SUB CRUCE LUMEN
THE UNIVERSITY
of ADELAIDE

Experimental SUSY searches at the LHC
Lecture 1

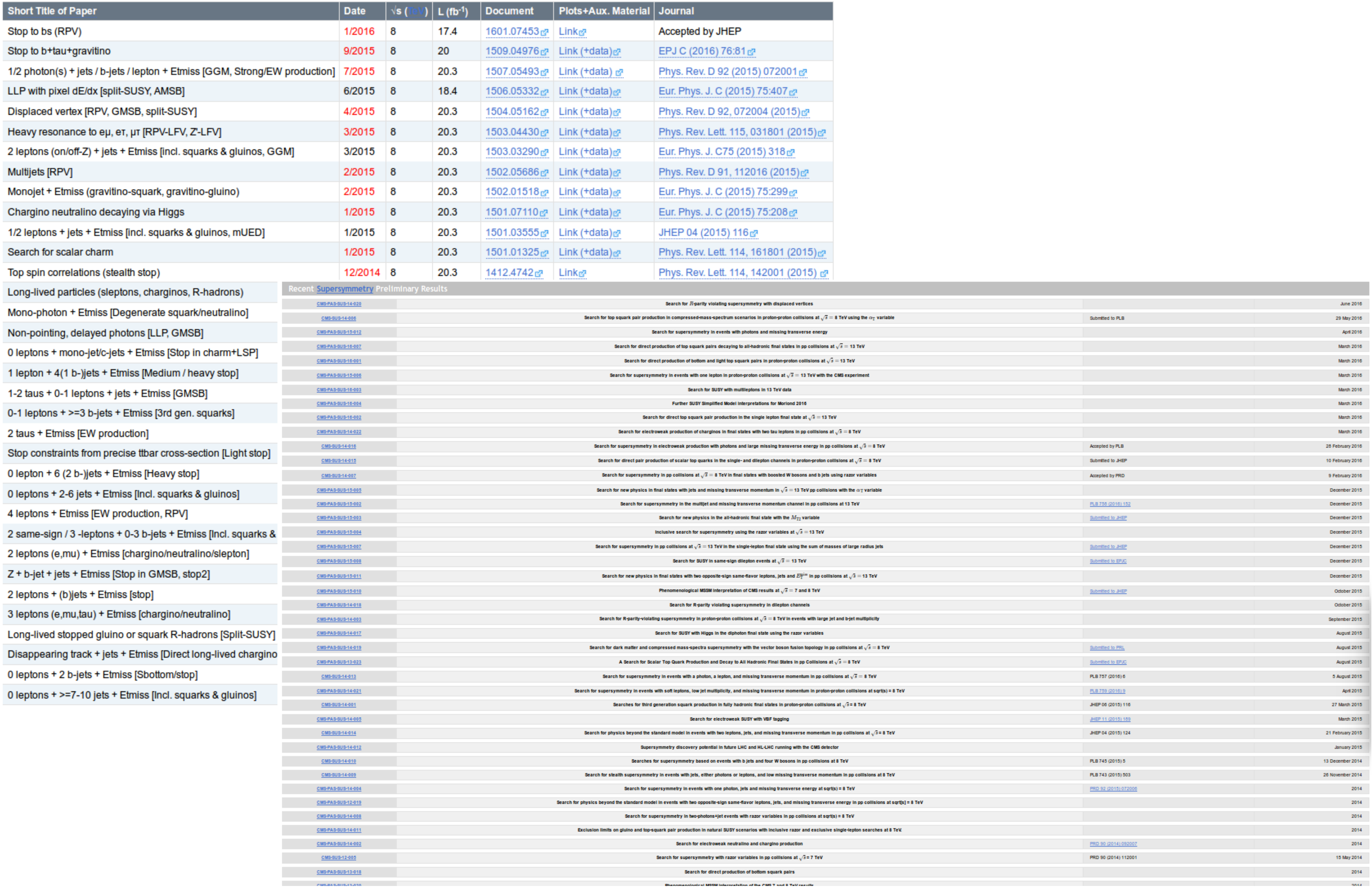
Martin White

CoEPP
ARC Centre of Excellence for
Particle Physics at the Terascale

Bibliography

- www.physik.uzh.ch/lectures/empp/15/lectures/empp15_LC_Trigger.pdf
- https://www2.warwick.ac.uk/fac/sci/physics/staff/.../chill_warwick_lhc_2010_2.pdf
- https://www-conf.slac.stanford.edu/ssi/2012/Presentations/Pralavorio-1.pdf
- ias.ust.hk/program/shared_doc/2016/.../20160118_Xuai_Zhuang_2042.pdf
- www.desy.de/~csander/Talks/131001_SUSYSummary.pdf
- www.hep.ph.imperial.ac.uk/~tapper/lecture/susy-lecture-1.pdf
- www.hep.ph.imperial.ac.uk/~tapper/lecture/susy-lecture-2.pdf
- moriond.in2p3.fr/QCD/2014/WednesdayMorning/Sekmen.pdf
- https://indico.in2p3.fr/event/12279/session/12/contribution/194/material/slides/

Where we're headed



Short Title of Paper	Date	$\sqrt{s}$ (TeV)	L (fb^{-1})	Document	Plots+Aux. Material	Journal
Stop to bs (RPV)	1/2016	8	17.4	1601.07453	Link	Accepted by JHEP
Stop to b+tau+gravitino	9/2015	8	20	1509.04976	Link (+data)	EPJ C (2016) 76:81
1/2 photon(s) + jets / b-jets / lepton + Etmiss [GGM, Strong/EW production]	7/2015	8	20.3	1507.05493	Link (+data)	Phys. Rev. D 92 (2015) 072001
LLP with pixel dE/dx [split-SUSY, AMSB]	6/2015	8	18.4	1506.05332	Link (+data)	Eur. Phys. J. C (2015) 75:407
Displaced vertex [RPV, GMSB, split-SUSY]	4/2015	8	20.3	1504.05162	Link (+data)	Phys. Rev. D 92, 072004 (2015)
Heavy resonance to eμ, eτ, μτ [RPV-LFV, Z'-LFV]	3/2015	8	20.3	1503.04430	Link (+data)	Phys. Rev. Lett. 115, 031801 (2015)
2 leptons (on/off-Z) + jets + Etmiss [incl. squarks & gluinos, GGM]	3/2015	8	20.3	1503.03290	Link (+data)	Eur. Phys. J. C75 (2015) 318
Multijets [RPV]	2/2015	8	20.3	1502.05686	Link (+data)	Phys. Rev. D 91, 112016 (2015)
Monojet + Etmiss (gravitino-squark, gravitino-gluino)	2/2015	8	20.3	1502.01518	Link (+data)	Eur. Phys. J. C (2015) 75:299
Chargino neutralino decaying via Higgs	1/2015	8	20.3	1501.07110	Link (+data)	Eur. Phys. J. C (2015) 75:208
1/2 leptons + jets + Etmiss [incl. squarks & gluinos, mUED]	1/2015	8	20.3	1501.03555	Link (+data)	JHEP 04 (2015) 116
Search for scalar charm	1/2015	8	20.3	1501.01325	Link (+data)	Phys. Rev. Lett. 114, 161801 (2015)
Top spin correlations (stealth stop)	12/2014	8	20.3	1412.4742	Link	Phys. Rev. Lett. 114, 142001 (2015)
Long-lived particles (sleptons, charginos, R-hadrons)						
Mono-photon + Etmiss [Degenerate squark/neutralino]						
Non-pointing, delayed photons [LLP, GMSB]						
0 leptons + mono-jet/c-jets + Etmiss [Stop in charm+LSP]						
1 lepton + 4(1 b-)jets + Etmiss [Medium / heavy stop]						
1-2 taus + 0-1 leptons + jets + Etmiss [GMSB]						
0-1 leptons + >=3 b-jets + Etmiss [3rd gen. squarks]						
2 taus + Etmiss [EW production]						
Stop constraints from precise ttbar cross-section [Light stop]						
0 lepton + 6 (2 b-)jets + Etmiss [Heavy stop]						
0 leptons + 2-6 jets + Etmiss [Incl. squarks & gluinos]						
4 leptons + Etmiss [EW production, RPV]						
2 same-sign / 3 -leptons + 0-3 b-jets + Etmiss [Incl. squarks &						
2 leptons (e,mu) + Etmiss [chargino/neutralino/slepton]						
Z + b-jet + jets + Etmiss [Stop in GMSB, stop2]						
2 leptons + (b)jets + Etmiss [stop]						
3 leptons (e,mu,tau) + Etmiss [chargino/neutralino]						
Long-lived stopped gluino or squark R-hadrons [Split-SUSY]						
Disappearing track + jets + Etmiss [Direct long-lived chargino						
0 leptons + 2 b-jets + Etmiss [Sbottom/stop]						
0 leptons + >=7-10 jets + Etmiss [Incl. squarks & gluinos]						

Recent Supersymmetry Preliminary Results

CMS-PAS-SUS-14-020	Search for R-parity violating supersymmetry with displaced vertices		June 2016
CMS-SUS-14-006	Search for top squark pair production in compressed-mass-spectrum scenarios in proton-proton collisions at $\sqrt{s} = 8$ TeV using the α_T variable	Submitted to PLB	29 May 2016
CMS-PAS-SUS-15-012	Search for supersymmetry in events with photons and missing transverse energy		April 2016
CMS-PAS-SUS-16-007	Search for direct production of top squark pairs decaying to all-hadronic final states in pp collisions at $\sqrt{s} = 13$ TeV		March 2016
CMS-PAS-SUS-16-001	Search for direct production of bottom and light top squark pairs in proton-proton collisions at $\sqrt{s} = 13$ TeV		March 2016
CMS-PAS-SUS-15-006	Search for supersymmetry in events with one lepton in proton-proton collisions at $\sqrt{s} = 13$ TeV with the CMS experiment		March 2016
CMS-PAS-SUS-16-003	Search for SUSY with multileptons in 13 TeV data		March 2016
CMS-PAS-SUS-16-004	Further SUSY Simplified Model Interpretations for Moriond 2016		March 2016
CMS-PAS-SUS-16-002	Search for direct top squark pair production in the single lepton final state at $\sqrt{s} = 13$ TeV		March 2016
CMS-PAS-SUS-14-022	Search for electroweak production of charginos in final states with two tau leptons in pp collisions at $\sqrt{s} = 8$ TeV		March 2016
CMS-SUS-14-016	Search for supersymmetry in electroweak production with photons and large missing transverse energy in pp collisions at $\sqrt{s} = 8$ TeV	Accepted by PLB	26 February 2016
CMS-SUS-14-015	Search for direct pair production of scalar top quarks in the single- and dilepton channels in proton-proton collisions at $\sqrt{s} = 8$ TeV	Submitted to JHEP	10 February 2016
CMS-SUS-14-007	Search for supersymmetry in pp collisions at $\sqrt{s} = 8$ TeV in final states with boosted W bosons and b jets using razor variables	Accepted by PRD	9 February 2016
CMS-PAS-SUS-15-005	Search for new physics in final states with jets and missing transverse momentum in $\sqrt{s} = 13$ TeV pp collisions with the α_T variable		December 2015
CMS-PAS-SUS-15-002	Search for supersymmetry in the multijet and missing transverse momentum channel in pp collisions at 13 TeV	PLB 758 (2016) 152	December 2015
CMS-PAS-SUS-15-003	Search for new physics in the all-hadronic final state with the M_{T2} variable	Submitted to JHEP	December 2015
CMS-PAS-SUS-15-004	Inclusive search for supersymmetry using the razor variables at $\sqrt{s} = 13$ TeV		December 2015
CMS-PAS-SUS-15-007	Search for supersymmetry in pp collisions at $\sqrt{s} = 13$ TeV in the single-lepton final state using the sum of masses of large radius jets	Submitted to JHEP	December 2015
CMS-PAS-SUS-15-008	Search for SUSY in same-sign dilepton events at $\sqrt{s} = 13$ TeV	Submitted to EPJC	December 2015
CMS-PAS-SUS-15-011	Search for new physics in final states with two opposite-sign same-flavor leptons, jets and E_T^{miss} in pp collisions at $\sqrt{s} = 13$ TeV		December 2015
CMS-PAS-SUS-15-010	Phenomenological MSSM interpretation of CMS results at $\sqrt{s} = 7$ and 8 TeV	Submitted to JHEP	October 2015
CMS-PAS-SUS-14-018	Search for R-parity violating supersymmetry in dilepton channels		October 2015
CMS-PAS-SUS-14-003	Search for R-parity-violating supersymmetry in proton-proton collisions at $\sqrt{s} = 8$ TeV in events with large jet and b-jet multiplicity		September 2015
CMS-PAS-SUS-14-017	Search for SUSY with Higgs in the diphoton final state using the razor variables		August 2015
CMS-PAS-SUS-14-019	Search for dark matter and compressed mass-spectra supersymmetry with the vector boson fusion topology in pp collisions at $\sqrt{s} = 8$ TeV	Submitted to PRL	August 2015
CMS-PAS-SUS-13-023	A Search for Scalar Top Quark Production and Decay to All Hadronic Final States in pp Collisions at $\sqrt{s} = 8$ TeV	Submitted to EPJC	August 2015
CMS-SUS-14-013	Search for supersymmetry in events with a photon, a lepton, and missing transverse momentum in pp collisions at $\sqrt{s} = 8$ TeV	PLB 757 (2016) 6	5 August 2015
CMS-PAS-SUS-14-021	Search for supersymmetry in events with soft leptons, low jet multiplicity, and missing transverse momentum in proton-proton collisions at sqrt(s) = 8 TeV	PLB 759 (2016) 9	April 2015
CMS-SUS-14-001	Searches for third generation squark production in fully hadronic final states in proton-proton collisions at $\sqrt{s}$= 8 TeV	JHEP 06 (2015) 116	27 March 2015
CMS-PAS-SUS-14-005	Search for electroweak SUSY with VBF tagging	JHEP 11 (2015) 169	March 2015
CMS-SUS-14-014	Search for physics beyond the standard model in events with two leptons, jets, and missing transverse momentum in pp collisions at $\sqrt{s}$= 8 TeV	JHEP 04 (2015) 124	21 February 2015
CMS-PAS-SUS-14-012	Supersymmetry discovery potential in future LHC and HL-LHC running with the CMS detector		January 2015
CMS-SUS-14-010	Searches for supersymmetry based on events with b jets and four W bosons in pp collisions at 8 TeV	PLB 745 (2015) 5	13 December 2014
CMS-SUS-14-009	Search for stealth supersymmetry in events with jets, either photons or leptons, and low missing transverse momentum in pp collisions at 8 TeV	PLB 743 (2015) 503	26 November 2014
CMS-PAS-SUS-14-004	Search for supersymmetry in events with one photon, jets and missing transverse energy at sqrt(s) = 8 TeV	PRD 92 (2015) 072006	2014
CMS-PAS-SUS-12-019	Search for physics beyond the standard model in events with two opposite-sign same-flavor leptons, jets, and missing transverse energy in pp collisions at sqrt[s] = 8 TeV		2014
CMS-PAS-SUS-14-008	Search for supersymmetry in two-photons+jet events with razor variables in pp collisions at sqrt(s) = 8 TeV		2014
CMS-PAS-SUS-14-011	Exclusion limits on gluino and top-squark pair production in natural SUSY scenarios with inclusive razor and exclusive single-lepton searches at 8 TeV.		2014
CMS-PAS-SUS-14-002	Search for electroweak neutralino and chargino production	PRD 90 (2014) 092007	2014
CMS-SUS-12-005	Search for supersymmetry with razor variables in pp collisions at $\sqrt{s}$= 7 TeV	PRD 90 (2014) 112001	15 May 2014
CMS-PAS-SUS-13-018	Search for direct production of bottom squark pairs		2014
CMS-PAS-SUS-13-020	Phenomenological MSSM interpretation of the CMS 7 and 8 TeV results		2014

Very rough outline

- We won't go through 200 different null SUSY searches at high speed with no details

  - you can get that at conferences (including this one)
  - I can't be bothered
  - **neither can you**

- What we will do

  - start with the basics, understand what we can measure in the LHC detectors
  - think about SUSY production processes at the LHC
  - walk through one analysis *in detail* so you can see how analyses are designed
  - sketch the main features of other analyses
  - learn how to tell if your favourite model is excluded from LHC data

- What I'd like us to discuss and learn:

  - what is good about LHC searches?
  - what is bad about LHC searches?
  - is SUSY dead, dying, stable or in good health?

Outline

- Lecture 1: the basics

    - what do I mean by SUSY?
    - what happens in an LHC collision?
    - how do the LHC detectors work?
    - which objects can we use to hunt for SUSY?
    - what (roughly) does SUSY look like at the LHC?

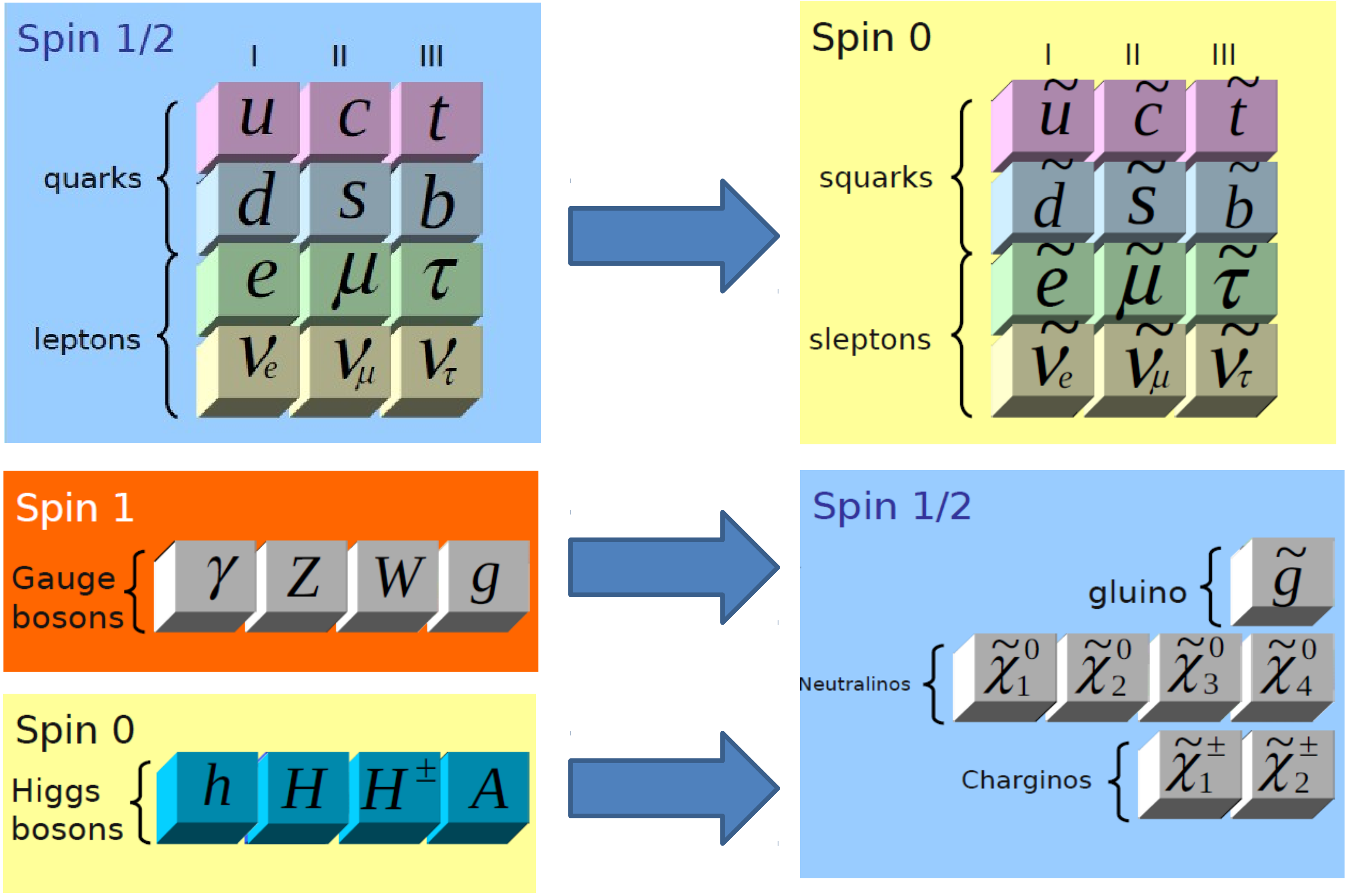
- Lecture 2 (mostly for experimentalists)

    - how are the LHC SUSY analyses designed?
    - discriminating variables
    - background measurements
    - detailed worked example (0 lepton search)
    - summary of different approaches

- Lecture 3 (mostly for theorists)

    - what have we learned about SUSY from the LHC (and LEP, etc...)
    - how can a theorist constrain a new model of SUSY (or other BSM physics?)

Supersymmetry



- “Supersymmetry” is a hypothesised symmetry connecting fermions and bosons

  - SM particles get partners that cancel the corrections to the Higgs mass
  - we also get viable dark matter candidates
  - we also find that the SM forces unify at high energies

What do I mean by SUSY?

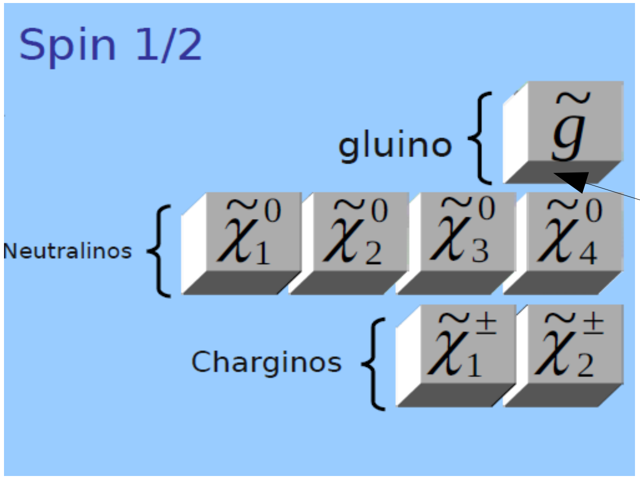
- Exact SUSY would require identical SM & SUSY partner masses
  - SUSY is broken

- Breaking mechanism is *a priori* unknown

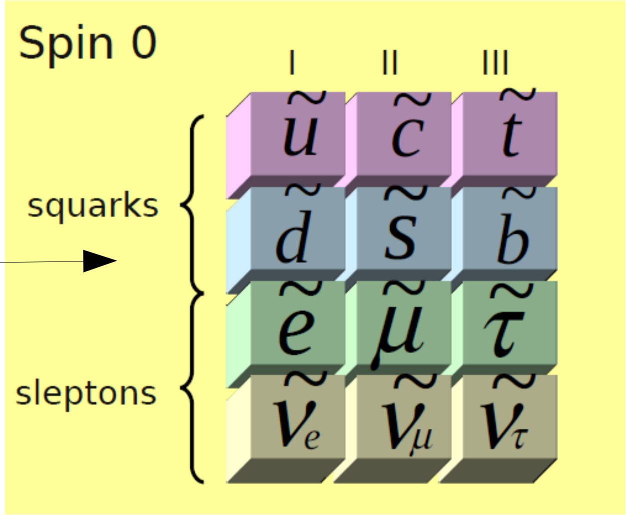
  - lots of GUT scale models (mSUGRA, GMSB, AMSB)
  - can use GUT or weak scale effective parameterisations (e.g. pMSSM)
  - lots of exotic SUSY models (e.g. NMSSM, E6SSM)

- For our purposes, SUSY means this:

  - any model that is supersymmetric and has some squarks, some sleptons, some extra Higgs bosons and some sort of EW gaugino sector



We want to try and measure these



Three sorts of paper on experimental searches

- Pre-LHC (up to 2007 or so)

  - how do we use the LHC to measure sparticle properties after discovery?

- Early LHC (2008 – 2011 or so)

  - how can we define new variables to better discover SUSY

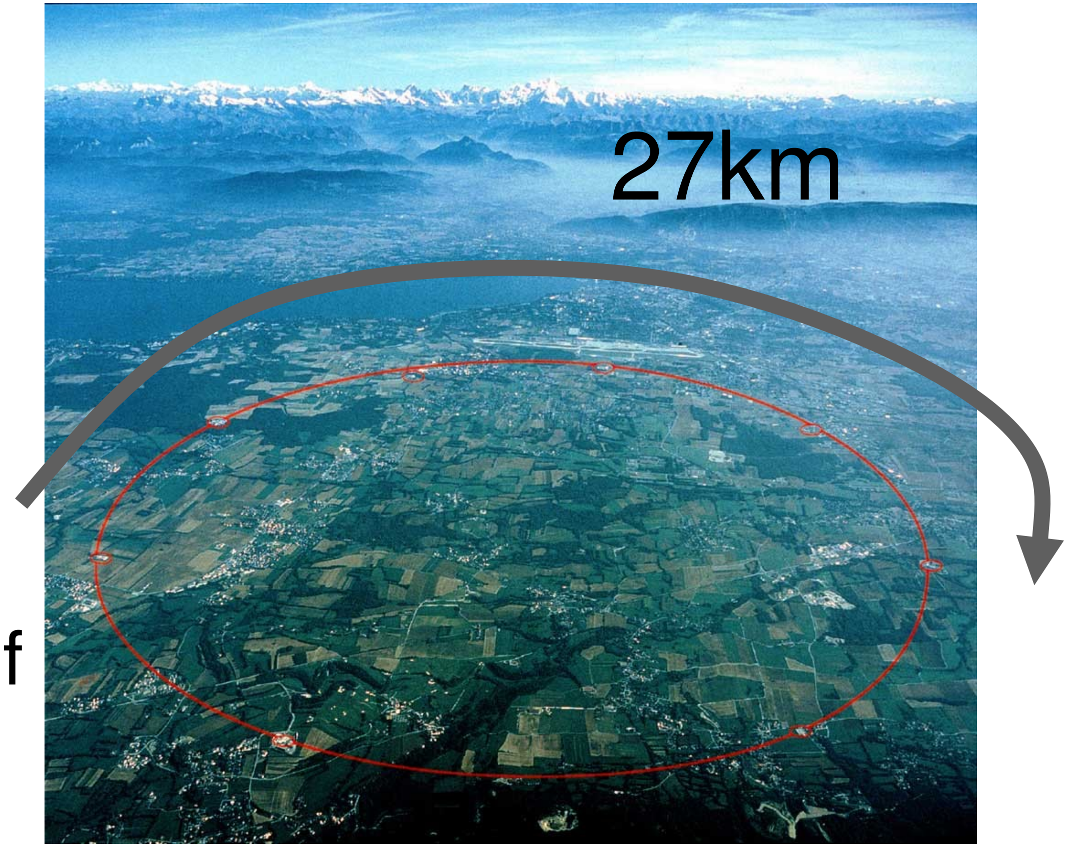
- Now (2012+): Why the f**k haven't we seen SUSY and what does it mean?

  - lots *and lots* of LHC exclusions
  - new baroque SUSY models that *are just around the corner*
  - why fine tuning doesn't matter, or why adding X@$% relieves fine tuning

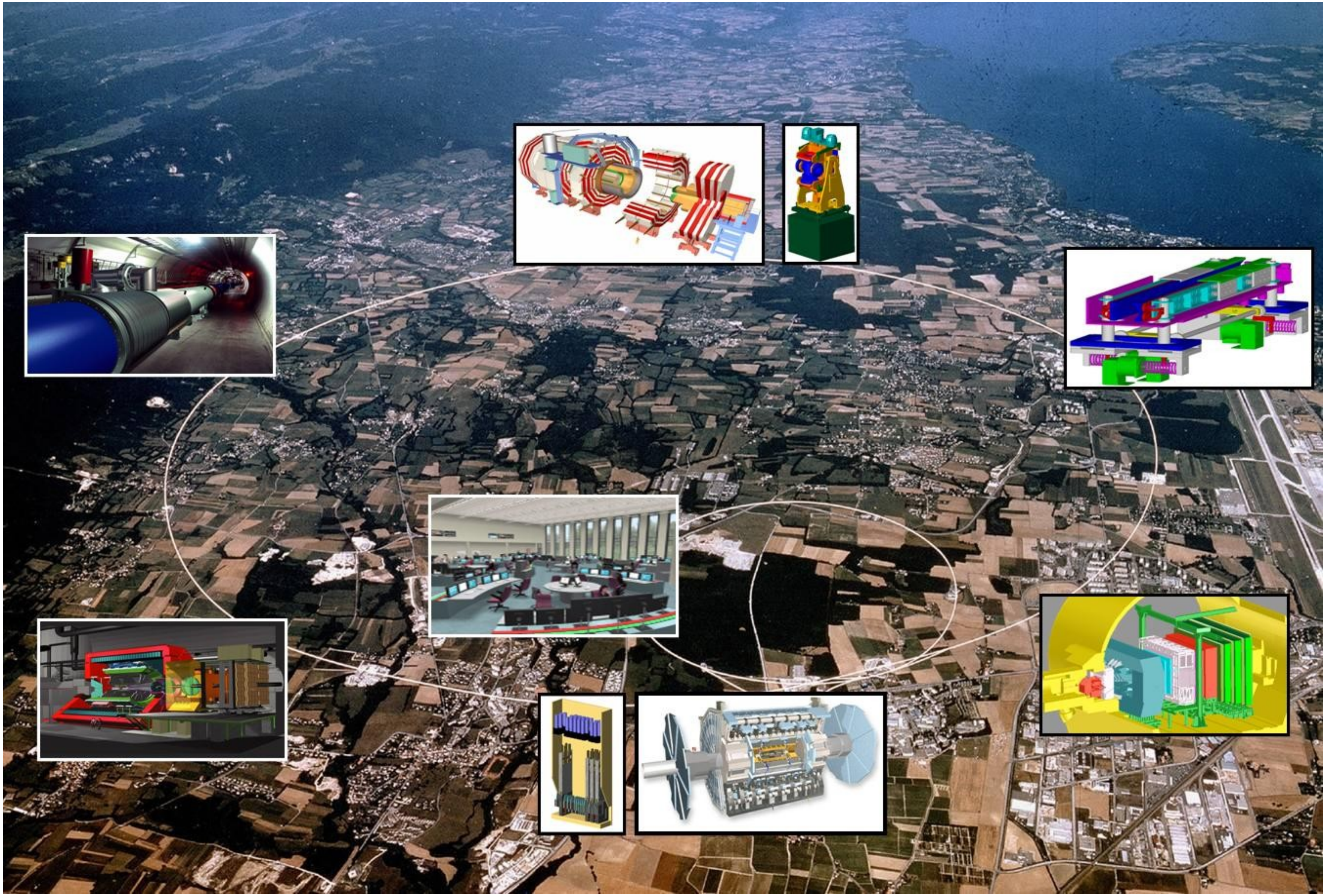
We won't spend much time on (1), but we will think a lot about (2) and (3)

The LHC

- Located at CERN
- Franco-Swiss border
- 27km circumference ring
- 100m underground
- Accelerates protons to *nearly* the speed of light
- Two counter rotating beams.



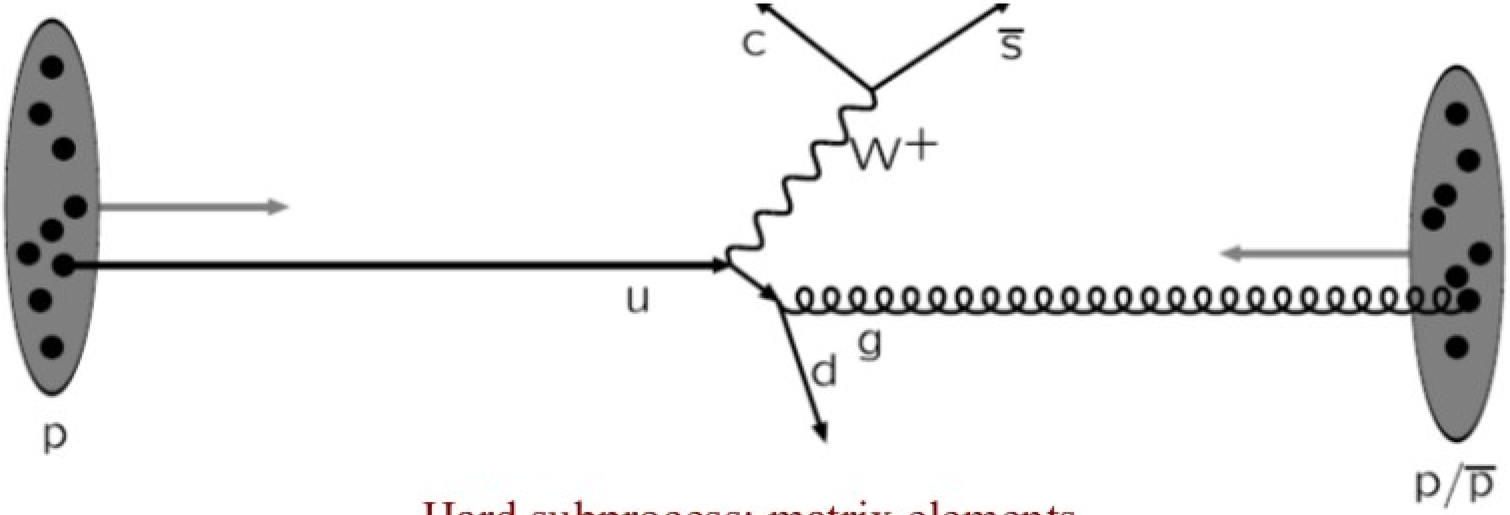
The LHC



What happens in a proton-proton collision

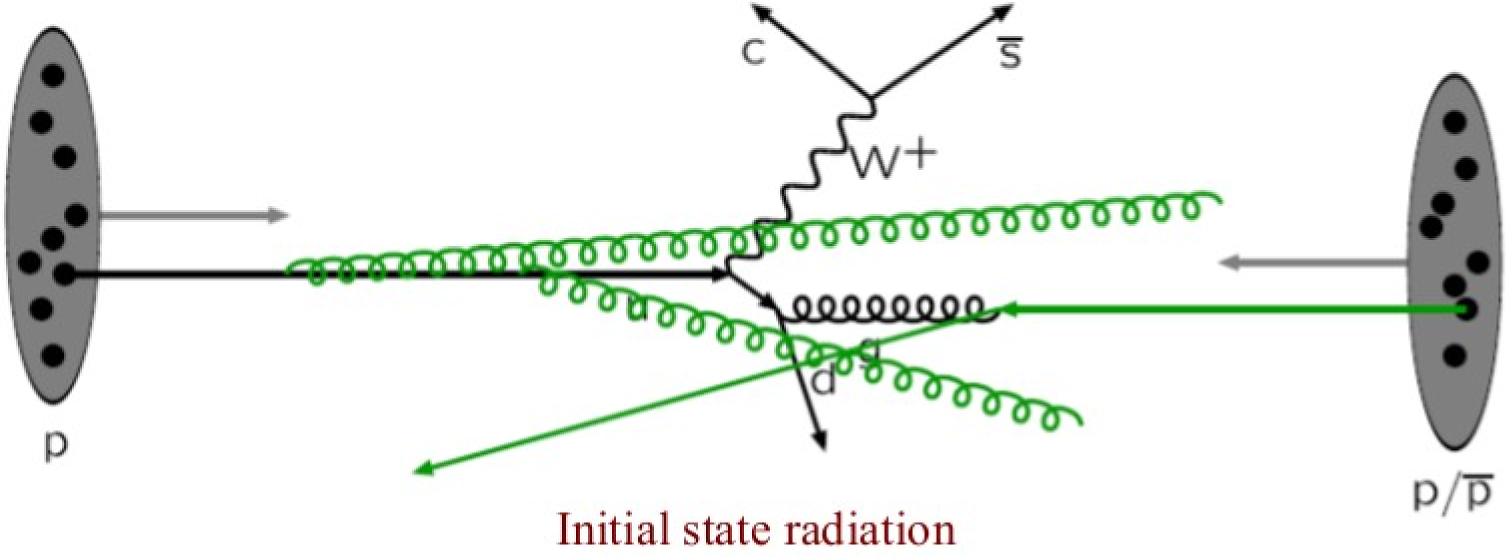
Incoming beams: parton densities

What happens in a proton-proton collision

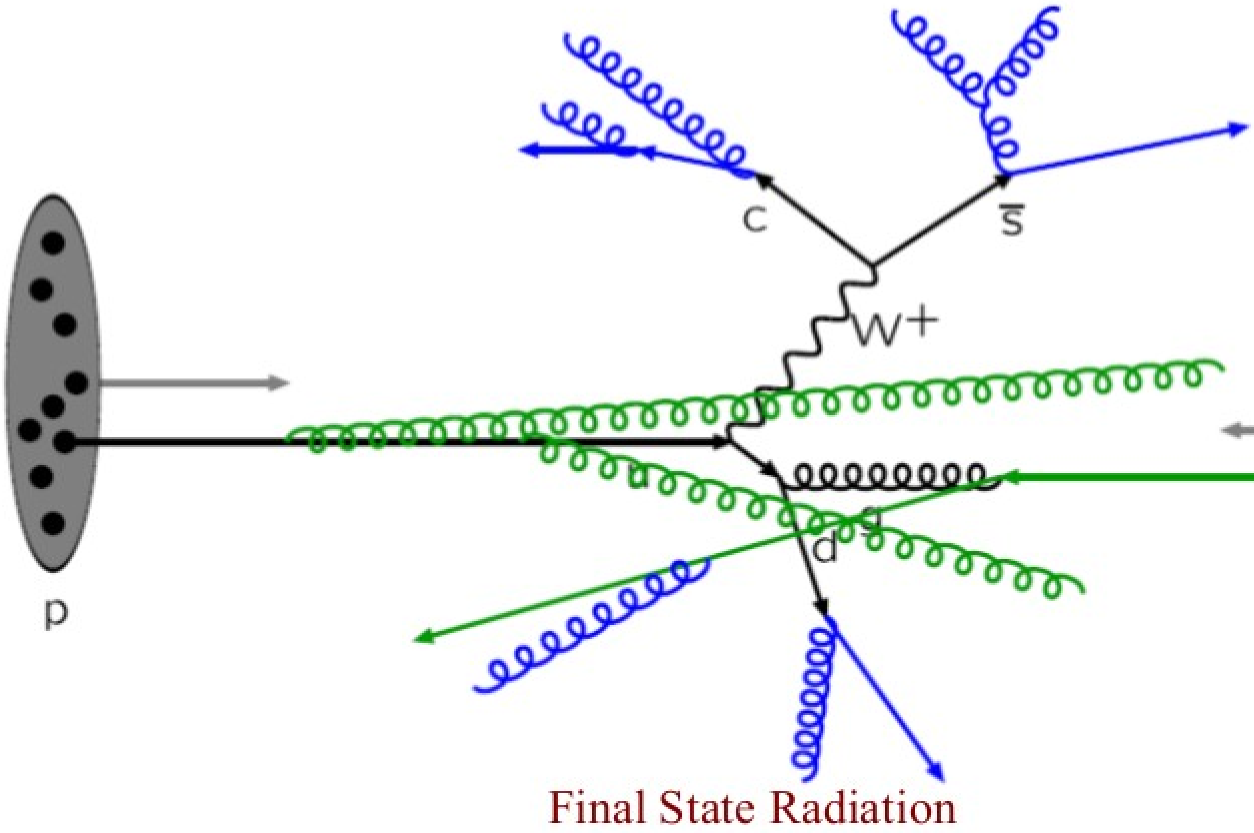


Hard subprocess: matrix elements,
Resonance decays (correlated to hard process)

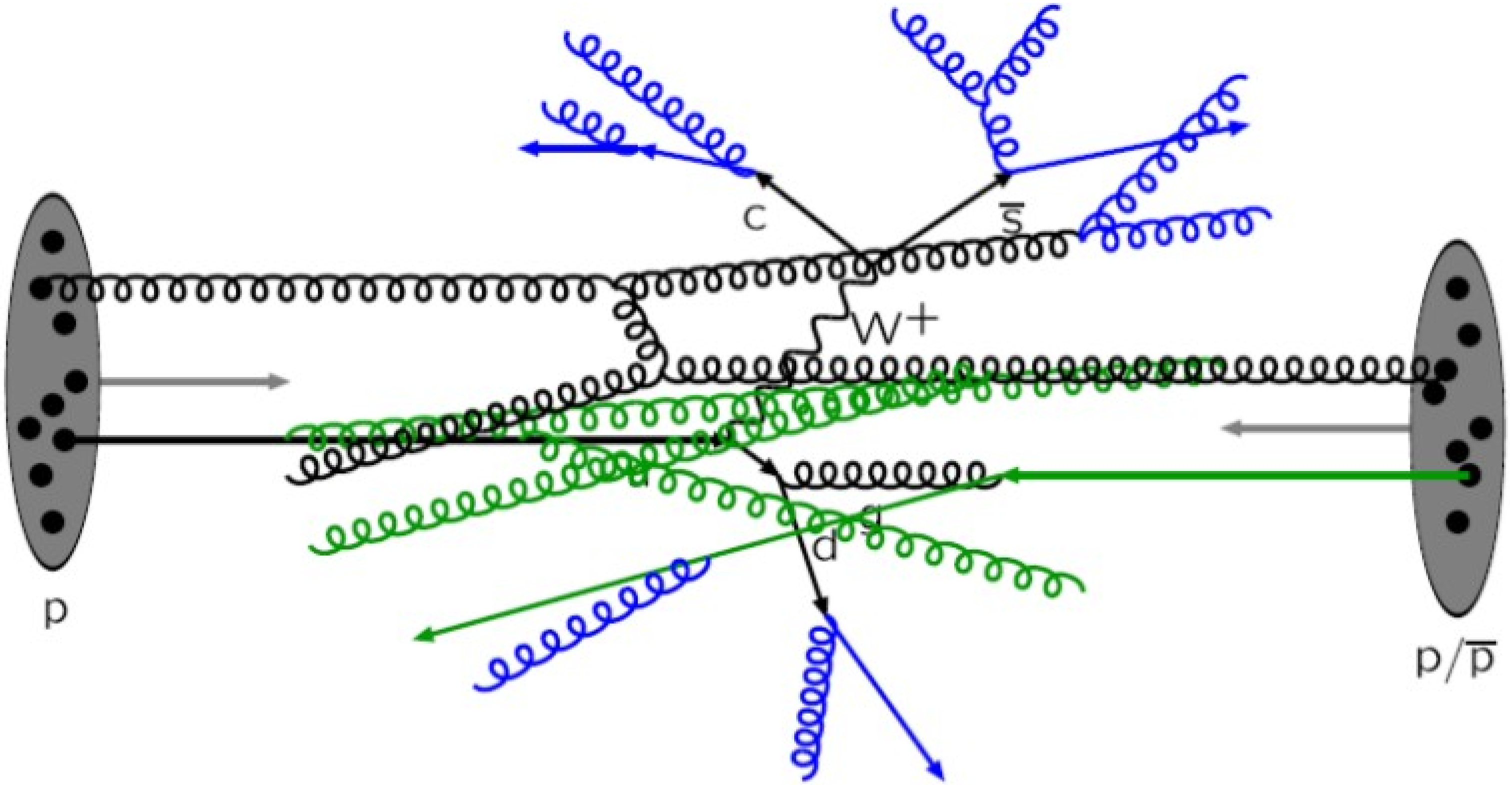
What happens in a proton-proton collision



What happens in a proton-proton collision

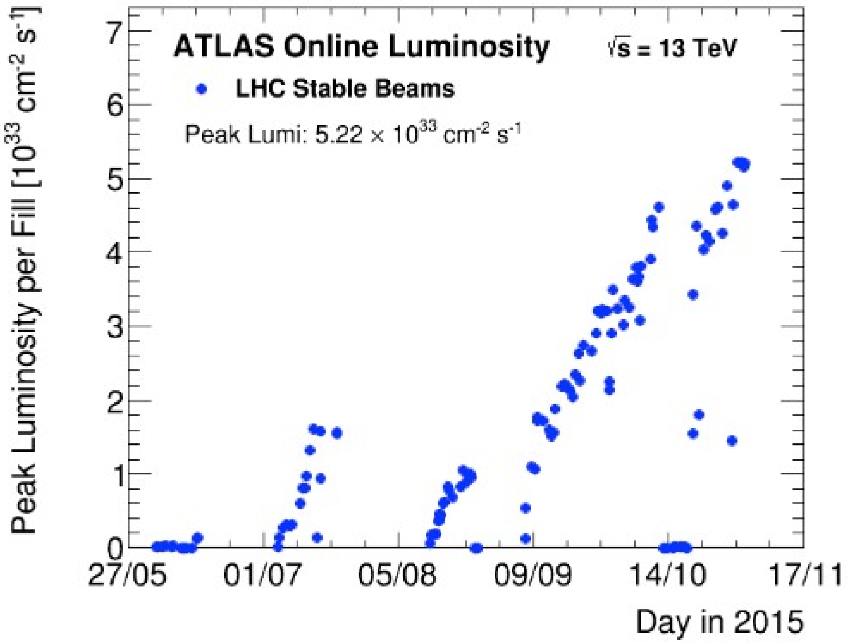


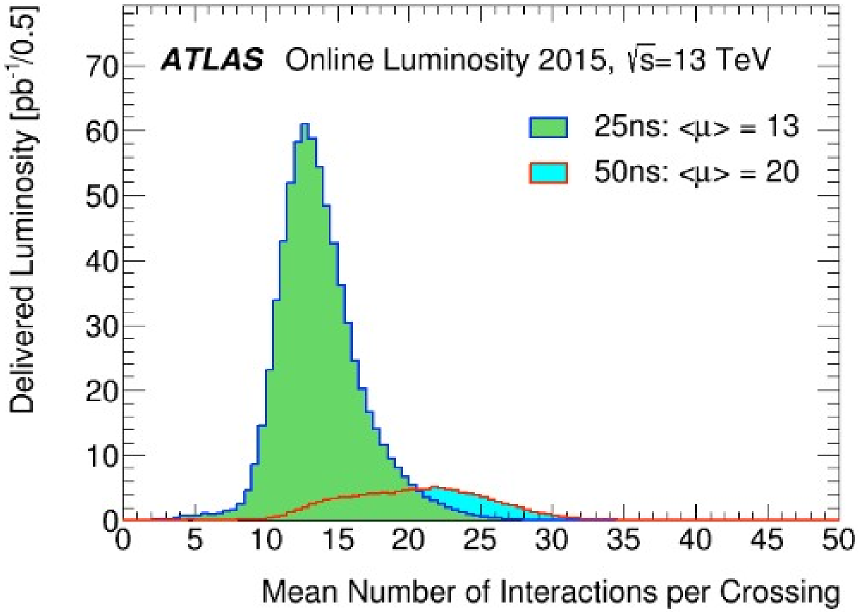
What happens in a proton-proton collision

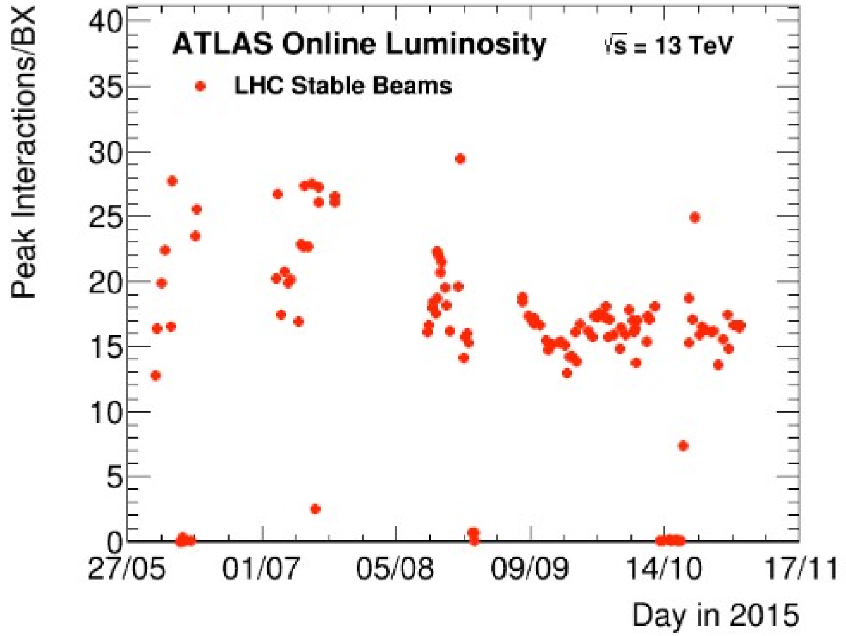


Multiple parton-parton interactions...
...with their ISR/FSR

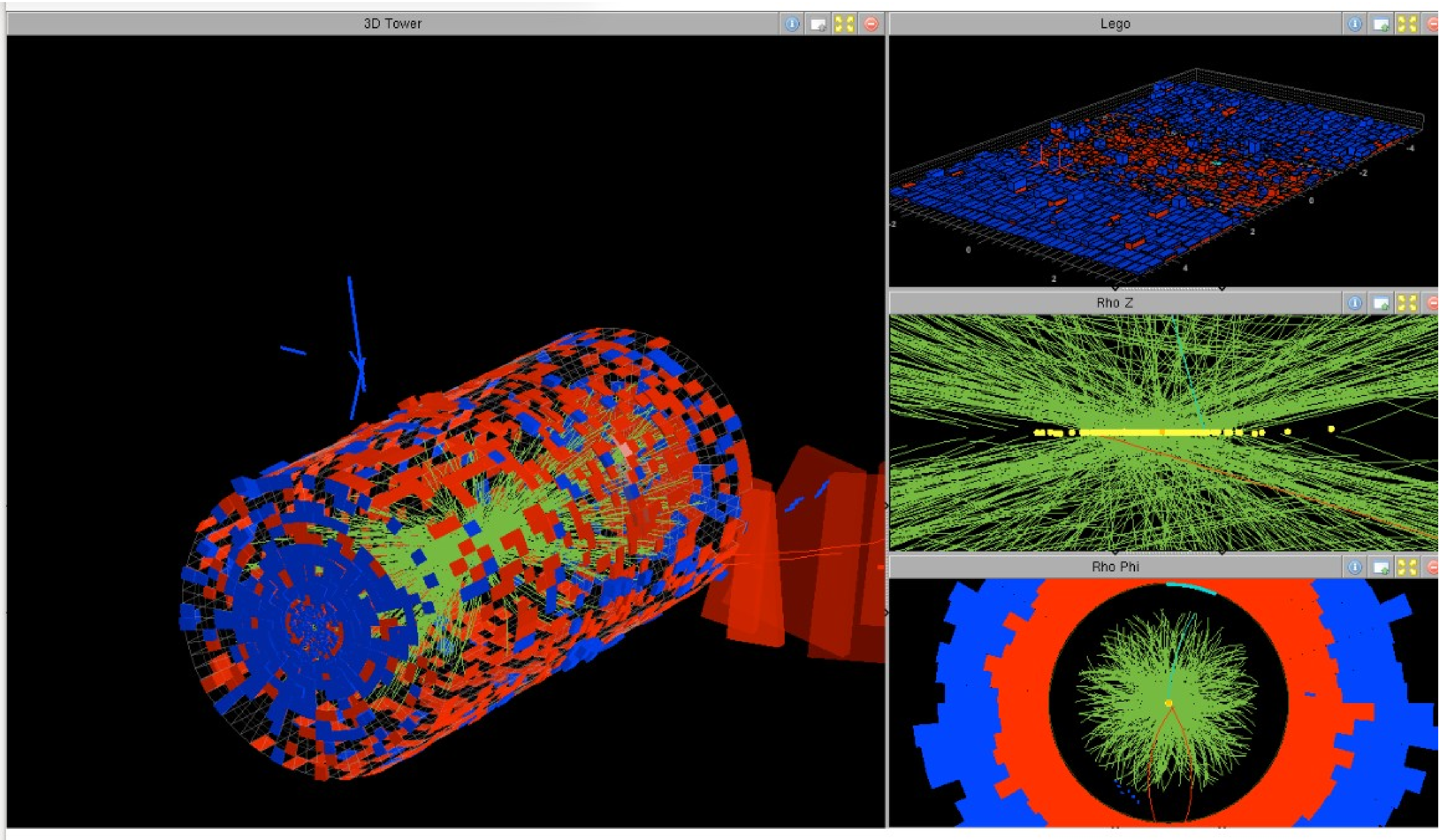
LHC collisions are messy







8 TeV CMS collision



ATLAS and CMS

- ATLAS and CMS were designed as *general purpose* experiments

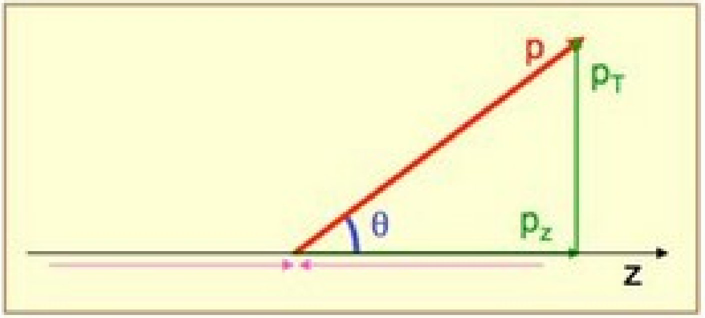
  - should be able to find any new physics at the Terascale
  - should also be able to cross-check each others results (different systematics)

- Need to be able to cope with intense environment of LHC collisions (for many years)

  - need radiation hard technology *or*
  - ability to replace components

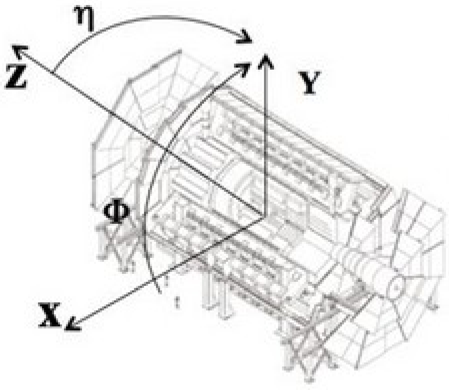
A word about coordinates

- The overall longitudinal boost is *not known* at a hadron collider
  - thus cannot know p_z for any four vector
  - can only work with transverse momentum $p_T^2 = p_x^2 + p_y^2$

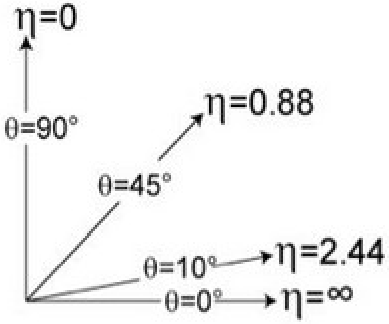


- The polar angle θ is not Lorentz invariant
- Instead use rapidity (usually use pseudo-rapidity):

$$y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z} \approx \eta = -\ln\left(\tan\frac{\vartheta}{2}\right)$$



rapidity ≈ pseudorapidity (|)
in massless approximation



- This *is* Lorentz invariant, and tends to infinity at the beam axis

LHC detector requirements

- An LHC detector needs:

  - full azimuthal coverage (need to measure **missing transverse energy**)

  - forward coverage (up to $|\eta| = 5$)

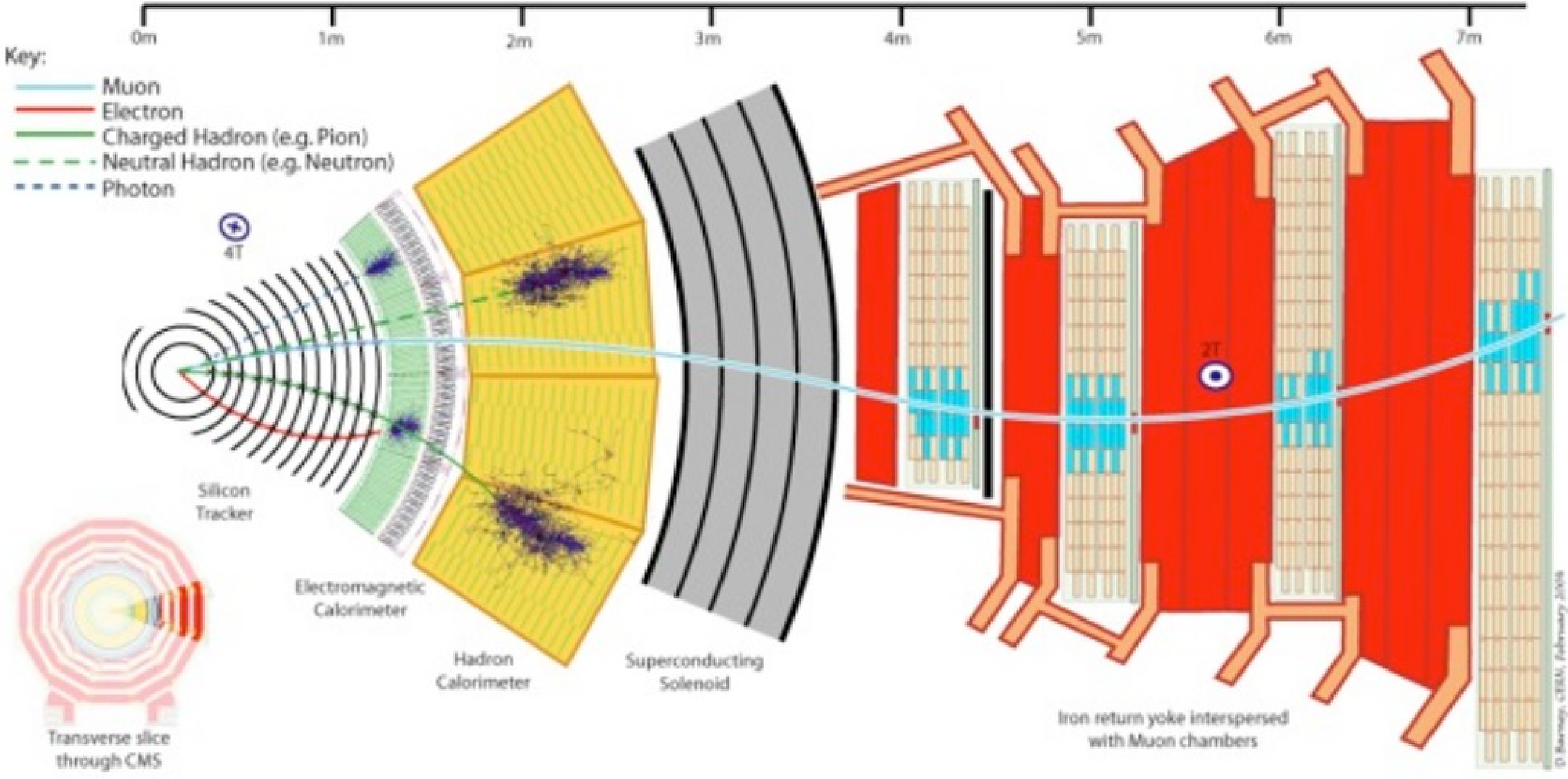
  - good **lepton identification** with excellent $\mathbf{p_T}$ resolution

  - good **photon identification**

  - good **jet energy resolution** (and **missing transverse energy** resolution)

  - efficient **secondary vertex finding** (b-tagging, tau ID)

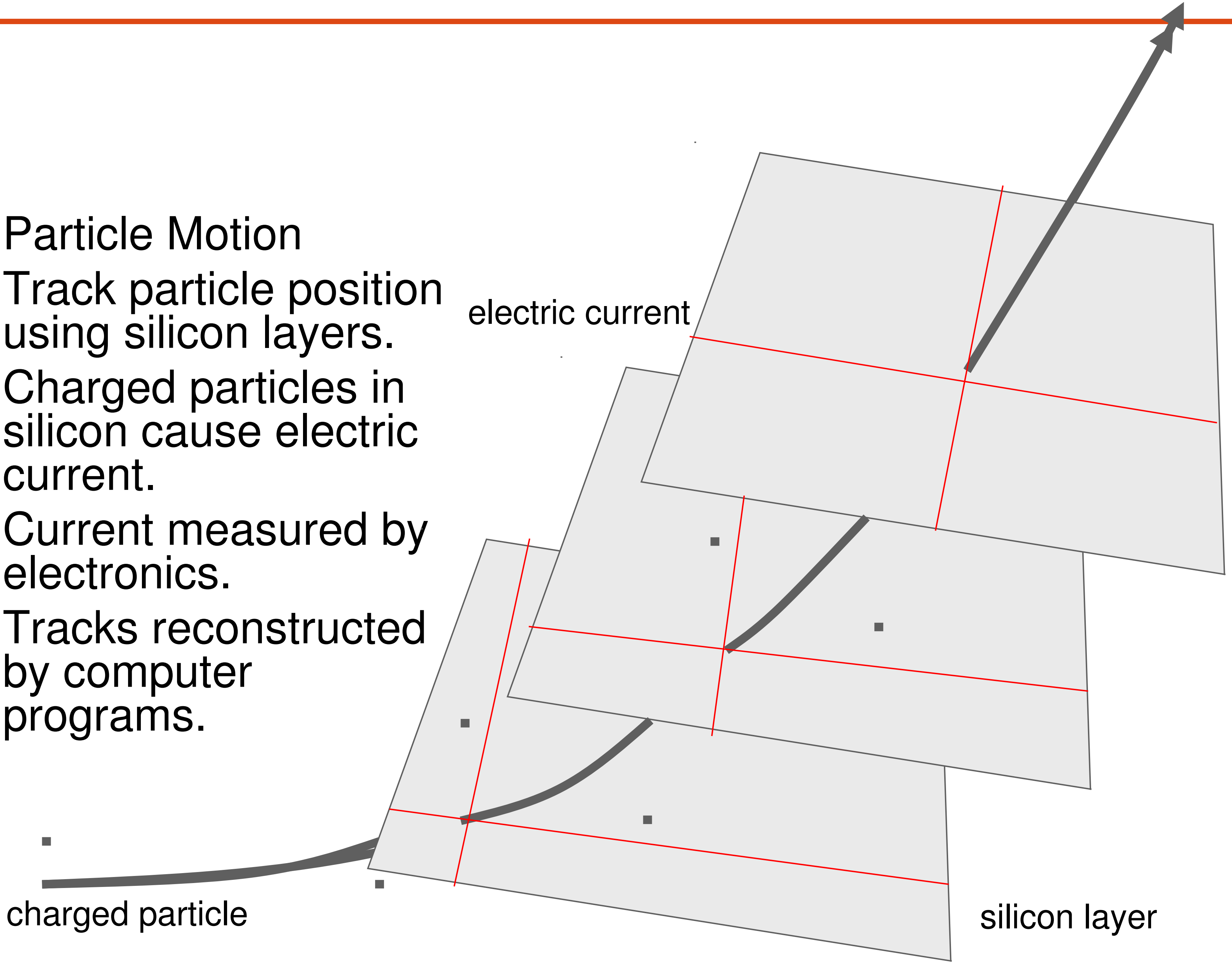
How does a detector work?



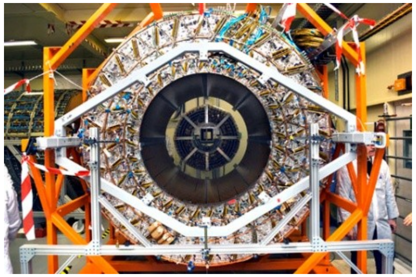
- Built around collision point → full azimuthal coverage
- Momentum: measure charged particle trajectories in inner part of detector (apply B field)
- Energy: slam particles into Pb or steel, stop them, measure the energy released (calorimeters)
- Muons: have special detectors on the outside of the detector

Measuring position

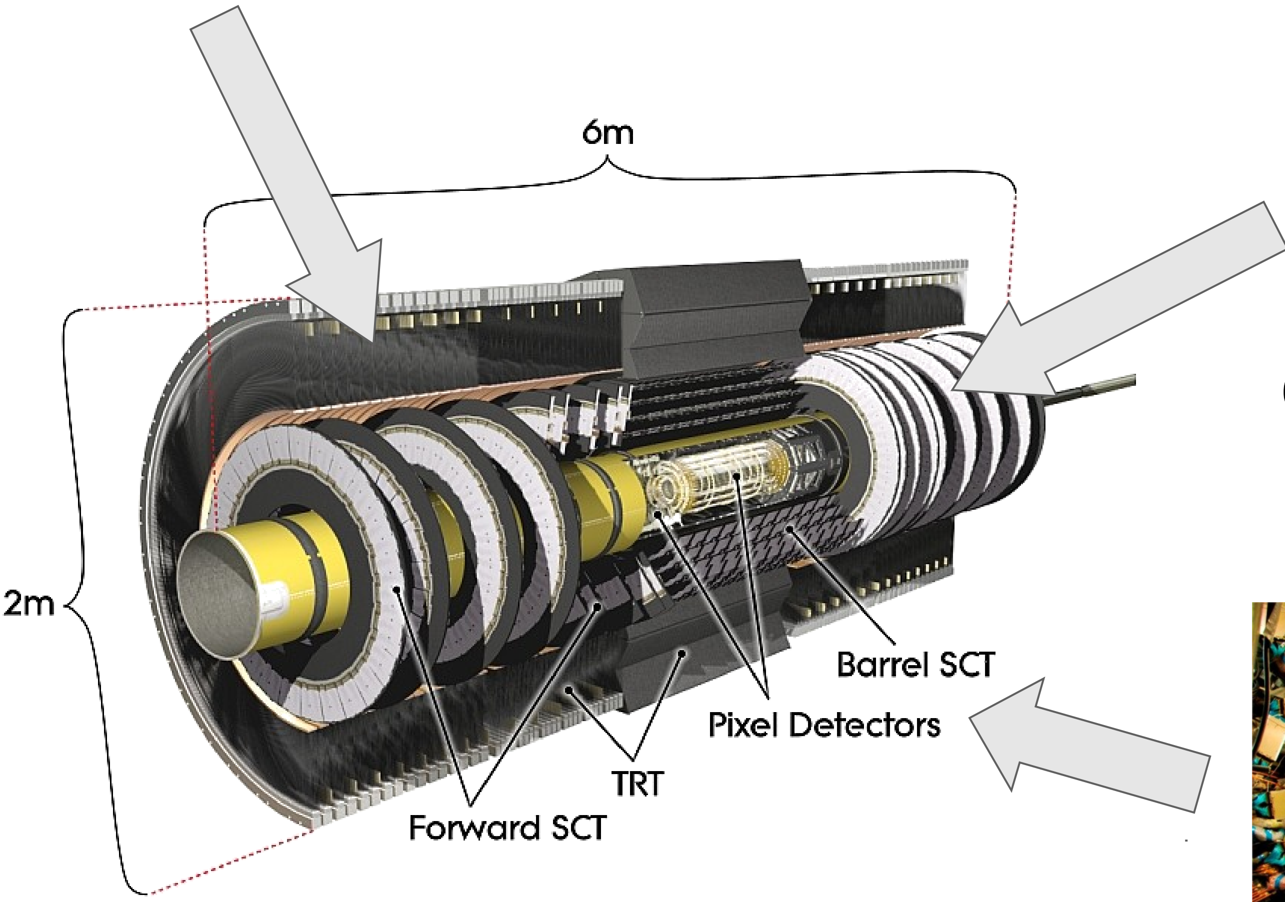
- Particle Motion
- Track particle position using silicon layers.
- Charged particles in silicon cause electric current.
- Current measured by electronics.
- Tracks reconstructed by computer programs.

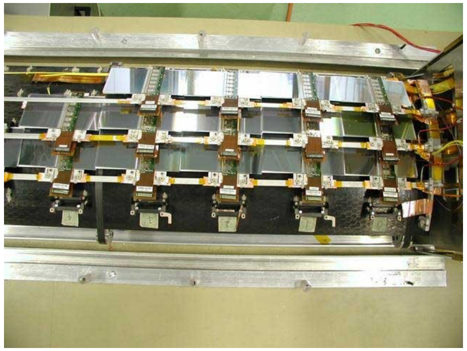


ATLAS tracker



420,000 **Xenon Straws**

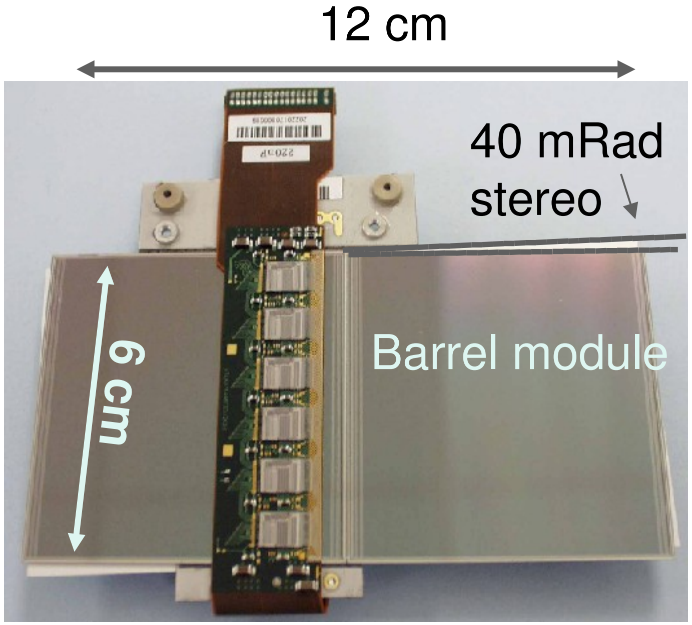




6 Million Silicon **Strips**

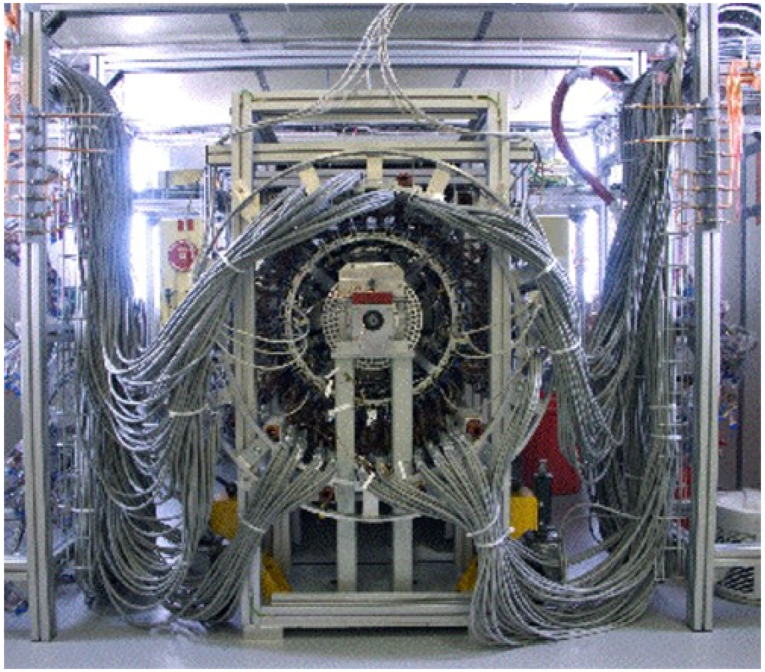
135 Million **Pixels**

ATLAS semiconductor tracker



- 4 barrel layers
- 9 endcap wheels
- 6 million silicon strips

- Need to configure and read-out each module.



Measuring momentum

- For a charged particle moving in a magnetic field:

$$p = B \times q \times r$$

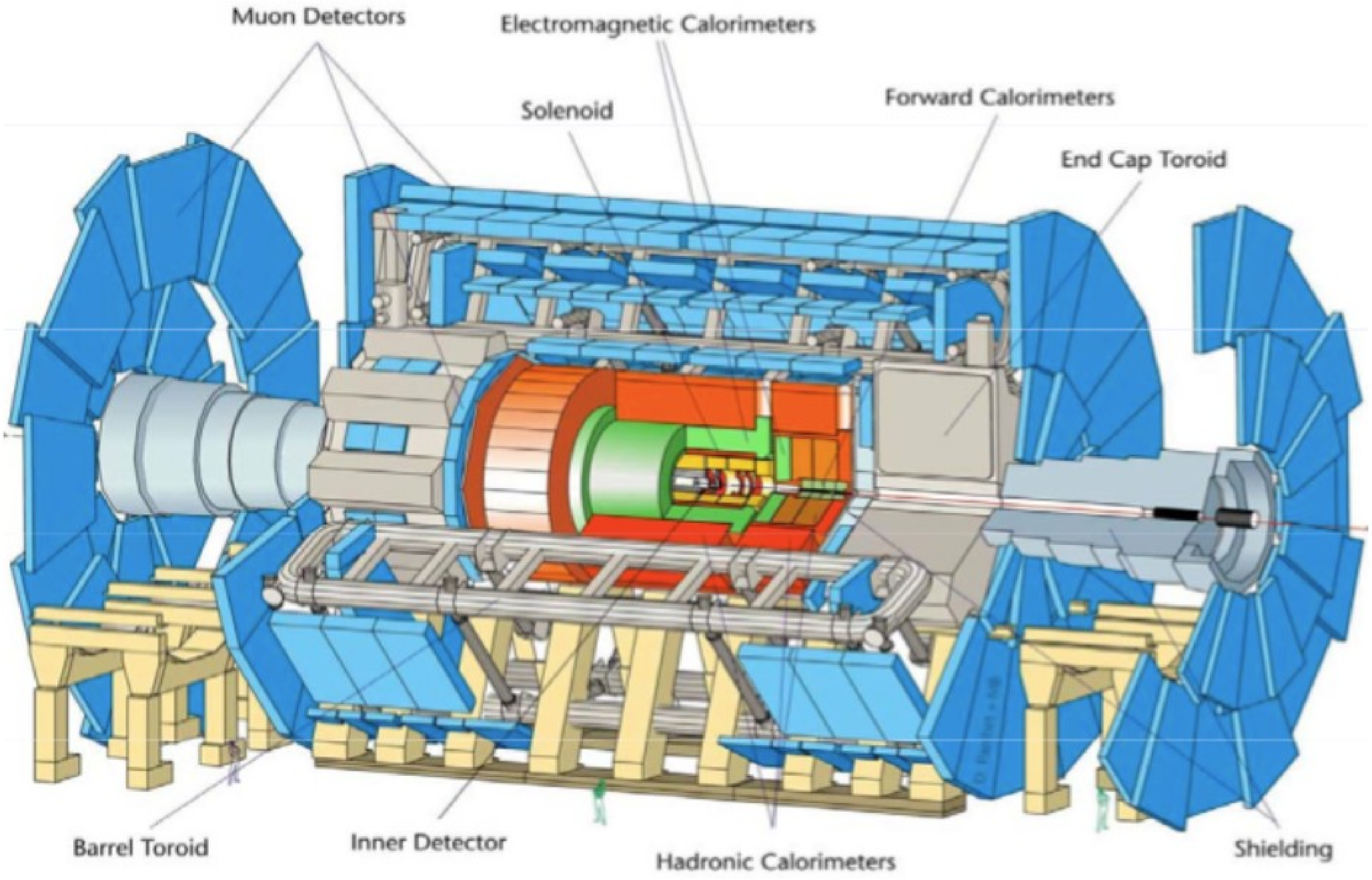
- The momentum resolution goes as:

$$\frac{dp}{p} \propto \frac{p}{B\ell^2}$$

- Therefore need either:

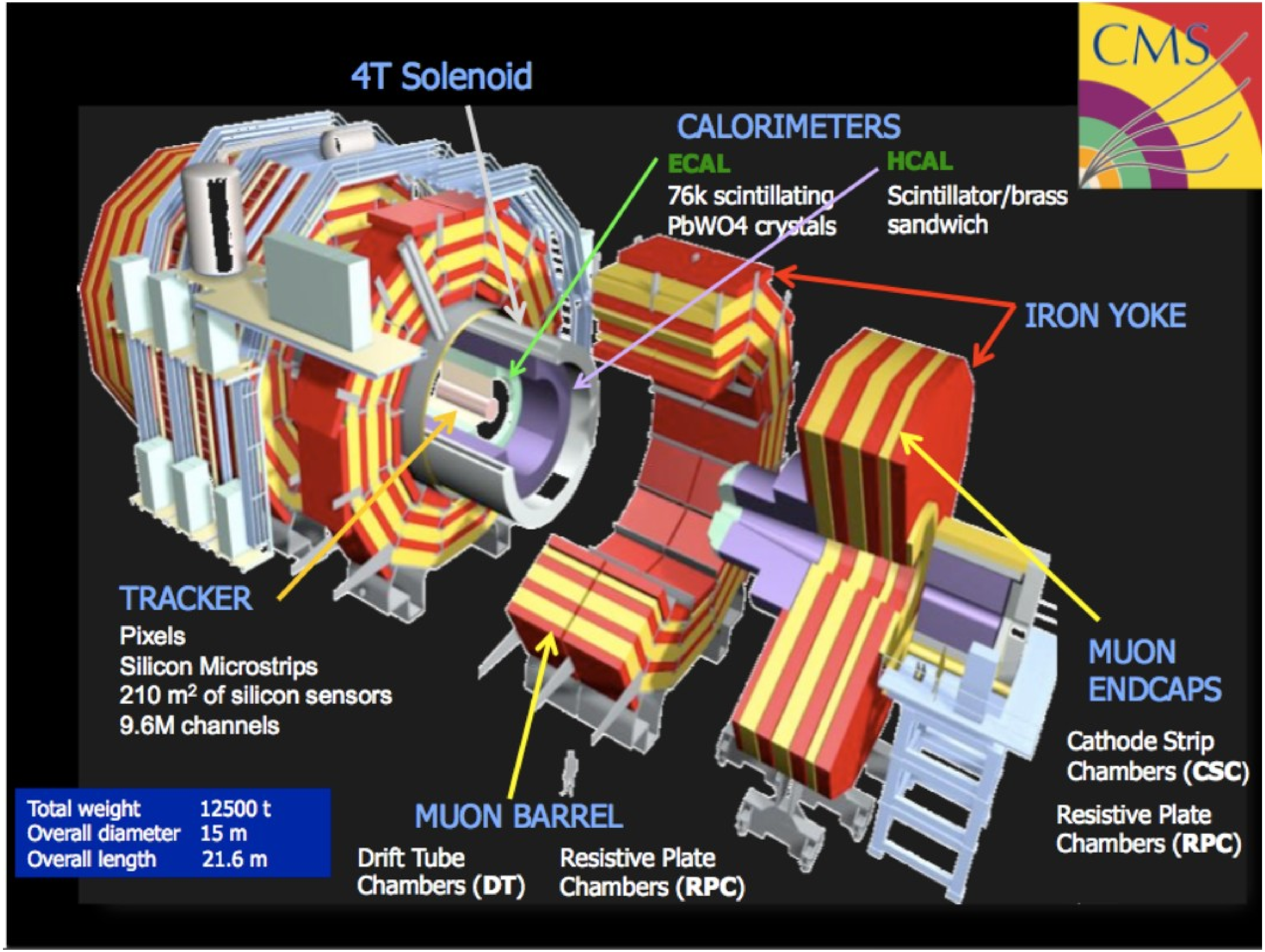
  - a large lever arm (this is basically what ATLAS did)
  - a large magnetic field (this is basically what CMS did)

ATLAS

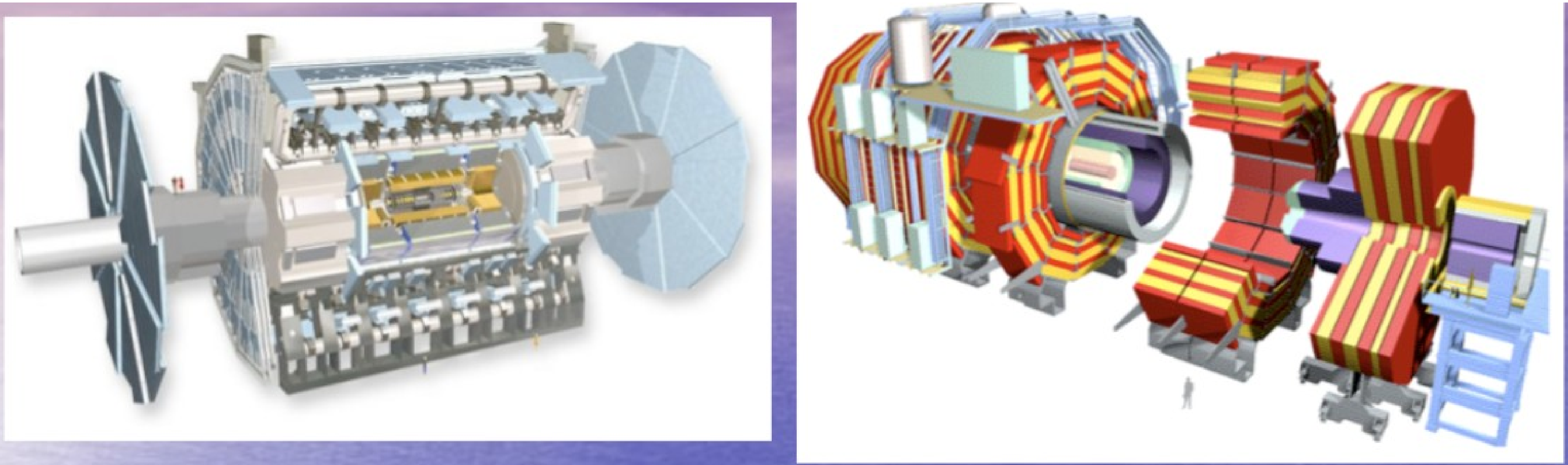


Diameter	25 m
Barrel toroid length	26 m
End-cap end-wall chamber span	46 m
Overall weight	7000 Tons

CMS


CMS
4T Solenoid
CALORIMETERS
ECAL
76k scintillating
PbWO4 crystals
HCAL
Scintillator/brass
sandwich
IRON YOKE
TRACKER
Pixels
Silicon Microstrips
210 m² of silicon sensors
9.6M channels
MUON ENDCAPS
Cathode Strip
Chambers (**CSC**)
Resistive Plate
Chambers (**RPC**)
MUON BARREL
Drift Tube
Chambers (**DT**)
Resistive Plate
Chambers (**RPC**)
Total weight 12500 t
Overall diameter 15 m
Overall length 21.6 m

Important numbers



Tracker	*|η|<2.5 coverage* $\sigma / p_T \approx 5 \cdot 10^{-5} p_T \oplus 0.01 [\mathrm{GeV}]$	*|η|<2.6 coverage* $\sigma / p_T \approx 1.5 \cdot 10^{-5} p_T \oplus 0.005$
EM Calorimeter	*|η|<4.9 coverage* $\sigma / E \approx 10\% / \sqrt{E} [\mathrm{GeV}]$	*|η|<4.9 coverage* $\sigma / E \approx 2-5\% / \sqrt{E}$
HAD Calorimeter	*|η|<4.9 coverage* $\sigma / E \approx 50\% / \sqrt{E} \oplus 0.03 [\mathrm{GeV}]$	*|η|<4.9 coverage* $\sigma / E \approx 100\% / \sqrt{E} \oplus 0.05$
Muon Spectrometer	*|η|<2.7 coverage:* $\sigma / p_T \approx 0.07$ *(1TeV muons)*	*|η|<2.6 coverage:* $\sigma / p_T \approx 0.10$ *(1TeV muons)*

b-jets

- All quarks except the top quark form bound states at the LHC

- In the case of *b* quarks, a single *B* or *D* meson carries most of the energy

- When a *B* meson decays it will:

    - typically travel 450 μm before decaying
    - typically decay to $Dl\nu$ or D + other hadrons
    - a *D* meson typically decays to kaons plus leptons or hadrons

- All of this makes *b* jets a bit special:

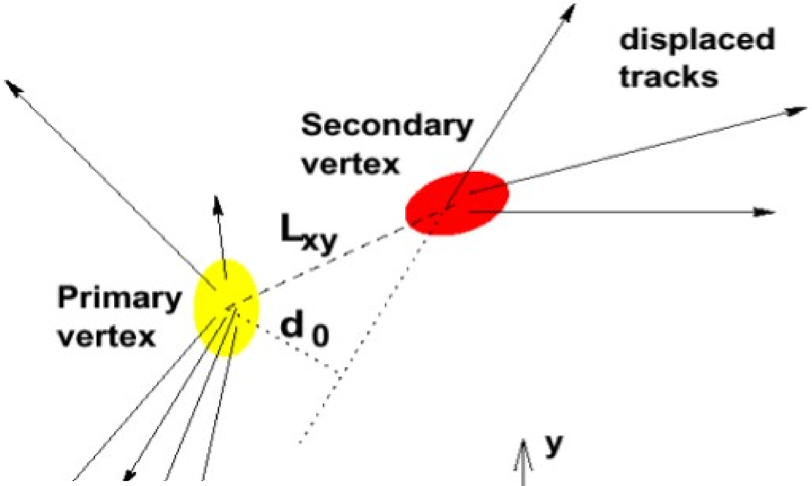
    - typically has a displaced vertex (or two)
    - often has more than 2 tracks missing the collision point by 200-1000 μm
    - has a muon embedded in it ~15% of the time

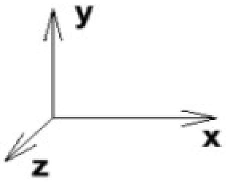
- Charm quarks show similar behaviour, but are less likely to have displaced tracks and vertices

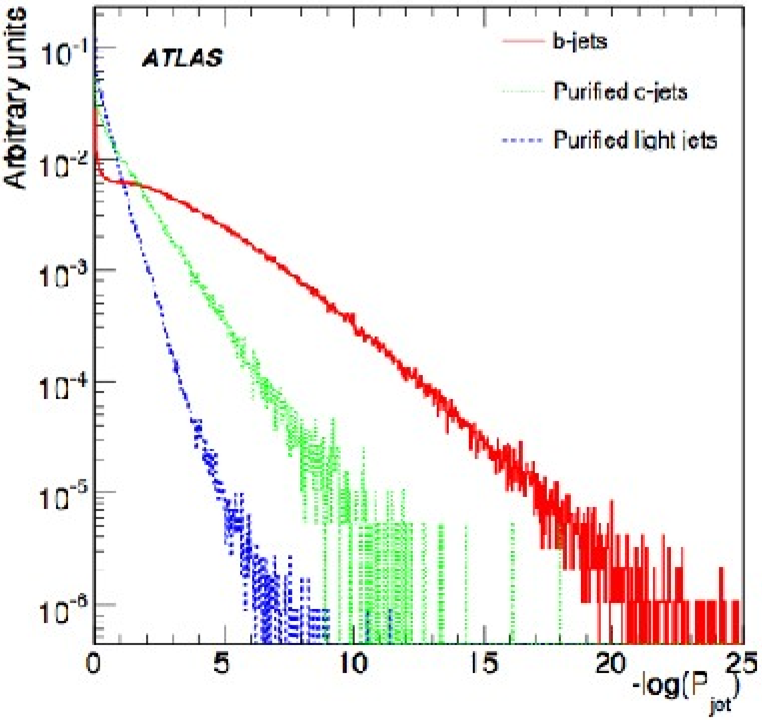
b-tagging

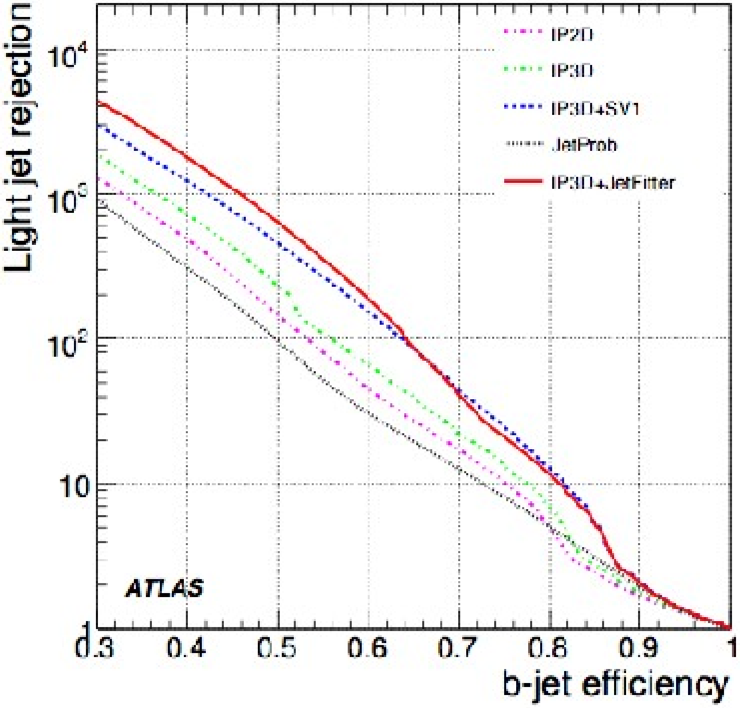
- Measure the decay length L_{xy} or impact parameter d_0

  - typically a modern *b* tag algorithm uses multivariate techniques



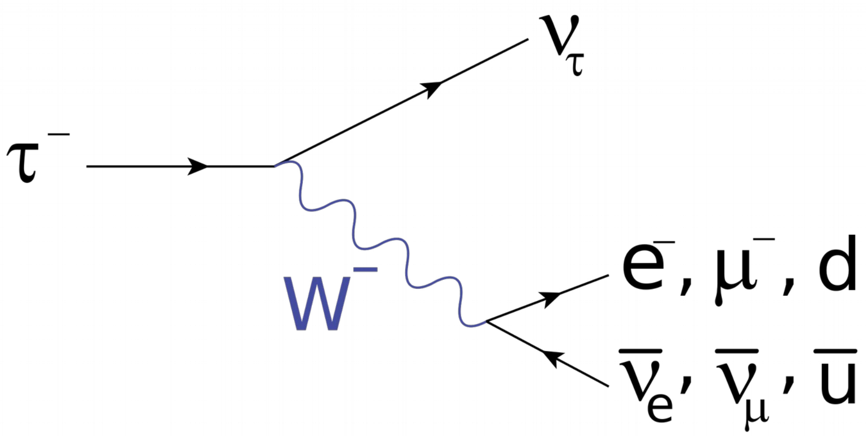


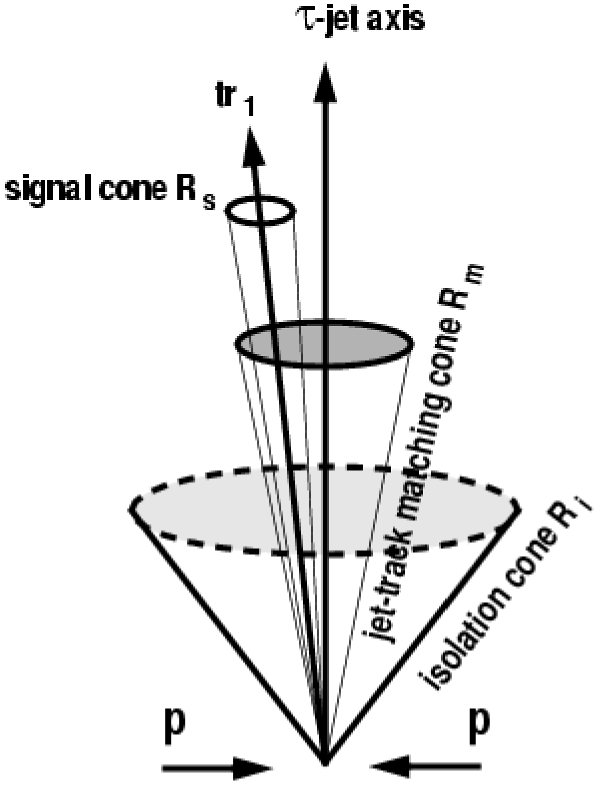




τ-tagging

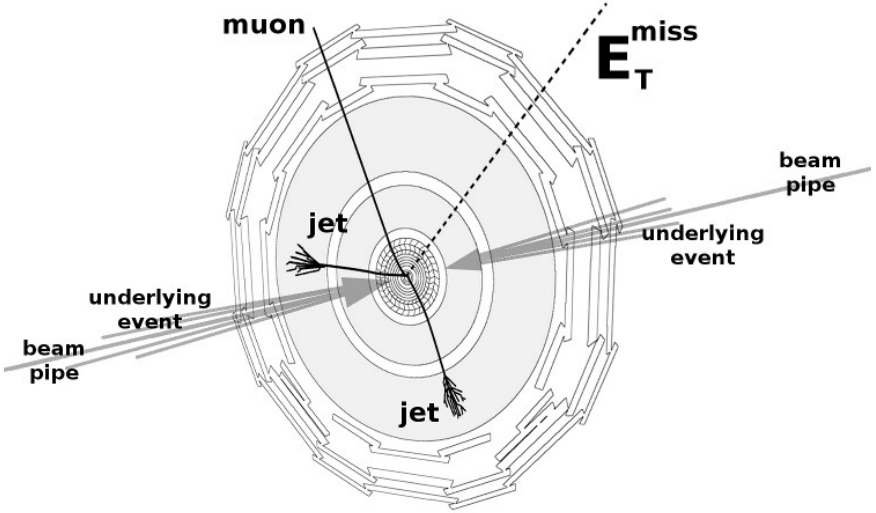
- 34% to *e* or μ
- 50% to one charged hadron (plus neutral hadrons)
- 15% to 3 charged hadrons (plus neutral hadrons)
- **Always** get a tau neutrino – can never measure E_τ!





- Leptonic taus look just like *e* or μ
- Hadronic taus look like special jets
  - - 1 or 3 tracks (typical jets ~ 5 – 20 tracks)
  - - invariant mass of decay products < m_τ ~ 1.8 GeV
- For, e.g. GMSB, tau searches are crucial
- Can tag taus with typical efficiency of 40%

Missing transverse energy



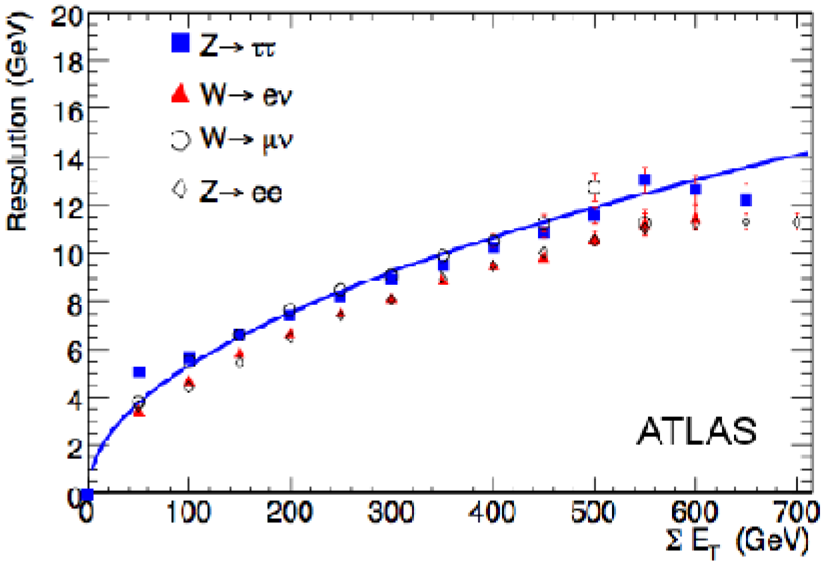
- We expect a certain amount of missing E_T in the SM

  - neutrino production
  - mismeasurement of visible objects
  - other fake sources (e.g. cosmic muons overlaid on collision data)

- Substantial missing E_T is a *generic* feature of models with dark matter candidates

  - these models are cooked to feature a Weakly Interacting Massive Particle (WIMP)
  - this is stable, neutral and invisible to ATLAS and CMS
  - e.g. SUSY, UED, Little Higgs with T parity, many more...

Missing transverse energy



- Careful calibration required for accurate MET

- Use standard processes known to have specific MET distributions

  - important to calibrate at several points → extrapolation to higher values

- Rough MET resolution follows the calorimeter resolution

$$\sigma = 0.57\sqrt{E\,(\mathrm{GeV})}$$

Summary of detector output

- LHC detector output (after reconstruction) consists of:
    - four vectors of jets, leptons and photons (plus particle identification)
    - tagging of *b* jets ~ 70% of the time
    - tagging of τ leptons ~ 40 % of the time
    - missing transverse energy
    - EXTRA: evidence for exotic objects (long-lived sparticles?)
- This is our complete LHC toolkit!

The whole game of experimental SUSY searches is to use only this information to discover sparticle production, then measure sparticle properties in case of discovery

One last thing: triggers

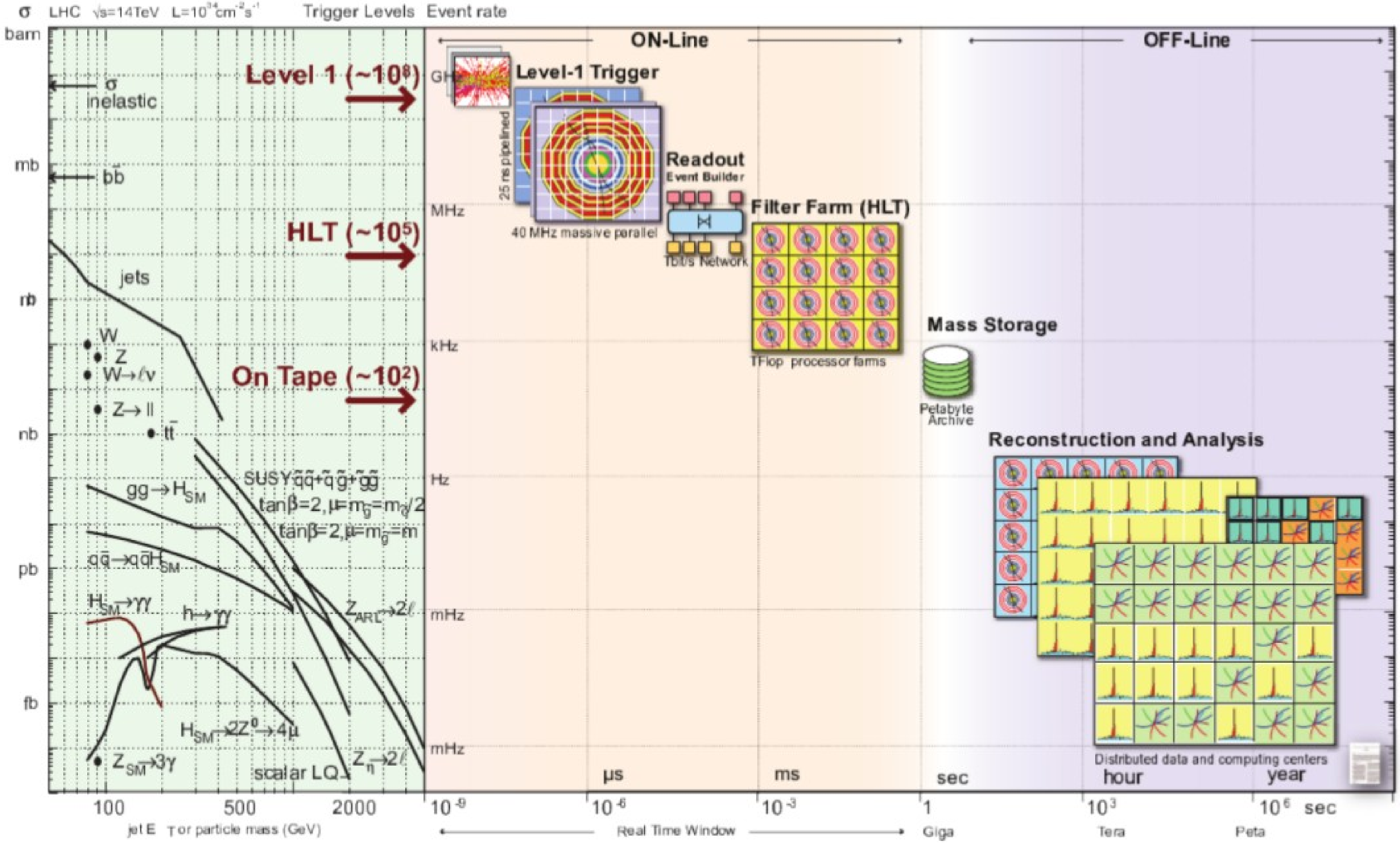
- Proton-proton collision rate at the LHC is 40 MHz
- Pixel detector has ~ 66M readout channels, O(10^4) are hit per event
- Data size to be stored per pixel is 4 bytes

⇒ > 120,000 TB of data per day!

- Need to reduce data volume online: use a **trigger**

  - hardware + software triggers reduce events in real time
  - can use a variety of detector information

Interesting things << boring things



Trigger design

- Good knowledge of detector and signatures is needed to efficiently select interesting events

  - relevant detector parts and their performance

  - needed/desired measurement precision

  - physical properties of signal and background events (kinematics, multiplicities, etc)

- Trigger strategy needs careful planning and has scientific, technical and political elements

  - bandwidth will always be limited

- Theorists:

  - don't forget that untriggered events are *lost forever!*
  - gives you a “get out of jail free card” for your favourite difficult models

- Experimentalists:

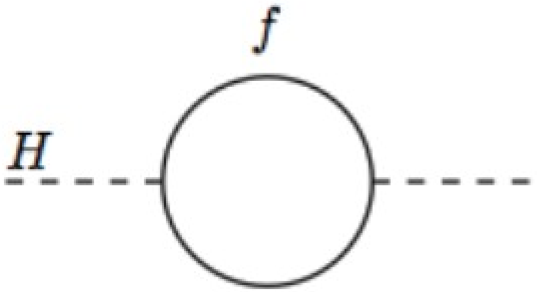
  - trigger strategy plays a central role in designing effective analyses
  - do not be afraid of rewriting the rule book (e.g. razor triggers)

A very simple trigger menu example

Object	Physics coverage	Object name
electrons	Higgs, new gauge bosons, extra dim., SUSY, W/Z, top	e25i, 2e15i, e60
Photons	Higgs, SUSY, extra dim.	γ60, 2γ20i
Muons	Higgs, new gauge bosons, extra dim., SUSY, W/Z, top	μ20i, 2μ10
Jets	SUSY,compositness,resonances	j400, 3j165, 4j110
Jets+missEt	SUSY, leptoquarks	j70+xE70
Tau+missEt	Extended Higgs models (e.g. MSSM), SUSY	τ35i+xE45

- Note SUSY trigger requirements overlap with a lot of other SM & BSM scenarios

Why bother with SUSY at the LHC at all?



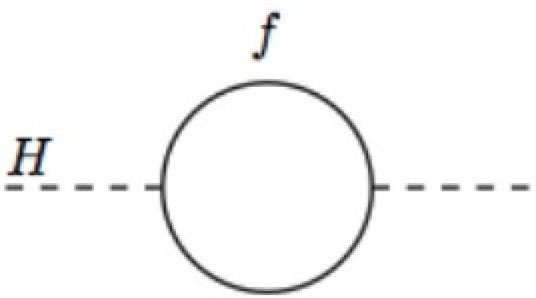
$$\Delta m_H^2 = \frac{\lambda_f^2}{8\pi^2}[-\Lambda^2 + 6m_f^2 ln\frac{\Lambda}{m_f}]$$

- The Higgs mass receives quantum corrections through Feynman diagrams as shown

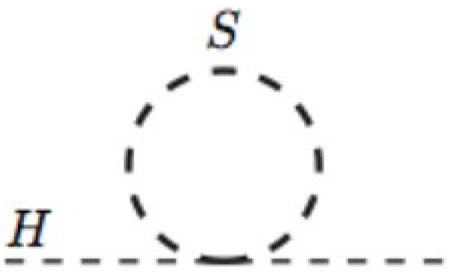
- We know that m_h ~ 125 GeV

  - naivelyately this should be of the order of the Planck scale
  - this is the **hierarchy problem**

The hierarchy problem solved



$$\Delta m_H^2 = \frac{\lambda_f^2}{8\pi^2}[-\Lambda^2 + 6m_f^2 ln\frac{\Lambda}{m_f}]$$



$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}[\Lambda^2 - 2m_S^2 ln\frac{\Lambda}{m_S}]$$

- Scalar sparticles provide extra contributions to the Higgs quantum corrections

  - these conspire to cancel the Λ^2 term

- We are left with a *much nicer* logarithmic correction:

$$\Delta m_H^2 \approx \frac{\lambda_f^2}{4\pi^2}(m_S^2 - m_f^2) ln\frac{\Lambda}{m_S}$$

- *But*: need m_s not too far from m_f ⇒ TeV scale SUSY?

Naturalness gets a bit more complicated

1. Tree level: light higgsinos

- For large tan β → EWSB condition $\frac{M_Z^2}{2} = \frac{(m_{H_d}^2 + \Sigma_d) - (m_{H_u}^2 + \Sigma_u)\tan^2\beta}{\tan^2\beta - 1} - |\mu|^2$

$\rightarrow M_Z^2 = -2(m_{H_u}^2 + |\mu|^2) + \cdots$

- $|\mu| \lesssim 200$ GeV for $\Delta \leq 10$ with $\Delta[a_i] = \frac{\partial \ln m_Z^2}{\partial \ln a_i^2}$, $\Delta = \max \Delta[a_i]$ and fundamental parameters a_i

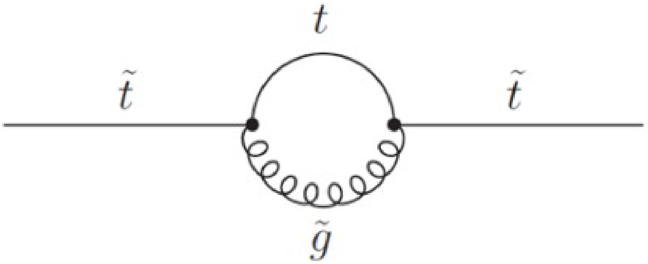
2. 1-loop: light stops and winos

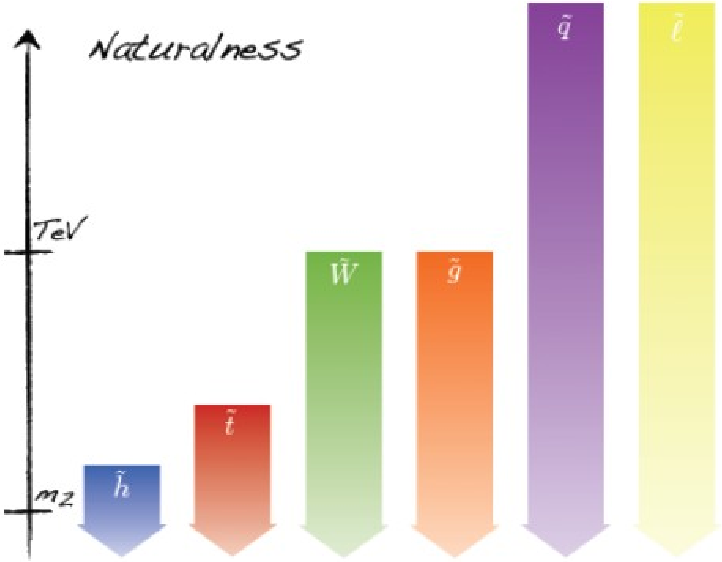
- Stop masses below 400 GeV for $\Delta \leq 10$
- Wino masses below 1 TeV

3. 2-loop: light gluinos

- Related to naturalness of other particles
- Stop mass gets corrections from gluino mass

$\rightarrow m_{\tilde{g}} \lesssim 2 m_{\tilde{t}}$





SUSY mass scales motivated by electroweak naturalness

N. Craigh, arXiv:1309.0528

What about the 125 GeV Higgs?

- Things get more complicated still

- We actually need the radiative corrections to m_h to be *rather large* in the MSSM

$$M_h^2 \approx M_Z^2 \cos^2 2\beta + \frac{3m_t^4}{4\pi^2 v^2}\left[\log\frac{\Delta_S^2}{m_t^2} + \frac{X_t^2}{\Delta_S^2}\left(1 - \frac{X_t^2}{12\Delta_S^2}\right)\right] \quad \text{with} \quad \Delta_S^2 = m_{\tilde{t}_1} m_{\tilde{t}_2}$$

- Either stops are heavy (≫1 TeV) → Tension to "naturalness" (→ fine tuning)
- or large stop mass splitting ("Maximal mixing")

$$\mathcal{M}_{\tilde{t}} = \begin{pmatrix} \tilde{m}_{t_L}^2 & \overbrace{m_t(A_t - \mu\cot\beta)}^{X_t} \\ m_t(A_t - \mu\cot\beta) & \tilde{m}_{t_R}^2 \end{pmatrix}$$

- So maybe we shouldn't be surprised that we don't see SUSY at the LHC?

  - or maybe the MSSM is too simple?

In any case we must continue to hunt!

R-parity conservation

- In the MSSM, baryon number and lepton number are no longer conserved

  - but we have precise limits on their conservation!

- Can introduce a Z_2 symmetry called "R-parity" that prevents the extra couplings:

$$P_{\mathrm{R}} = (-1)^{3(B-L)+2s}$$

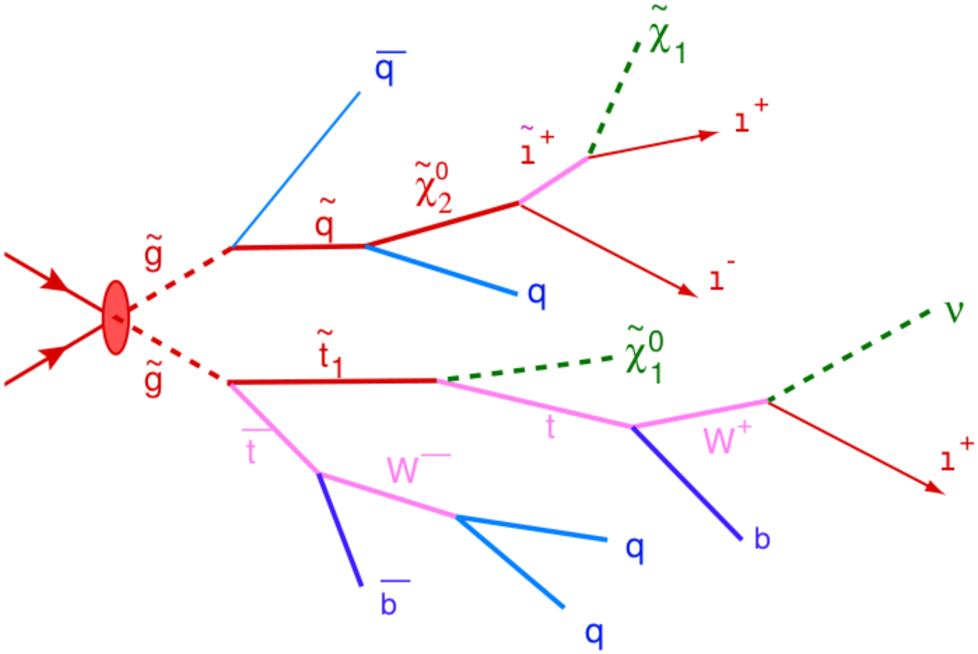
- Two immediate consequences:

  1) The lightest supersymmetric particle is absolutely stable

  2) Sparticles must be *pair-produced* at the LHC

- We will mostly concentrate on R-parity conserving (RPC) searches

A typical SUSY hard process (assuming R-parity conservation)



- $\not{E}_T$: from LSP escaping detection
- High E_T jets: guaranteed if squarks/gluinos if unification of gaugino masses assumed.
- Multiple leptons (Z): from decays of Charginos/neutralinos in cascade
- Multiple τ-jets or b-jets (h): Often abundant production of third generation sparticles

What would actually happen?

- The answer is **completely model-dependent**!

- Depends on the answers to at least the following questions:

  - is the gluino light?

  - how many of the squarks are light?

  - what are the details of weak gaugino mixing?

  - are there degeneracies in the mass spectrum?

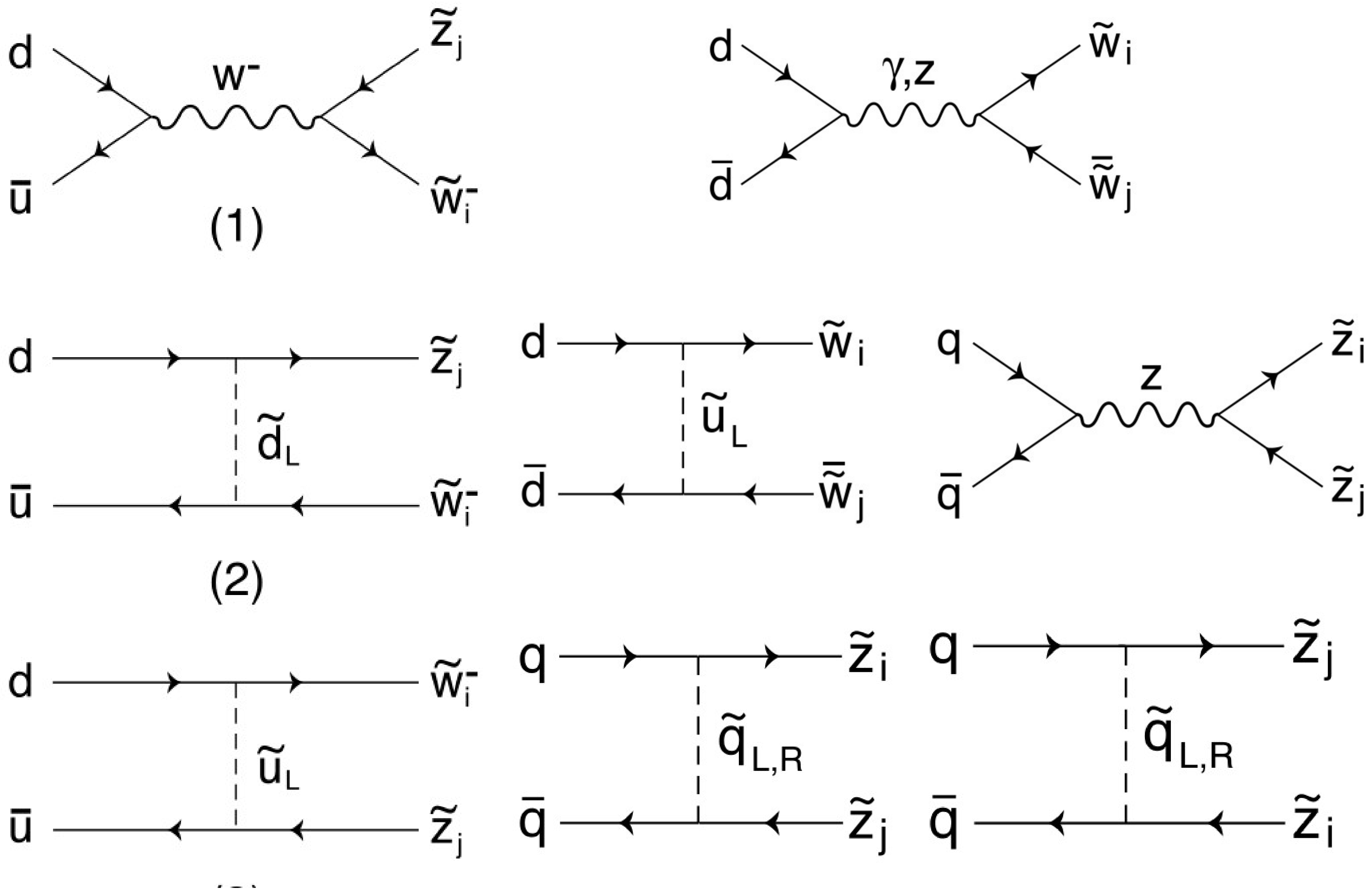
  - how heavy are the extra Higgs bosons, and what are their couplings?

  - is the MSSM true, or something more complicated?

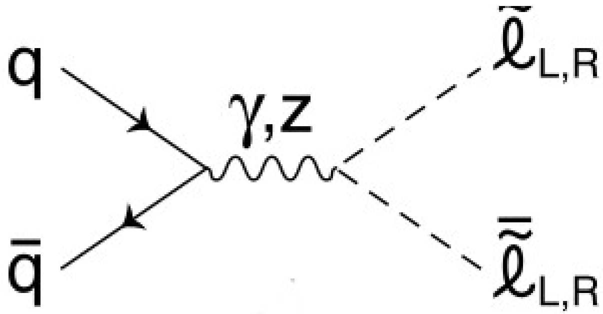
- Please don't forget that **every event is different**

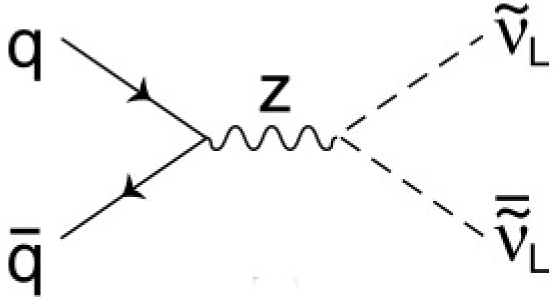
  - will come back to this when I tell you about simplified models

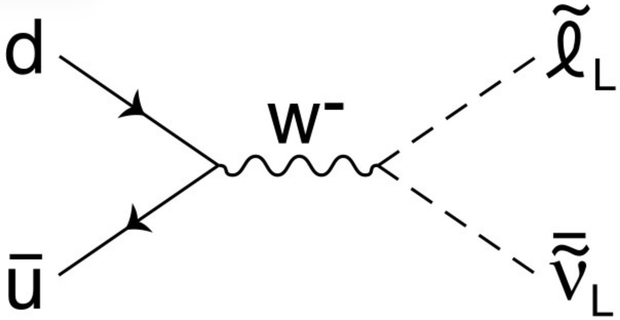
Tree level SUSY production diagrams: EW gauginos

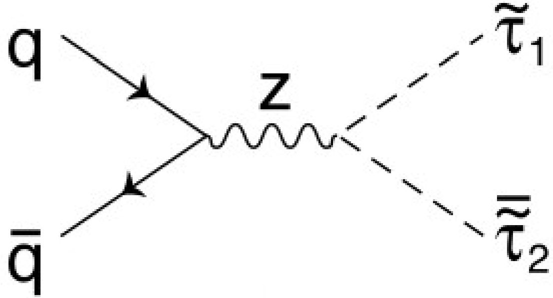


Tree level SUSY production diagrams: sleptons

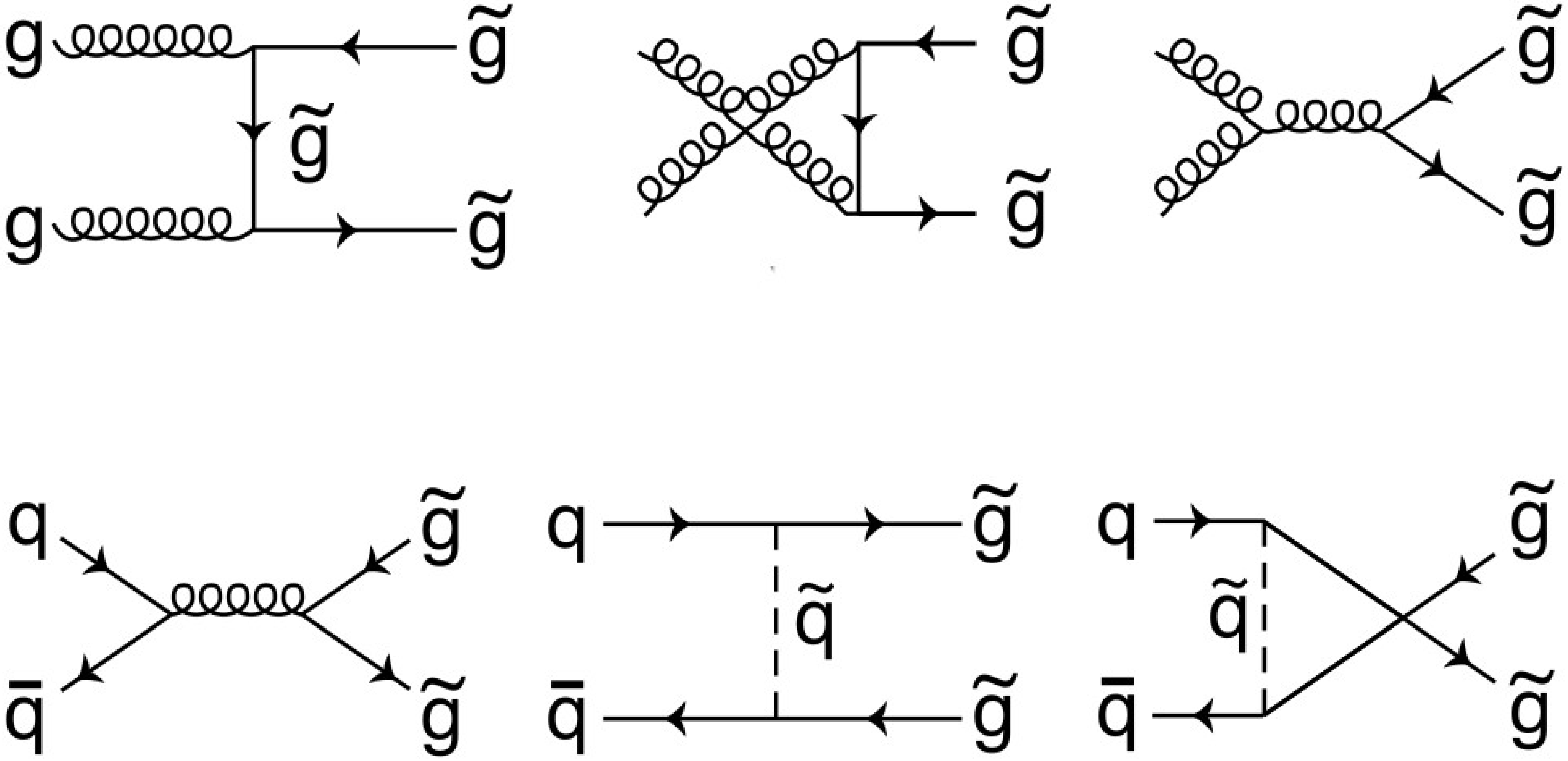




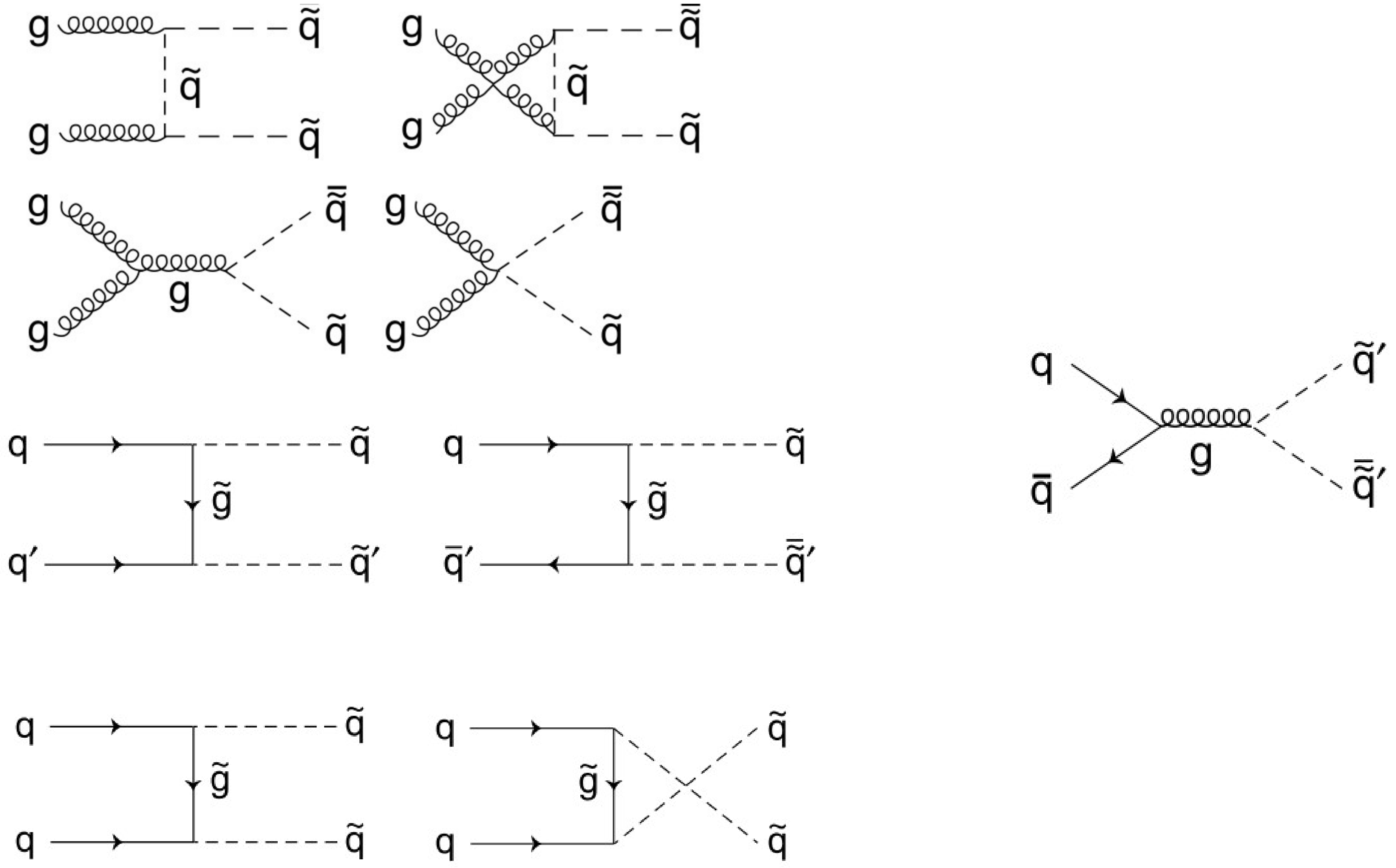




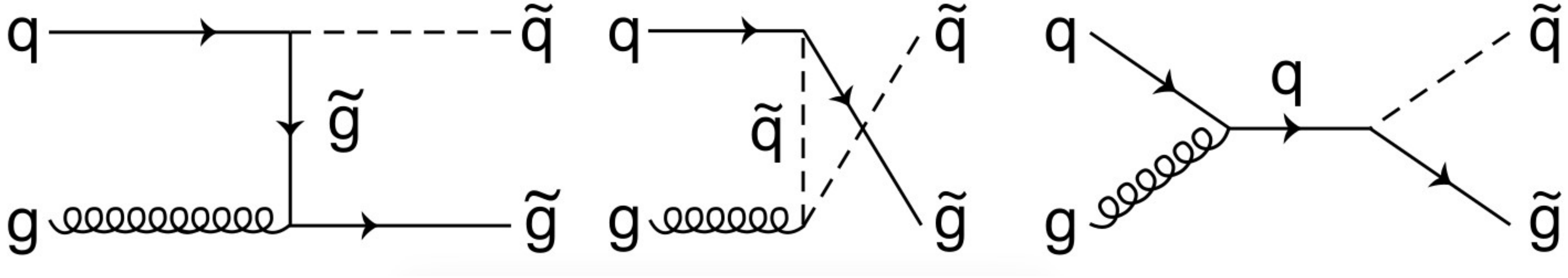
Tree level SUSY production diagrams: gluino pair



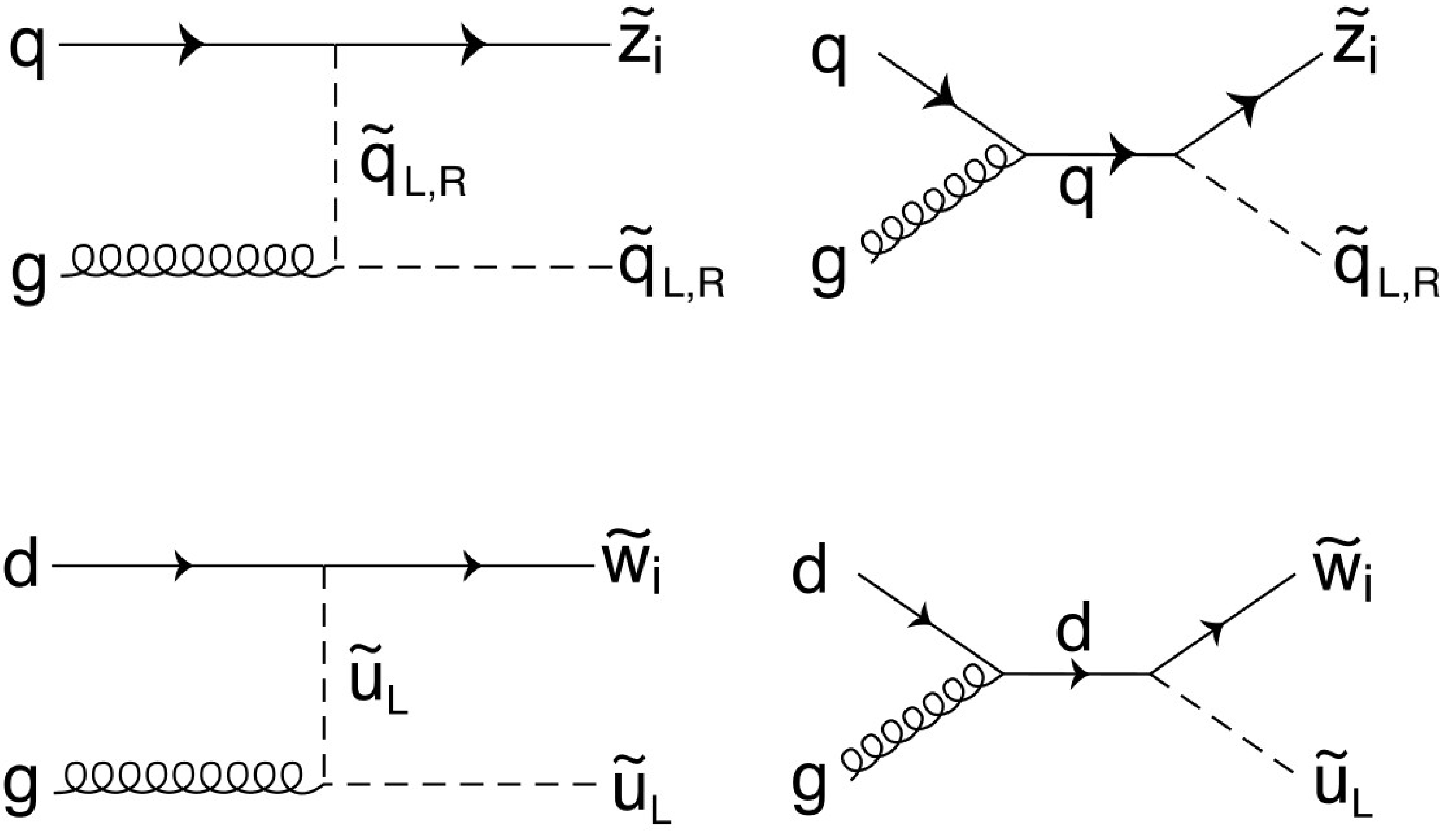
Tree level SUSY production diagrams: squark pair



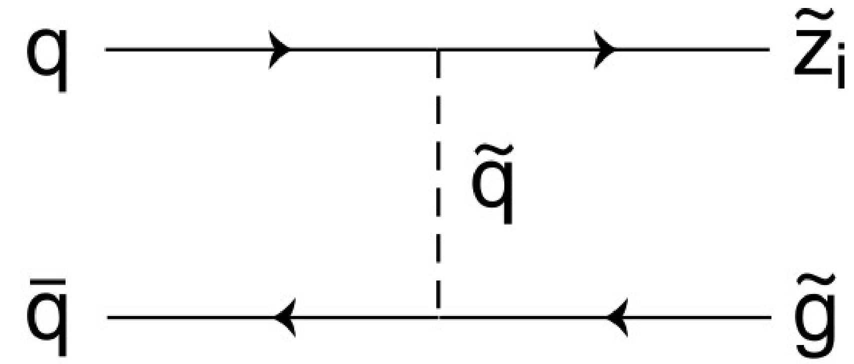
Tree level SUSY production diagrams: gluino-squark

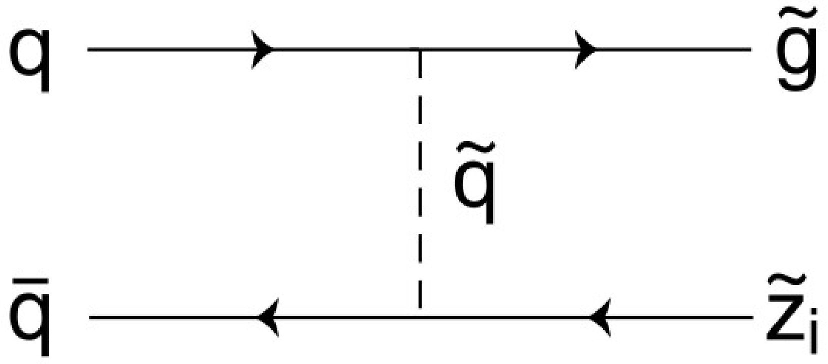


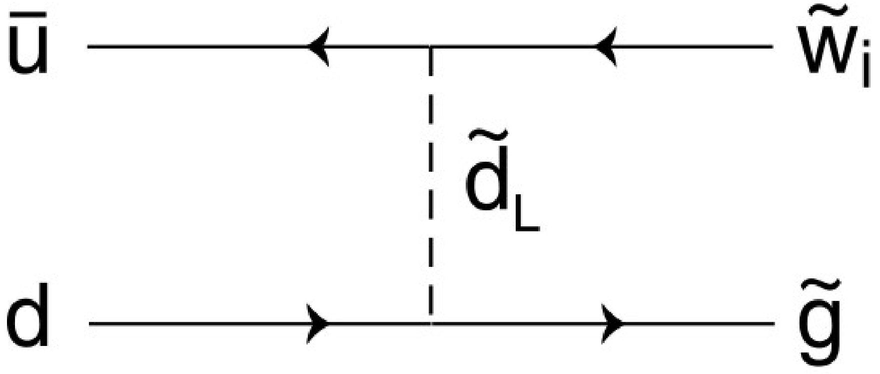
Tree level SUSY production diagrams: squark-neutralino/chargino

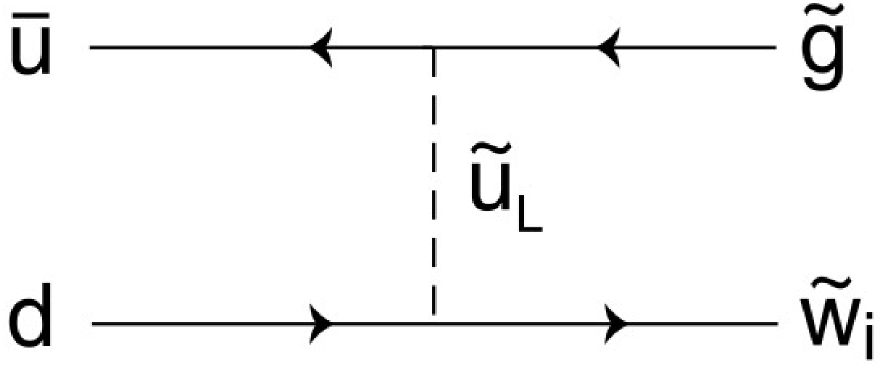


Tree level SUSY production diagrams: gluino-neutralino/chargino

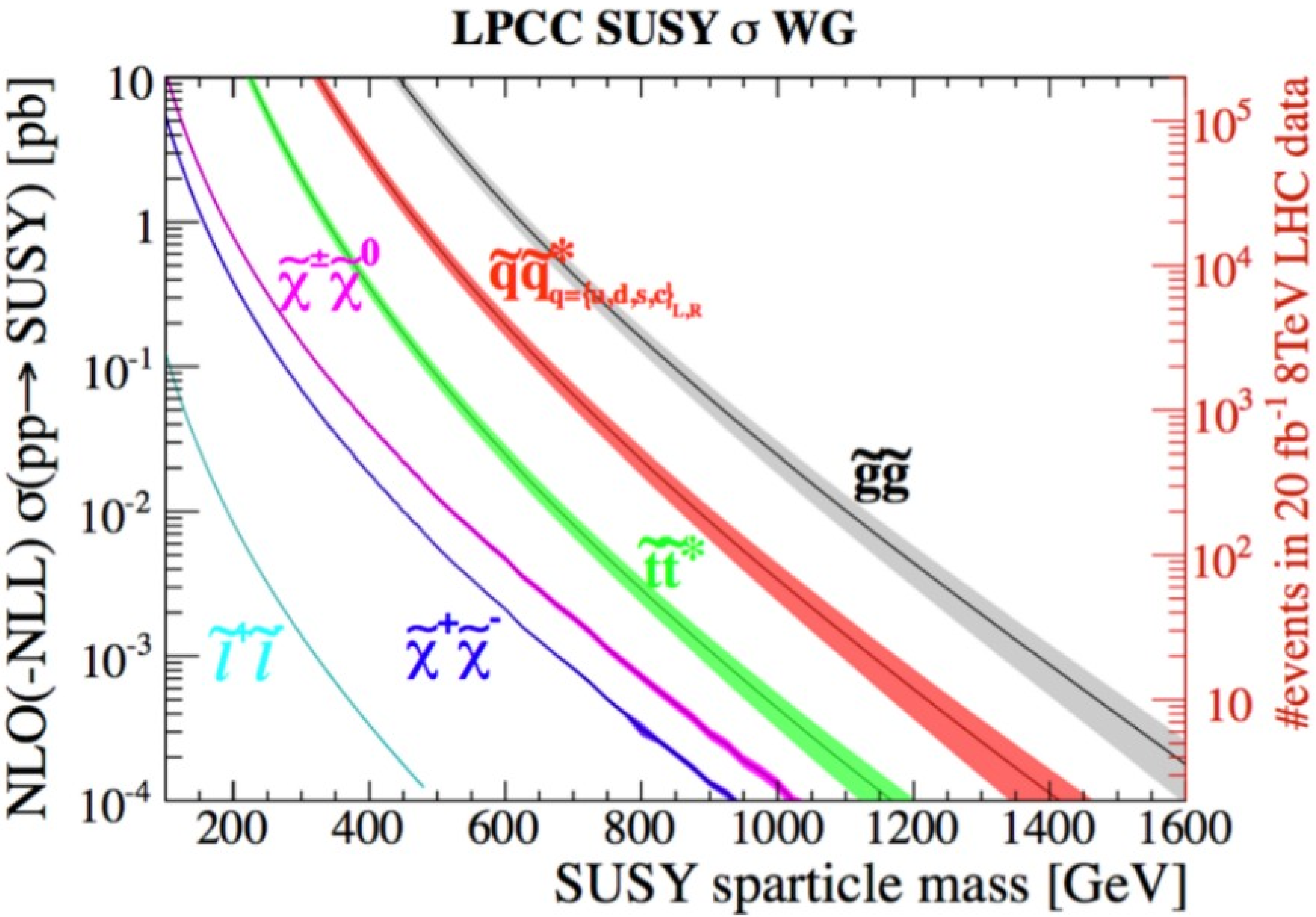








NLO+NLL cross-sections (caution advised)



Summary of lecture 1

- We have no idea exactly what SUSY will look like at the LHC
    - naturalness is nice, but doesn't give us many clues
    - the Higgs boson discovery complicates matters
    - null observation so far is perfectly consistent with both SUSY and the Higgs mass
- Lots of potential options to look for:
    - high multiplicities
    - lots of missing energy
- LHC detectors give us:
    - particle ID and four vectors for jets, leptons and photons
    - tau and b tagging
    - missing transverse energy

Next lecture: How do we use this information to discover SUSY?!