slepton Search in ATLAS

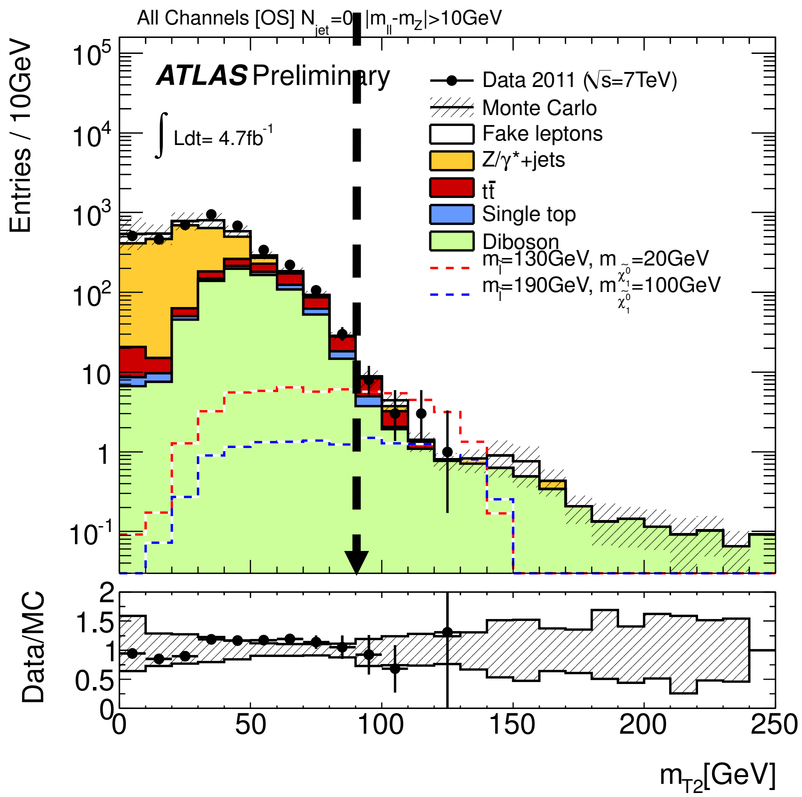
Select ATLAS collision events with $e^+e^-$ and $\mu^+\mu^-$ and exactly no jets and high $E_T^{miss}$.

Use $m_{T2} > 90$ GeV to remove the *tt, WW, WZ, ZZ* backgrounds



*In control region dominated by production of top-quark pairs*

$m_{T2} > 90$ GeV



*In the Signal Region*

**Backgrounds**

**Single and double top quark production**

remove with a veto on central jets

$Z/\gamma^*, ZW, ZZ$

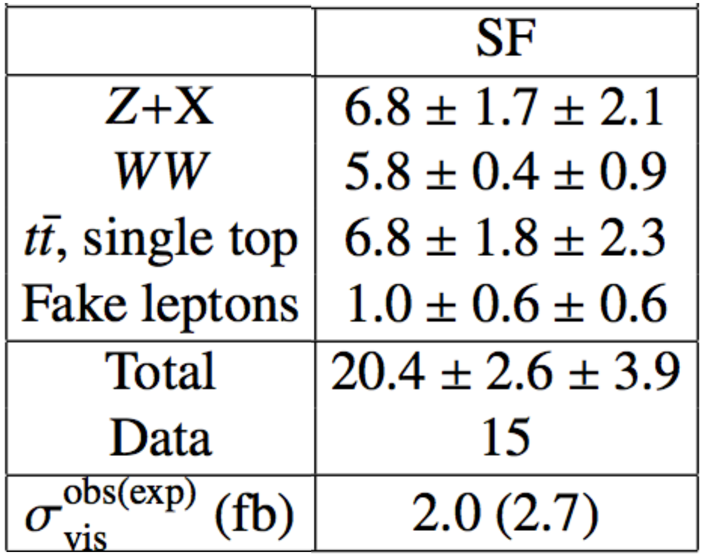
Veto on two leptons with Z mass

**WW production**

Removed with $m_{T2}$

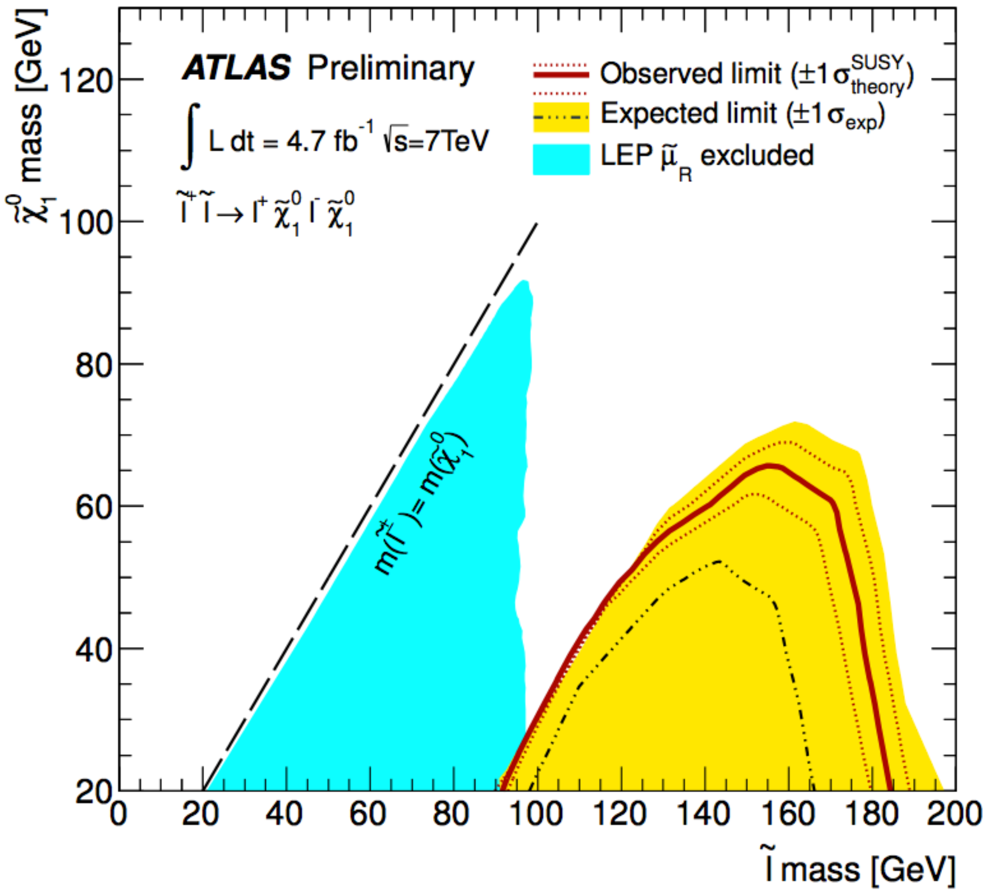
**Fake leptons**

Removed with lepton isolation



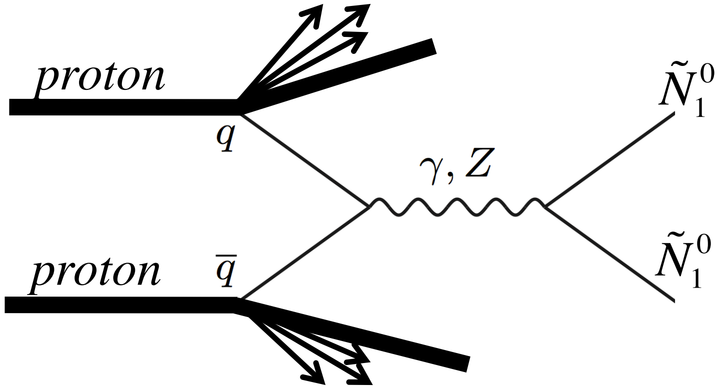
| | SF |
|---|---|
| Z+X | $6.8 \pm 1.7 \pm 2.1$ |
| $WW$ | $5.8 \pm 0.4 \pm 0.9$ |
| $t\bar{t}$, single top | $6.8 \pm 1.8 \pm 2.3$ |
| Fake leptons | $1.0 \pm 0.6 \pm 0.6$ |
| Total | $20.4 \pm 2.6 \pm 3.9$ |
| Data | 15 |
| $\sigma_{\mathrm{vis}}^{\mathrm{obs(exp)}}$ (fb) | 2.0 (2.7) |

## *Direct Slepton Limit with ATLAS*



ATLAS Collaboration
https://cdsweb.cern.ch/record/1460273/

# Mono-Jet Search

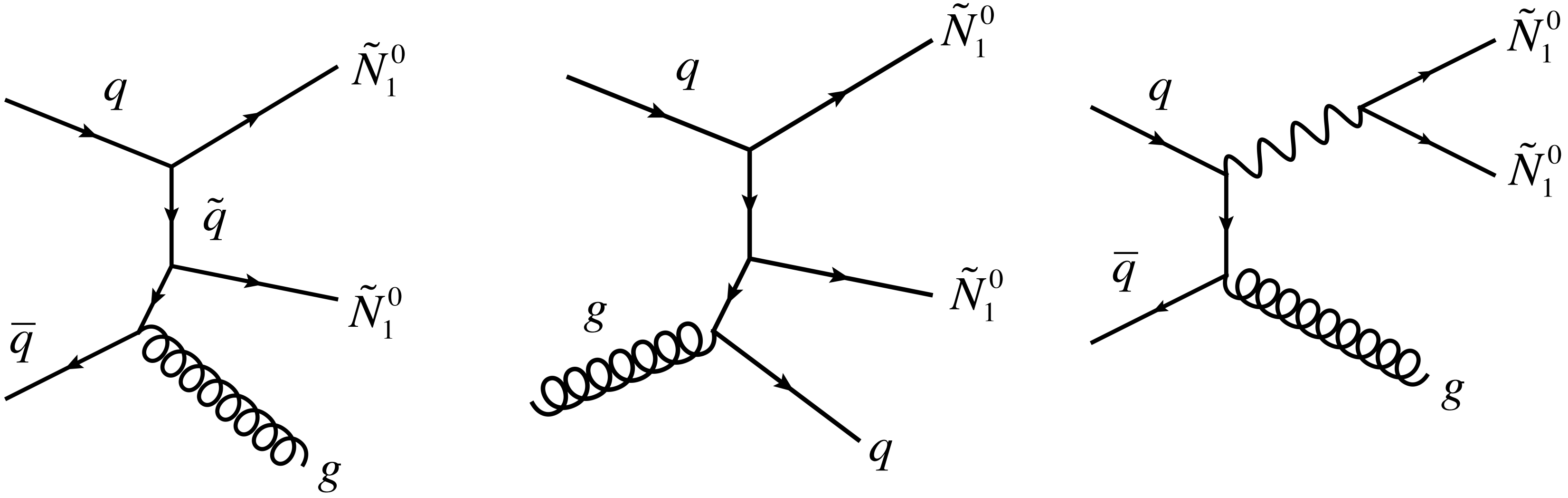


*direct production of two LSP (= Dark Matter particles)*

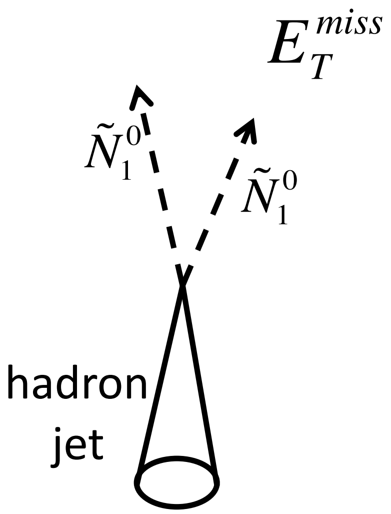
*All final particles are invisible!*

*Look instead for* $p + p \rightarrow \tilde{N}_1^0 + \tilde{N}_1^0 + 1\,jet$

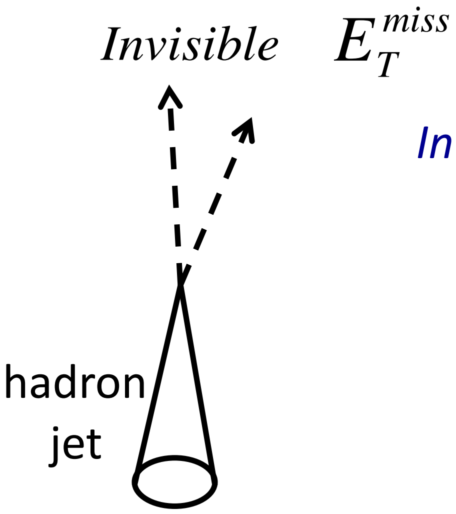
*has a lower cross section, especially if the jet* $p_T$ *is high but makes this final state now detectable*



# Mono-Jet Search



$$p + p \rightarrow \tilde{N}_1^0 + \tilde{N}_1^0 + 1\,jet$$



$$p + p \rightarrow X + 1\,jet$$
$$\rightarrow Invisible + 1\,jet$$

*In principle can look for all sorts of invisible particles in this way.*

*The mono-jet is a "tag" that there was something energetic going in the other direction*

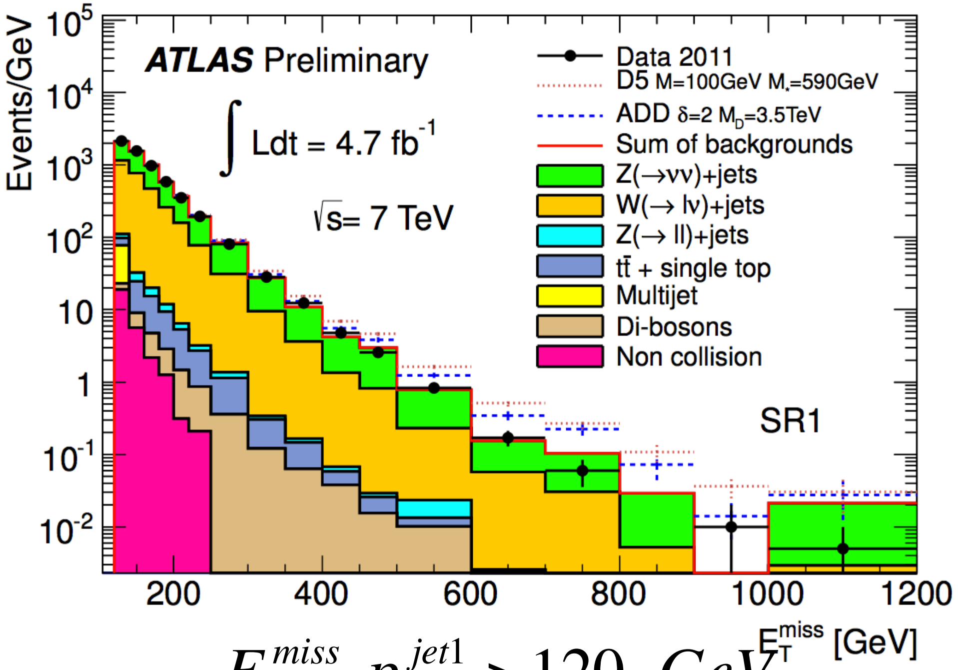
The jet and the $E^{miss}_T$ are opposite to each other and balanced

| Signal regions | SR1 | SR2 | SR3 | SR4 |
|---|---|---|---|---|
| Common requirements | Data quality + trigger + vertex + jet quality + $\lvert\eta^{\rm jet1}\rvert < 2.0$ + $\lvert\Delta\phi(\mathbf{p}_{\rm T}^{\rm miss}, \mathbf{p}_{\rm T}^{\rm jet2})\rvert > 0.5$ + $N_{\rm jets} \leq 2$ + lepton veto | | | |
| $E_{\rm T}^{\rm miss}$, $p_{\rm T}^{\rm jet1}$ > | 120 GeV | 220 GeV | 350 GeV | 500 GeV |

**Other Important selection:**
0-lepton

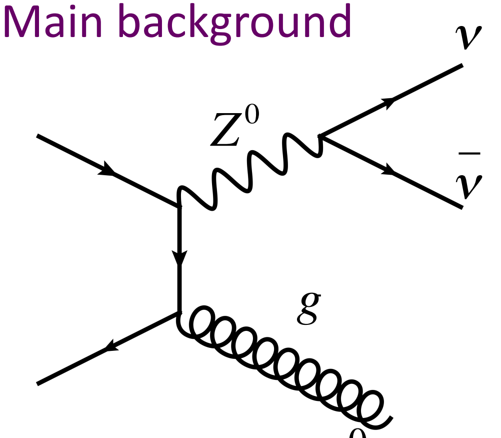
ATLAS Collaboration "Search for Dark Matter candidates and large extra dimensions …"
https://cdsweb.cern.ch/record/1460396

# Mono-Jet Search



$$E_T^{miss}, p_T^{jet1} > 120\ \ GeV$$

Main background

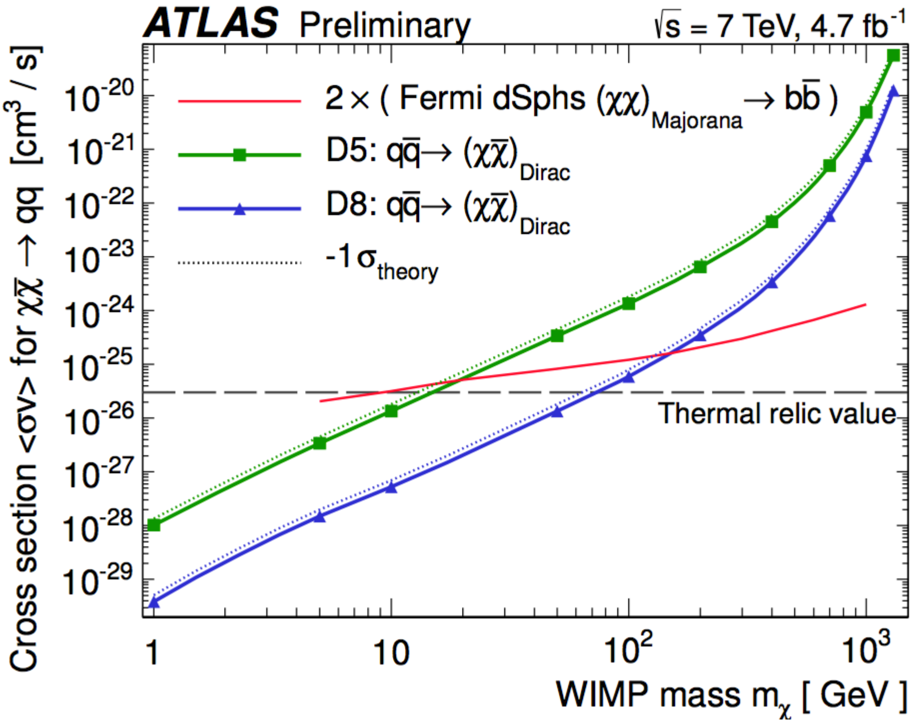


$$p + p \rightarrow Z^0 + 1\,jet \rightarrow \nu + \nu + 1\,jet$$

**Remember?**

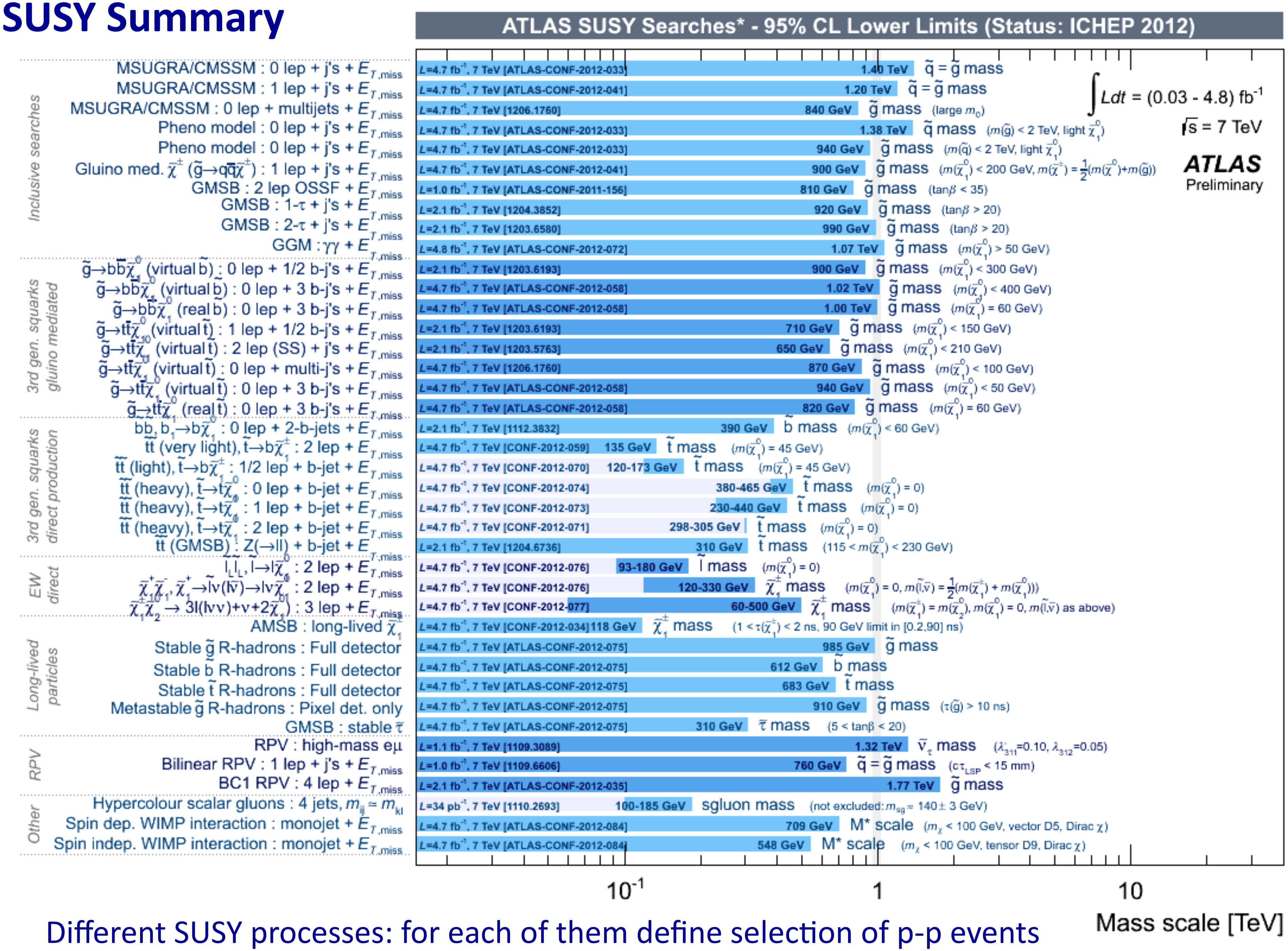
Relic dark matter density

$$\Omega_{\rm DM} \sim \langle \sigma_A v \rangle^{-1}$$



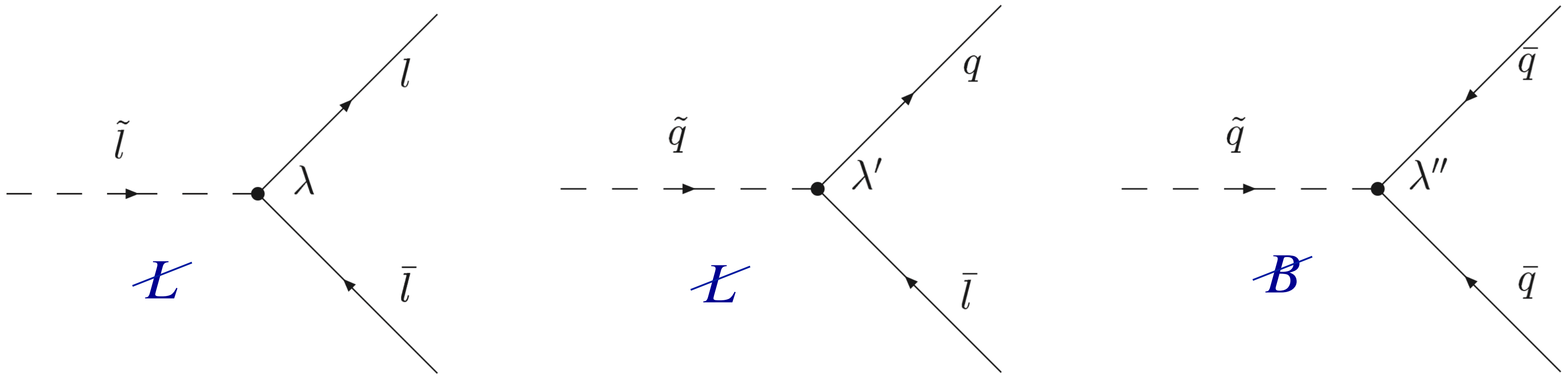
Can put indirect limits on the **production of dark matter particles** and **their annihilation** cross section

# SUSY Summary



Different SUSY processes: for each of them define selection of p-p events

# R-Parity Violating Supersymmetry - RPV (Reminder)



$$p + p \to X \to \tilde{N}_1^0 + \tilde{N}_1^0 \to (qql) + (qql)$$
$$\to (llv) + (llv)$$
$$\to (qqq) + (qqq)$$

*The LSP does not have to be* $\tilde{N}_1^0$

*If* $\lambda$ *or* $\lambda$’ *or* $\lambda$” *is small enough the Neutralino 1 is long lived.*

*$\lambda$ / $\lambda$’ / $\lambda$”*

**Lifetime**

<$10^{-13}$s

<$10^{-9}$s

<$10^{-8}$s <$10^{-7}$s

prompt
LSP decay

displaced vertex
inside tracking volume

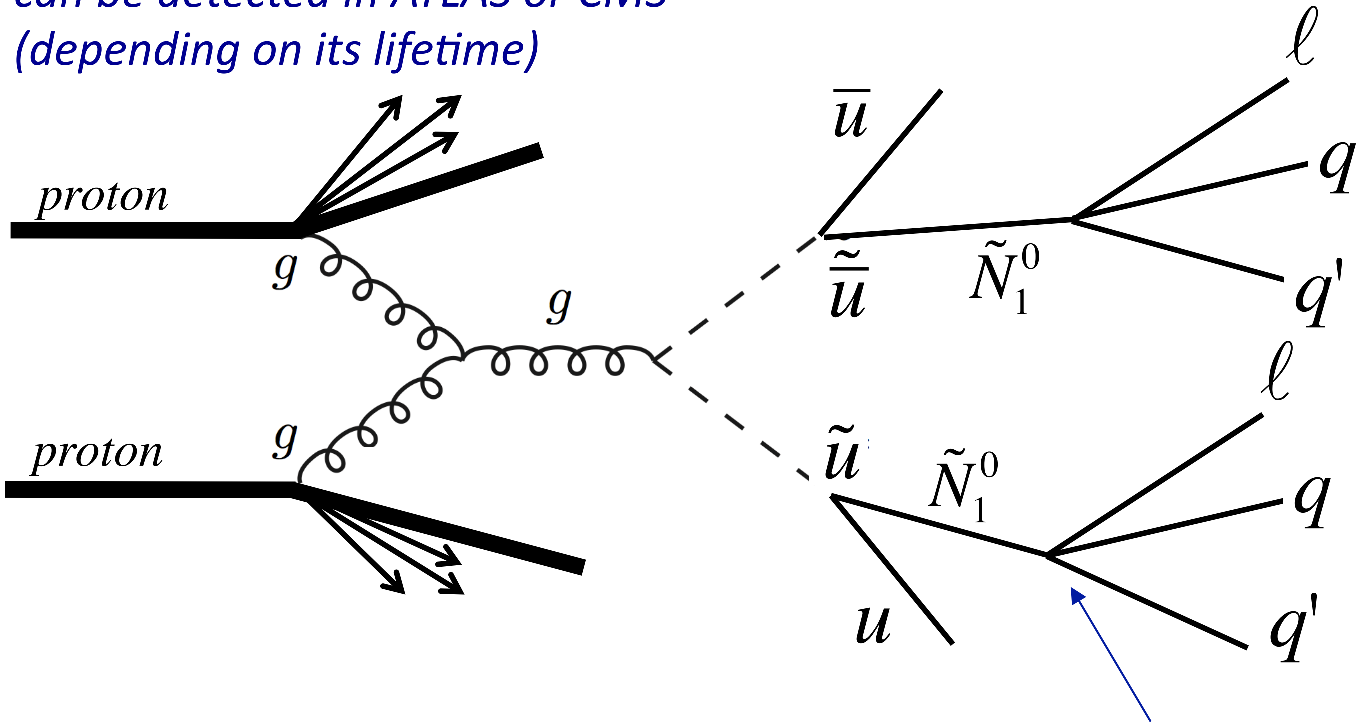
decay inside
calorimeter

decay outside ATLAS,
cannot differentiate from
R-Parity conservation

# A RPV SUSY Collision …

*$\tilde{N}_1^0$ is now unstable and its decay products can be detected in ATLAS or CMS (depending on its lifetime)*

*a possible 3-body decay of the lightest neutralino*



**Final state with**

- 6 quarks -> ~6 hadronic jets
- 2 leptons

**Depending on the lifetime of $\tilde{N}_1^0$:**

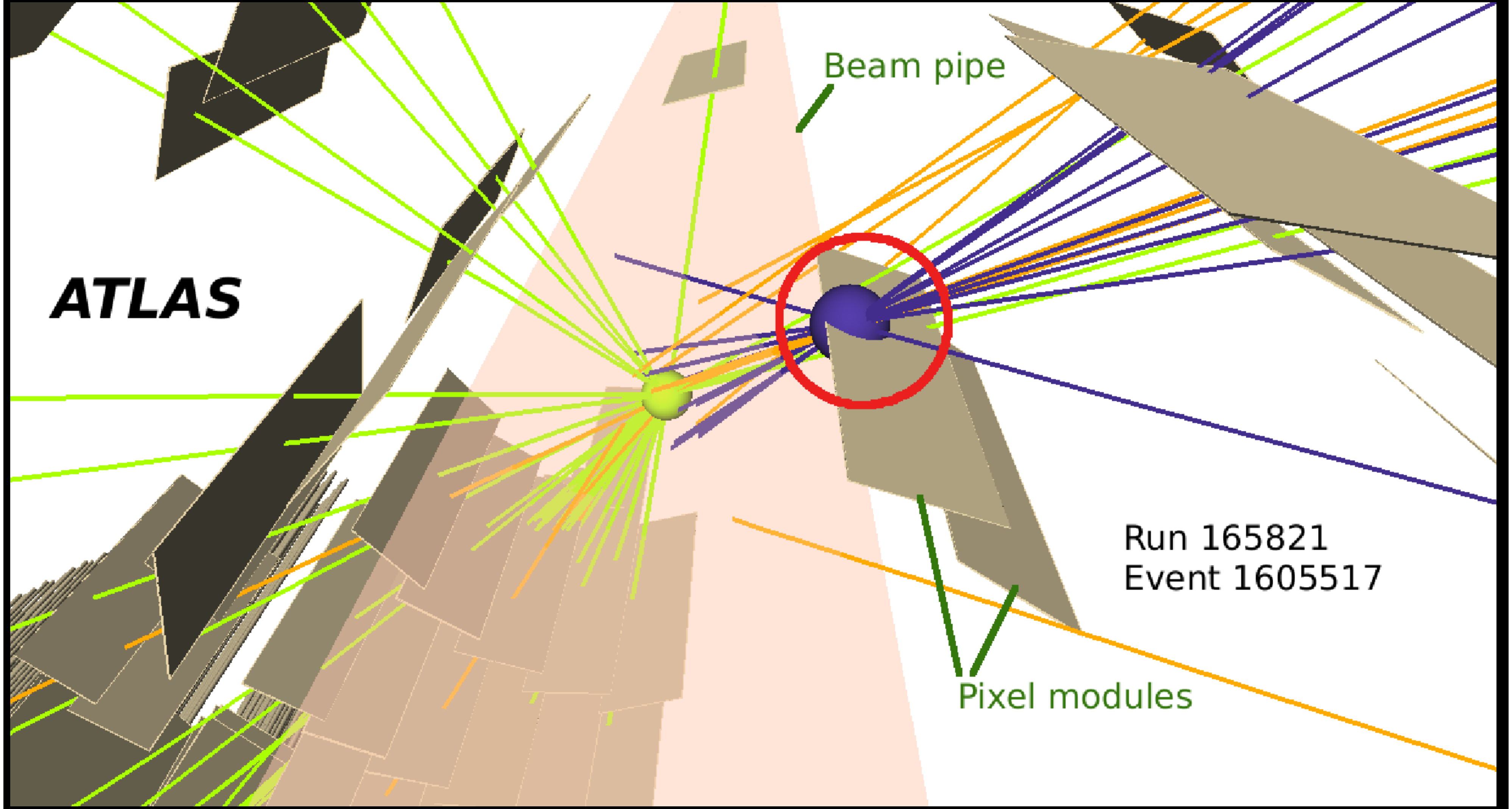
- qql comes from the primary vertex (short lifetime)
- qql comes from a displaced vertex.

a possible displaced vertex with tracks + a muon/ electron

$\mathbf{m}_{\mathbf{Vertex}}$ = Invariant mass of the tracks attached to that vertex.

$\mathbf{m}_{\mathbf{Vertex}}$ should be > 100 GeV for the signal

# Displaced vertex analysis in ATLAS



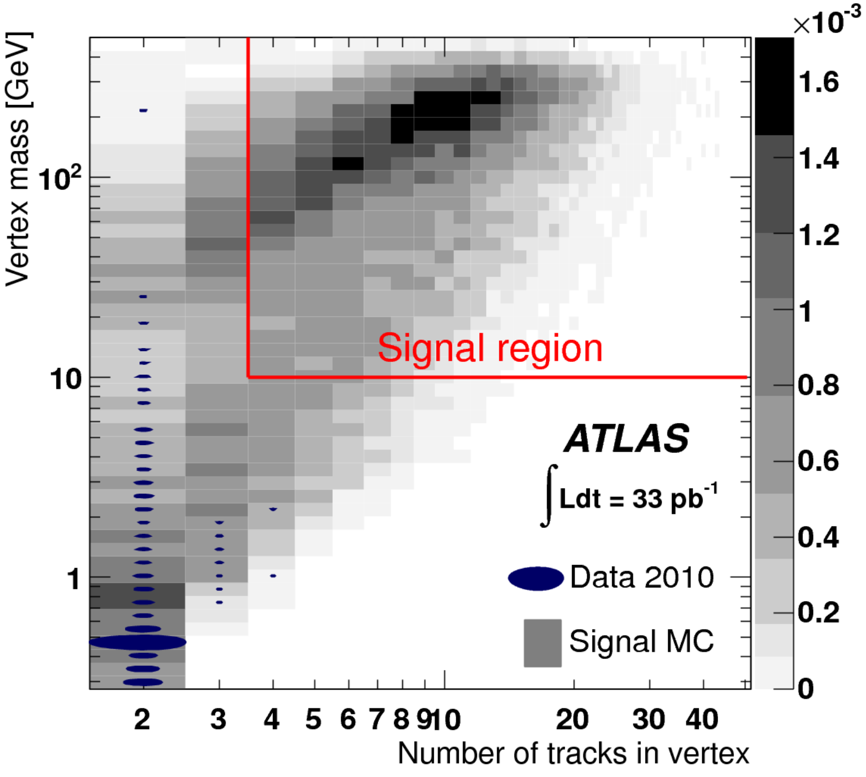
**A displaced vertex**

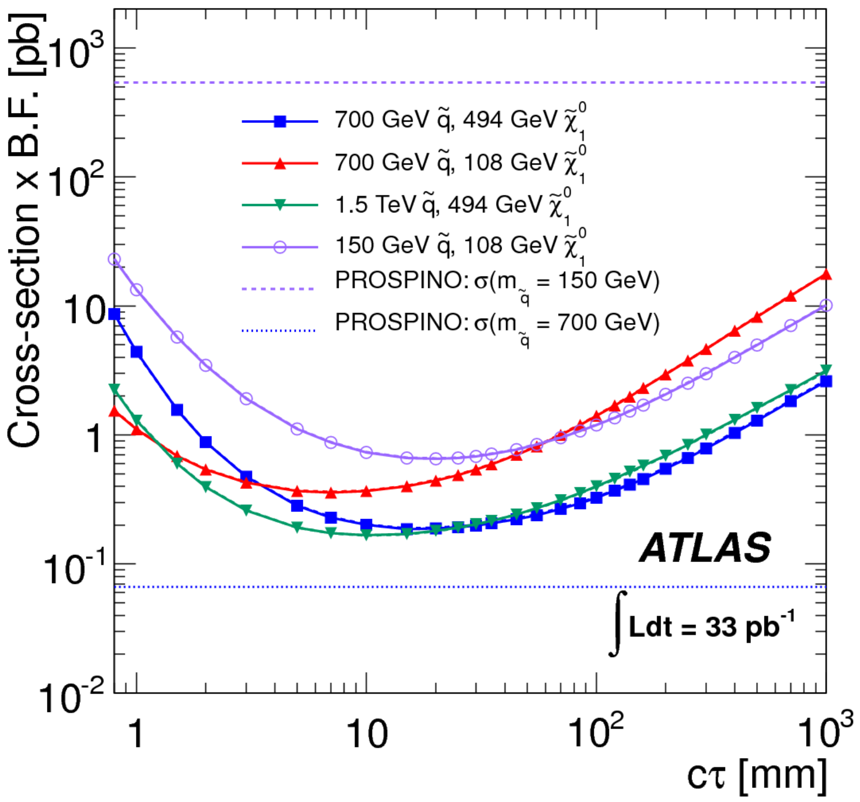
Can compute vertex mass $m_{Vertex}$

Can check whether there is a muon track in that vertex

On this display low mass hadronic interaction in pixel model: a background collision

# Displaced vertex analysis in ATLAS





The signal region is constituted
by collisions with a high mass vertex
with large number of tracks

The exclusion limit is placed in
the space of (life-time, cross section)

# Structure of the SUSY & Exotics Lectures

1. **What questions do we want to answer?** (and that are not answered by SM)
   - The Planck and GUT Scale
   - The hierarchy problem
   - Dark Matter
   - Sakharov's conditions
   - Other Problems with the Standard model

Part I

2. **Suypersymmetry**
   - Construction of supersymmetry
   - Particle spectrum
   - SUSY Particle production and decay
   - R-Parity
   - Some experimental searches

Part II

Part III

3. **Extra-dimensions and other BSM theories**
   1. Extra-dimensions
   2. Experimental signature
   3. Other BSM

Part IV

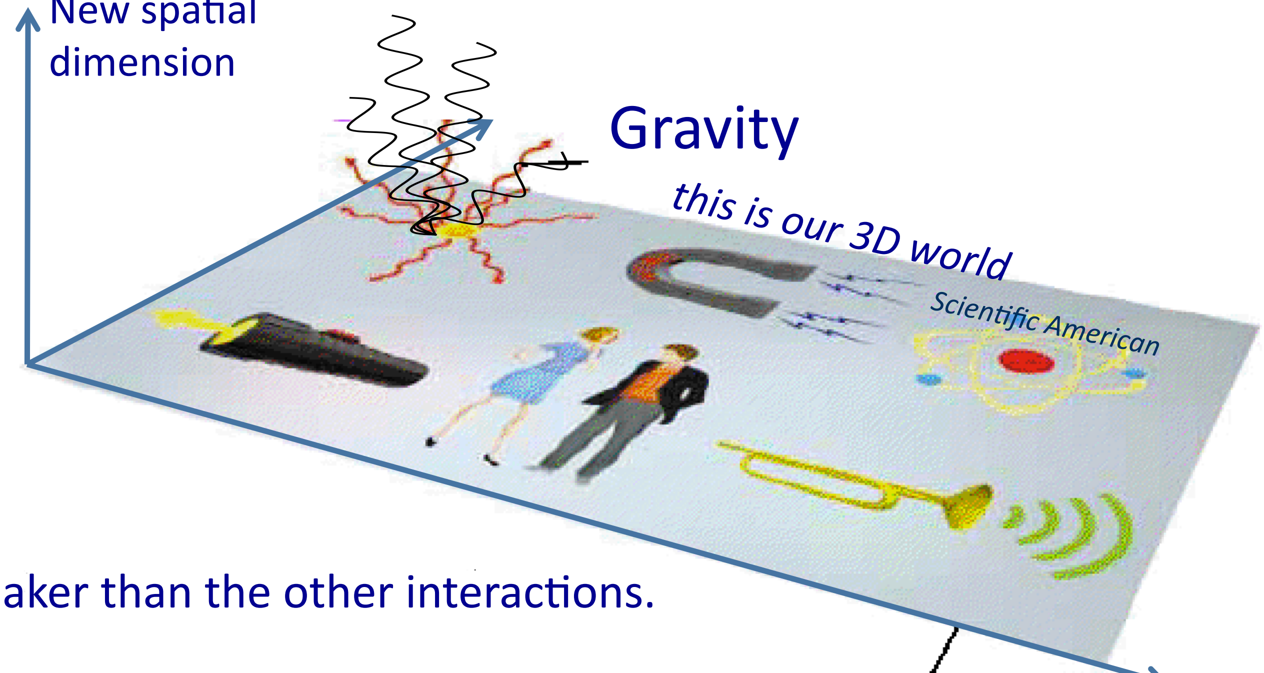
# Extra-Dimensions

Kaluza and Klein around the 1920's explored this idea in an attempt to unify general relativity and electromagnetism.

- What does it mean **extra dimensions**?
- *Perhaps some particles could* propagate in a new direction, not $x, y, z\ldots!$
- **Do not see extra-dimensions** either with our senses our in our experiments.
- The extra-dimensions could be very small, hence they escaped us so far
- String theory has many extra dimensions, generally Planck length $\ell_P = 10^{-33} cm$

# Extra-Dimensions

Standard space-time: 3+1D
Number of extra dimensions $n$

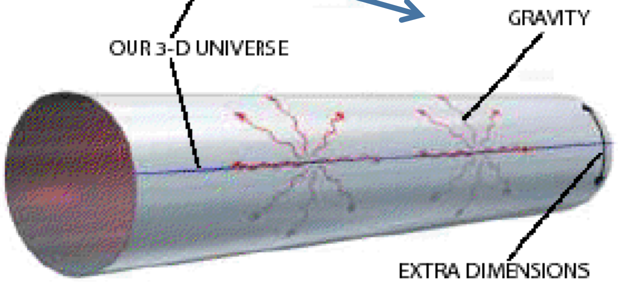


Gravitation is much weaker than the other interactions.

Explain **weakness of gravity** by a number of additional spatial dimensions.

**Gravity can propagate** in the extra-dimensions (ED) but other gauge interactions are confined to 3+1 D

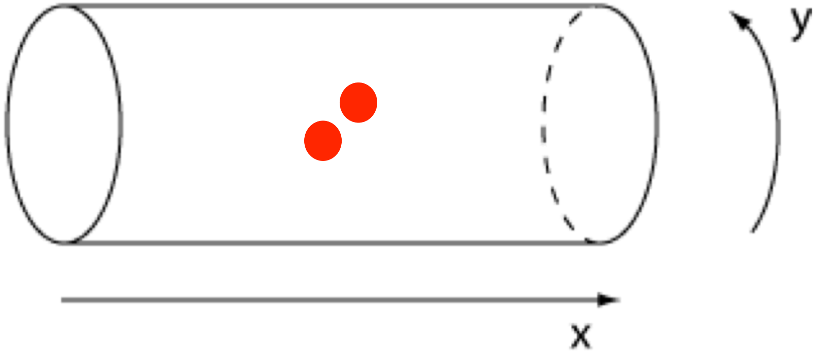
Gravitational effects could become manifest at **1 TeV** instead of the **Planck scale $M_{Pl}$~$10^{19}$ GeV**



# How Large Can the Extra-Dimension be?

Experimental studies have tested gravity down to ~0.1 mm and it follows $1/r^2$

What happens to gravity if there are extra compact dimensions of fine-size, radius $R$?



*$n$ compact extra-dimensions of Radius R.*

*normal dimensions : $O(10^{10})$ light years*

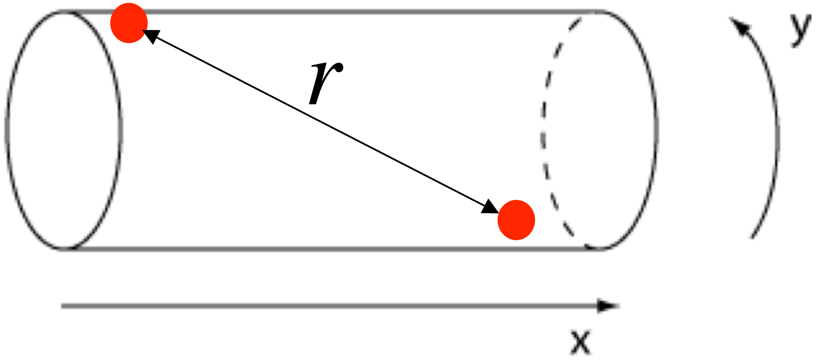
Consider two test masses $m_1$ and $m_2$ whose distance $r << R$

$$V(r) = G_* \frac{m_1 m_2}{r^{n+1}}$$

*Gauss law in n-dimensions, the gravitational flux crosses a surface in n-dimensions.*

*G* is the gravitational constant in n-dimensions.*

# How Large Can the Extra-Dimension be?



*$n$ compact extra-dimensions of Radius R.*

*We increase the distance between the test masses so that* $r >> R$
*The distance in the extra-dimensions cannot exceed R.*

$$V(r) = G_* \frac{m_1 m_2}{r^{n+1}} \longrightarrow G_* \frac{1}{R^n} \frac{m_1 m_2}{r}$$

At large distances we must find the classical Newtow's law: $V(r) = G \frac{m_1 m_2}{r}$

$$\Rightarrow G_* \frac{1}{R^n} \frac{m_1 m_2}{r} = G \frac{m_1 m_2}{r} \qquad \Rightarrow G = \frac{G_*}{R^n}$$

**Prediction**

In a test of the force of gravitation, when $r << R$ the force should follow: $1/r^{2+n}$ instead of $1/r^2$

# Planck Mass Revisited

The gravitational flux leaks into the other dimensions $\Rightarrow$ **gravity appears much weaker**

The Newton's gravitational law can be written as:

$$V(r) = G\frac{m_1 m_2}{r} = \frac{m_1 m_2}{m_P^2 r} \qquad \textit{using} \qquad m_P^2 = \frac{1}{G}$$

But if we think the real gravitation potential is: $V(r) = G_* \frac{m_1 m_2}{r^{n+1}}$

We should rather write (for large distances): $V(r) = \frac{m_1 m_2}{m_*^{2+n} R^n r}$ ***in natural units r is in*** $GeV^{-1}$ **.**

the exponent $2+n$ is necessary so that $m_*$ has units of GeV

So we have a **new fundamental mass scale** $m_*^{2+n} = \frac{m_P^2}{R^n}$ or $m_P^2 = m_*^{2+n} R^n$

The Planck mass is artificially large because we used the wrong expression for gravitation (we forgot some extra dimensions…)

**The mass scale $m_*$ can be much lower that the Planck mass.**

# Hierarch Problem Again…

$$\Delta m_H^2 = \frac{\lambda_f^2}{16\pi^2}\left[-2M_{\rm UV}^2 + \right.$$

The highest mass scale in the theory is now $m^*$. **Can it be of the order of $m_{EW}$=1 TeV?**

$$m_P^2 = m_*^{2+n} R^n \Rightarrow R^n = m_P^2 / m_*^{2+n} \qquad R = (m_P^2)^{\frac{1}{n}} \times \left(\frac{1TeV}{m_{EW}}\right)^{\frac{2+n}{n}}$$

$$\boxed{R = 10^{30/n - 17}\, cm \times \left(\frac{1TeV}{m_{EW}}\right)^{1+\frac{2}{n}}}$$

**Example for $m_{EW}$=1 TeV**

For $n=1$ R=$10^{11}$ m ~ size of the solar system → excluded!

For $n=2$ R=0.1 mm → current experimental tests of gravity, not excluded experimentally!

**2 extra dimensions of size 0.1 mm** would still yield an *apparent* 4D Planck scale of $10^{19}$GeV

Would **not be excluded experimentally** (or close)

But in reality the **new physics scale would be 1 TeV** ~ 0.1 mm.

There would be **no hierarchy problem** anymore, because $M_{\rm UV} = m_*$=1 TeV !

# What happens when a particle can propage into the ED?

As an example consider a spin-zero particle obeying the Klein Gorde relativistic equation:

$$\left(\frac{1}{c^2}\frac{\partial^2}{\partial t^2} - \nabla^2 + \frac{m^2c^2}{\hbar^2}\right)\Phi(t,\boldsymbol{x}) = 0$$

We add a 5th dimension

$$\left(\frac{1}{c^2}\frac{\partial^2}{\partial t^2} - \nabla^2 - \frac{\partial^2}{\partial x_5^2} + \frac{m_5^2c^2}{\hbar^2}\right)\Phi(t,\boldsymbol{x},x_5) = 0$$

# What happens when a particle can propage into the ED?

The 5th dimension is periodic $x_5 = x_5 + 2\pi R$

Therefore we can Fourier develop the wave function w.r.t $x_5$

$$\Phi(t, \boldsymbol{x}, x_5) = \sum_{n=-\infty}^{\infty} \phi_n(t, \boldsymbol{x}) \exp\left(\frac{inx_5}{R}\right)$$

Deriving $\frac{\partial^2}{\partial x_5^2}$ is equivalent to adding a factor $i\frac{n^2}{R^2}$

Yields:

$$\underbrace{\left(\frac{1}{c^2}\frac{\partial^2}{\partial t^2} - \nabla^2 + \frac{m_{5\mathrm{D}}^2 c^2}{\hbar^2} + \frac{n^2}{R^2}\right)}_{} \phi_n(t, \boldsymbol{x}) = 0$$

This is like a standard 4D Klein Gordon equation, **but with a modified mass**!

$$m_{4D}^2 = m_{5D}^2 + \frac{n^2}{R^2}$$

The particle moving in 5D follows the same equation as in 4D but the momentum in the 5th dimension appears to us as extra mass.

# KK Towers

A particle propagating in the extra dimension **appears to us a series or "tower" of particles**

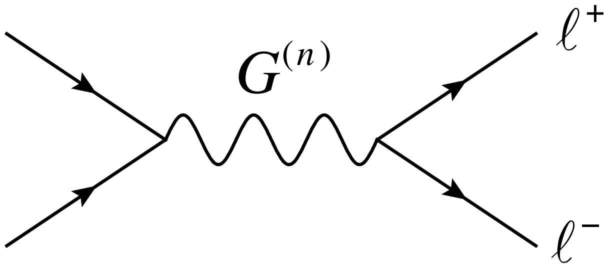
of increasing masses: $$m_{4D}^2 = m_{5D}^2 + \frac{n^2}{R^2}$$

For n=0 we retrieve the normal masses.

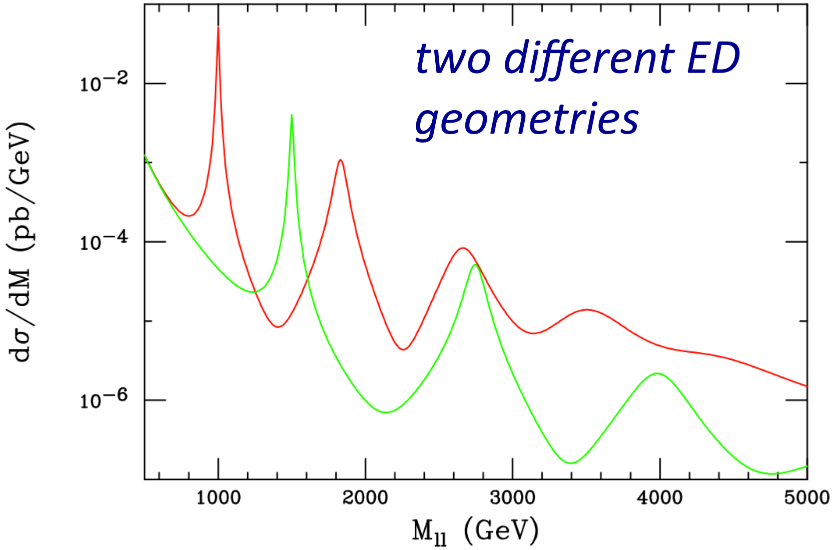
With R~1 TeV the mass of the *n=1* KK particles is around 1 TeV

The Graviton must propagate to the extra dimension (maybe other particles too…)

**=> lead at least to tower of gravitons of increasing masses.**



Can yield dramatic signal at the LHC



# Experimental Boundaries

Electroweak physics tested to ~$10^{-18}$cm ⇒ cannot freely propagate into large extra dimensions, but could possibly do so at smaller distances / higher energies.

Many experimental **boundaries from astrophysics**.

The Graviton must propagate to the extra dimension. Will show an experimental search.

**Many scenarios leading to a large variety of phenomenologies**

- Number of dimensions
- Geometry of the extra dimensions
- What particles / gauge interactions are allowed to propagate into the extra dimensions
- …

**Experimental Program**

- Test gravitation at small distances. Deviations from $1/r^2$?

- Look for KK particles at LHC.

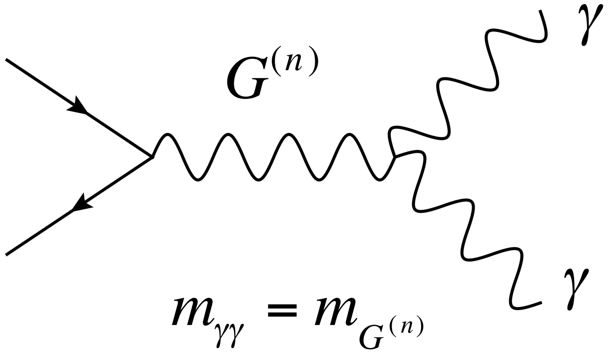
# Example of Search for Extra Dimension in ATLAS

In large extra-dimensions eg. ADD model R must be relatively large.

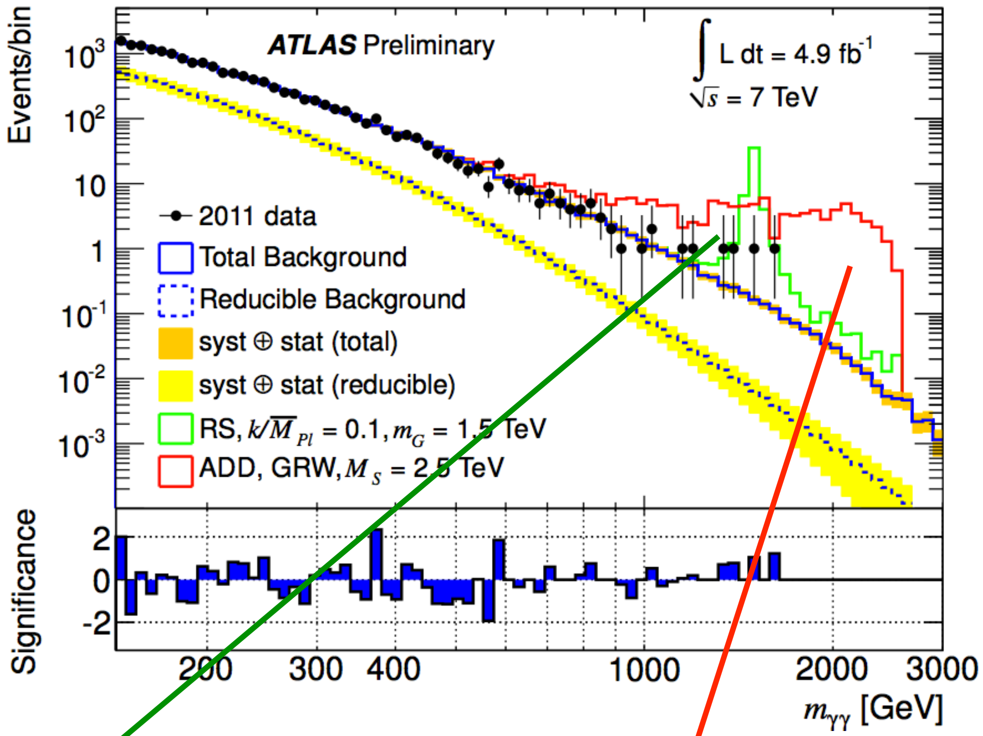
$$m_{G^{(n)}} \rightarrow \frac{n}{R}$$

Mass splitting is small $\frac{1}{R}$

⇒ Almost continuous spectrum



$$m_{\gamma\gamma} = m_{G^{(n)}}$$



Another model "RS" where the splitting between the KK-Graviton spectrum leads to 1 well defined mass peak

expected deviation from KK-graviton exchange

Exclude in case of large ED
M<4 TeV for n=3 and
M<2.6 TeV for n=7

ATLAS Collaboration
http://cdsweb.cern.ch/record/1460399

# Conclusions

The Standard Model is largely incomplete.

**Hierarchy problem** and **dark matter** problem both hints for new physics close to 1 TeV

Supersymmetry is a new symmetry b/w fermions and bosons, can adress several questions at once.

Extra-dimensions can also provide an elegant solution to the hierarchy problem

Extra-dimensions could allow to understand the weakness of the gravitation.

Whether these theories are fullfilled in Nature remains to be seen.

Thanks to the LHC experiments ATLAS and CMS the coming years should tell us.