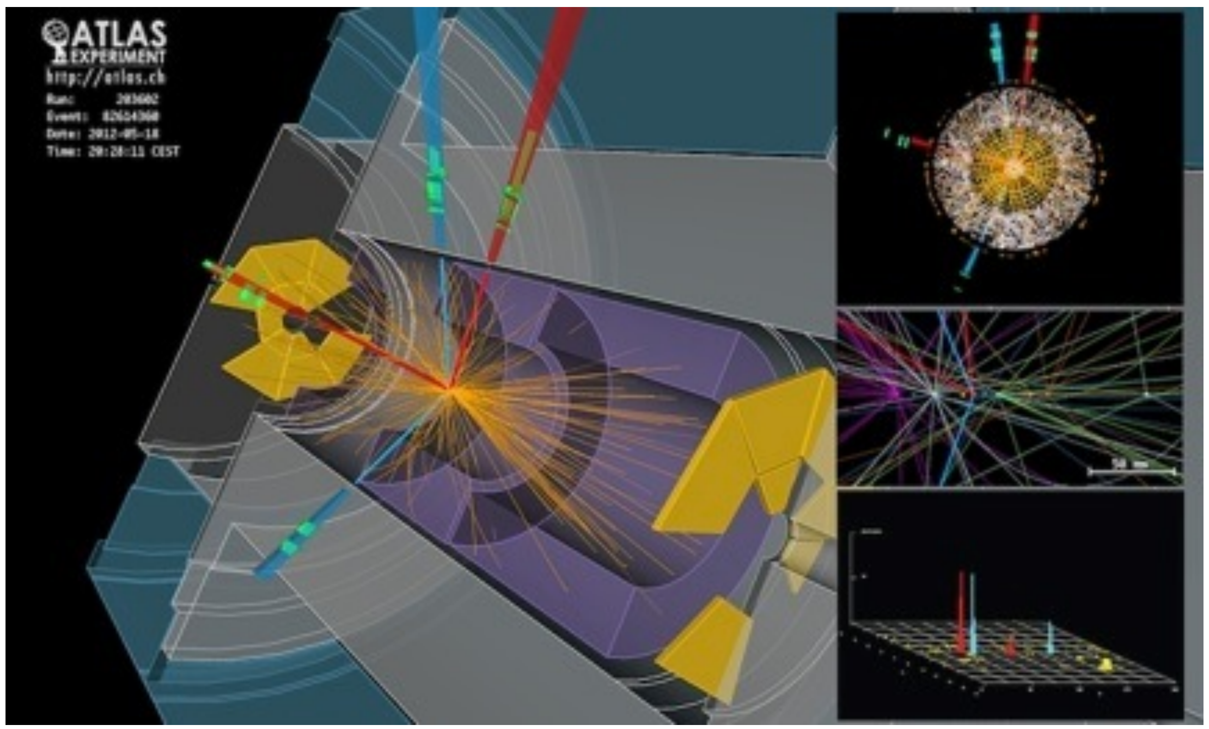
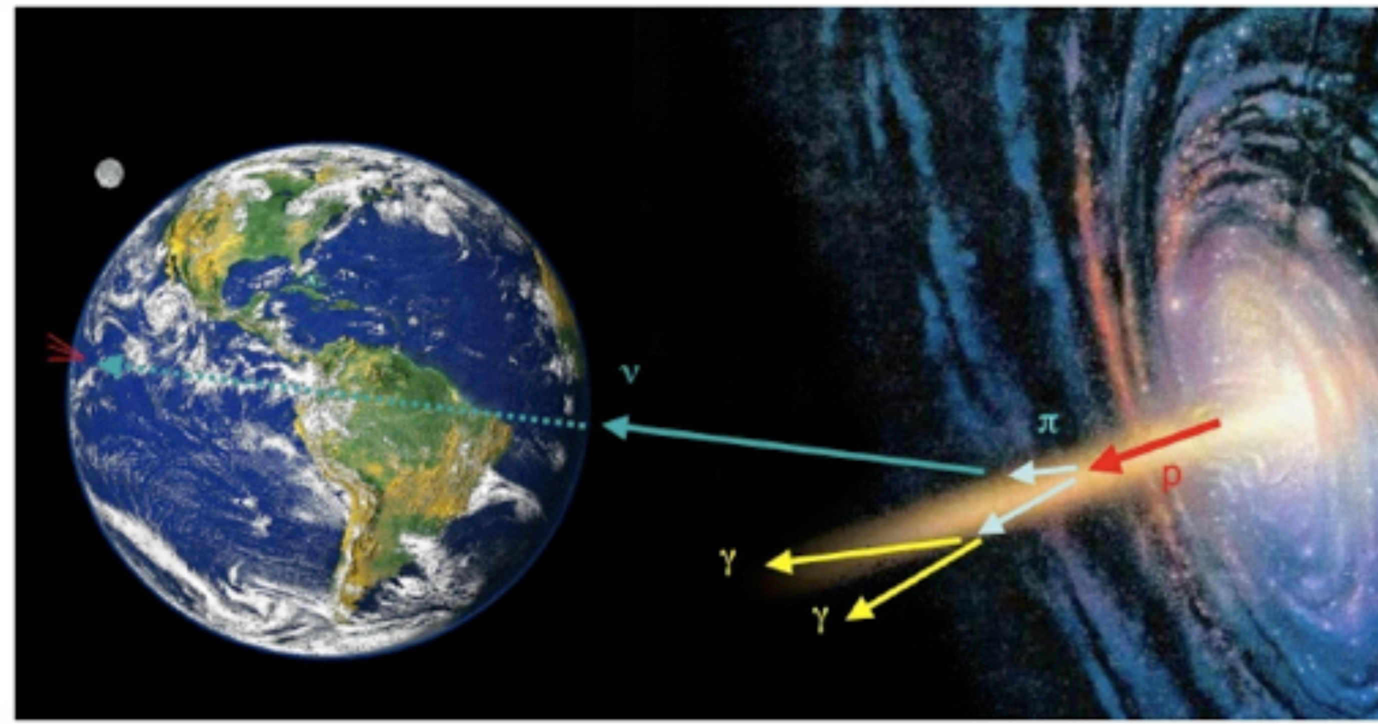
Particle Physics at Colliders and in the High Energy Universe





14. New Physics at the Energy Frontier

28.01.2019

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Dr. Frank Simon
Dr. Bela Majorovits

Overview

- Shortcomings of the Standard Model and Motivations for New Physics
- Features of Grand Unified Theories
- Supersymmetry
- LHC Searches for
  - SUSY
  - Dark Matter
  - Extra Dimensions
- A Broad Look at Current LHC Limits

Introduction: Beyond the Standard Model at LHC

- A significant fraction of all analyses performed at the LHC search for phenomena beyond the standard model - typically classified in:
  - ***Supersymmetry***: Searching for indications for a concrete, popular and well-motivated extension of the Standard Model
  - ***Exotics***: More generic new phenomena searches - often also motivated by theoretical ideas, but also very general searches for deviations from Standard Model expectations

Introduction: Beyond the Standard Model at LHC

- A significant fraction of all analyses performed at the LHC search for phenomena beyond the standard model - typically classified in:
  - ***Supersymmetry***: Searching for indications for a concrete, popular and well-motivated extension of the Standard Model
  - ***Exotics***: More generic new phenomena searches - often also motivated by theoretical ideas, but also very general searches for deviations from Standard Model expectations

Impossible to cover this in a single lecture - here:
A focus on Supersymmetry as an example to illustrate motivations and properties of BSM theories
A few examples of other phenomena and search strategies

Reminder: Limitations of the Standard Model

- The Standard Model with:
  - Fundamental fermions (3 pairs of quarks, 3 pairs of leptons)
  - Fundamental interactions through gauge fields, manifested through
    - W, Z, γ (electroweak - SU(2) x U(1))
    - gluons (strong - SU(3))

successfully describes all HEP experiments and observations.

BUT:

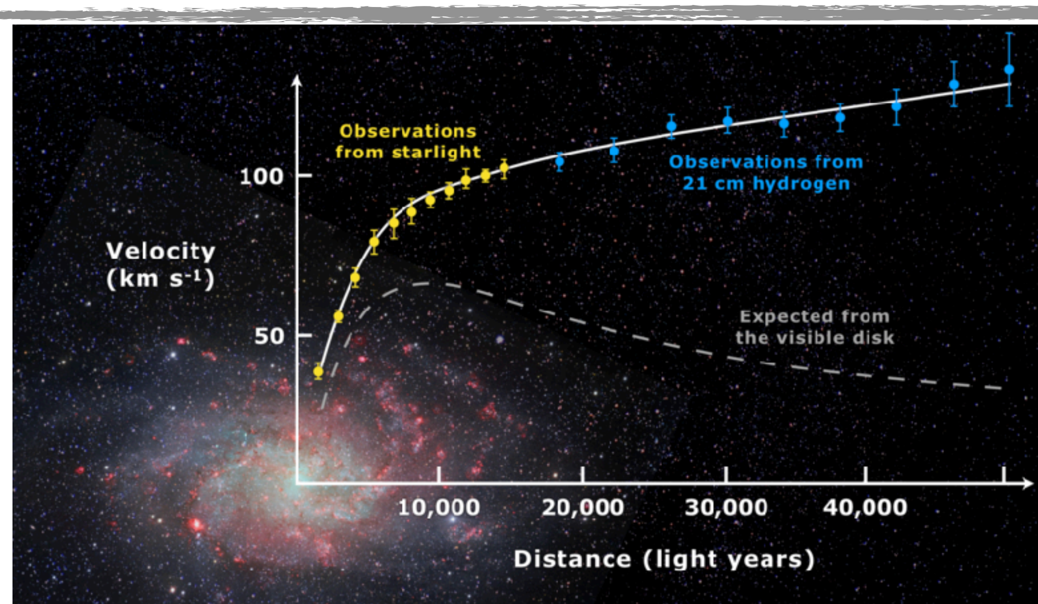
- it has conceptual problems
- it is incomplete: Fails to describe astrophysical / cosmological observations.

Limitations: Conceptual Problems

	possible solution
• Too many free parameters: ~18 masses, couplings, mixing angles	
• No unification of electroweak and strong interaction	GUT; E ~ 10^{16} GeV
• No inclusion of quantum gravity	TOE; E ~ 10^{19} GeV
• Family replication: Why 3 families of fundamental fermions?	
• Hierarchy problem: “Fine tuning” of precise cancellation of radiative corrections	SUSY, Extra dimensions, … E ~ 10^{3} GeV
• Why 1/3 - charges of quarks - or: What ensures exactly equal charge of protons and electrons?	GUT; E ~ 10^{16} GeV

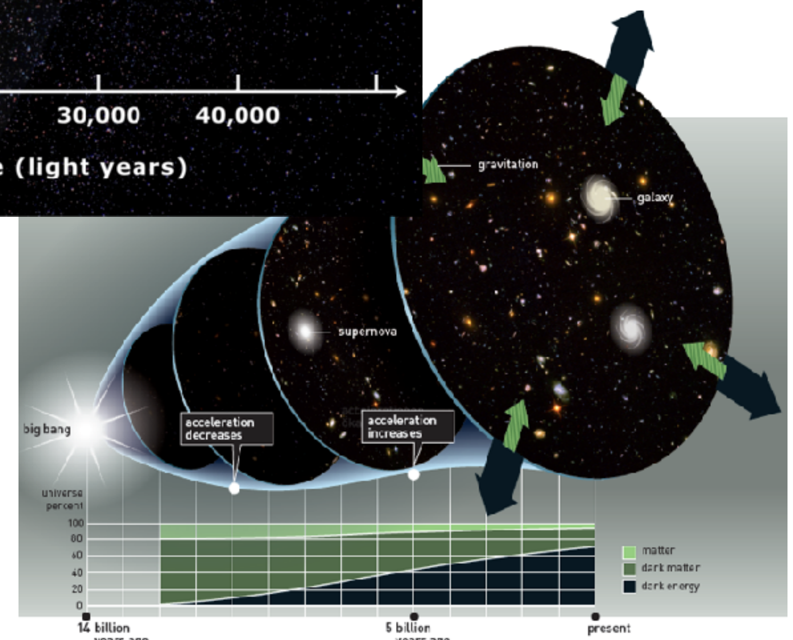
Limitations: Observations

- Dark Matter

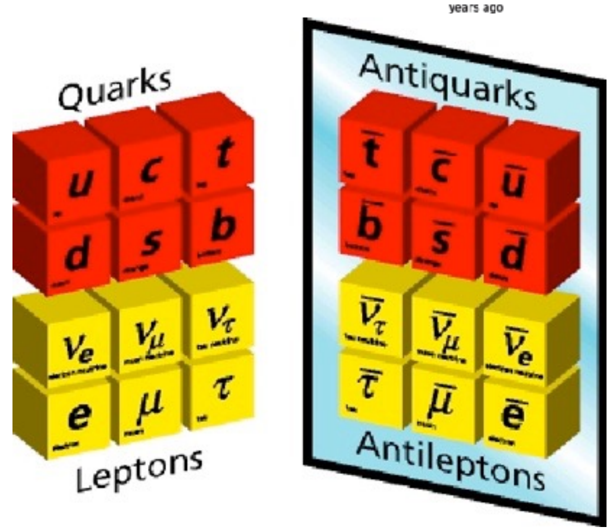


New particles?

- Dark Energy



- Baryon asymmetry



New interactions?

- Neutrino masses

Ideas Beyond: Grand Unified Theories

- The simplest symmetry that contains U(1), SU(2) and SU(3): SU(5) (Georgi, Glashow 1974)

Ideas Beyond: Grand Unified Theories

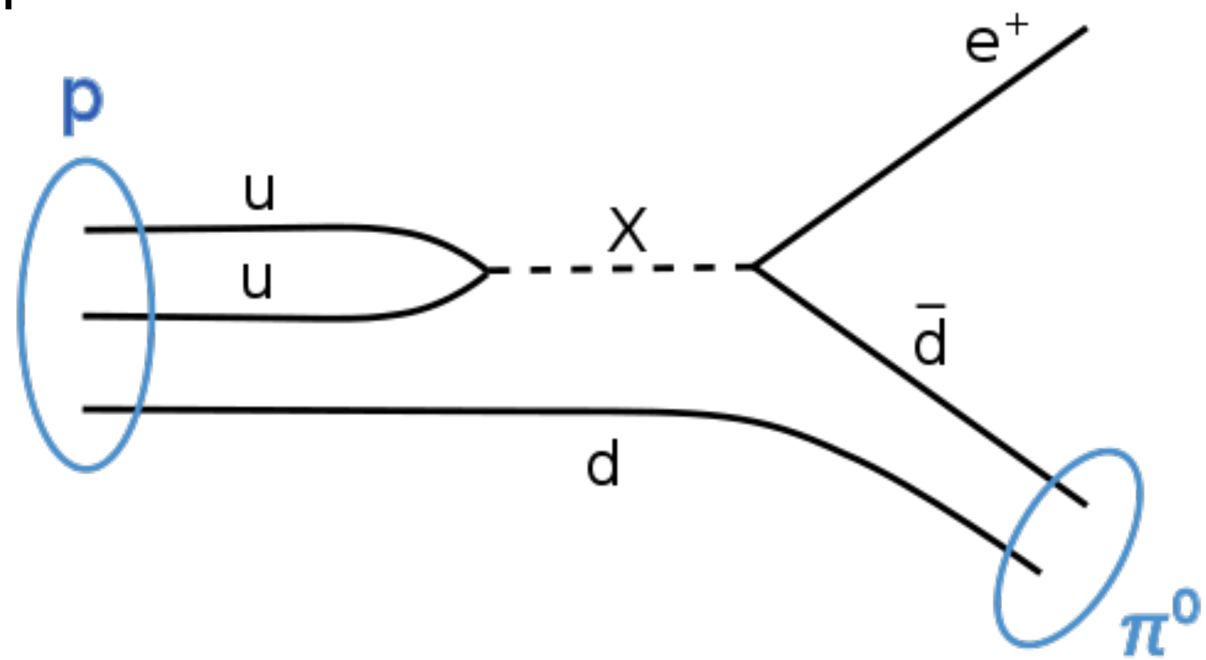
The particle structure in SU(5) GUT:

- Multiplets of (known) leptons and quarks, which can be transformed by the exchange of new heavy bosons ("leptoquarks") X, Y with -1/3 and -1/4 charge

a direct consequence: Proton decay via p → $\pi^0 e^+$

$$\tau_p \sim \frac{M_X^4}{\alpha_{GUT}^2 M_p^5} \sim 10^{30\pm1} \text{ yr}$$

for $M_X \sim 10^{15}$ GeV



already excluded by SuperKamiokande: Standard SUSY-GUT excluded.

more next week!

Ideas Beyond: Grand Unified Theories

- Electric charge is one of the generators of SU(5)
  - Quantisation of charge follows from exchange rules
  - Sum of all charges in eac˙ fermion multiplet = 0
    (e.g. each family: neutrino, lepton, 3 x up-type quark, 3 x down-type quark)

=> Explains 1/3 charges of quarks by existence of 3 colors
=> Guarantees equal charge of proton and electron

Additional consequences:

- Small, but finite neutrino mass
- Existence of heavy magnetic monopoles

Coupling Constants: Unification?

- For GUTs: unification of running coupling constants?

$\alpha_1(M_X) = \alpha_2(M_X) = \alpha_3(M_X)$ with: $\alpha_1 = 8\,\alpha_{em}/3 = 8(e^2/4\pi)/3$;

$\alpha_2 = g^2/4\pi$; $(g = e / \sin\theta_w)$

$\alpha_3 = \alpha_s$

energy dependence: $$\alpha\left(q^2\right) = \frac{\alpha(\mu^2)}{1-\beta_0\alpha(\mu^2)\ln(q^2/\mu^2)} \;;\; \text{mit} \;\; -\beta_0 = \frac{11N_c - 4N_f}{12\pi}$$

N_c= 0, 2, 3 für U(1), SU(2), SU(3),

N_f = 3 (Number of fermion generations)

Coupling Constants: Unification?

- For GUTs: unification of running coupling constants?

$\alpha_1(M_X) = \alpha_2(M_X) = \alpha_3(M_X)$ with: $\alpha_1 = 8\,\alpha_{em}/3 = 8(e^2/4\pi)/3$;

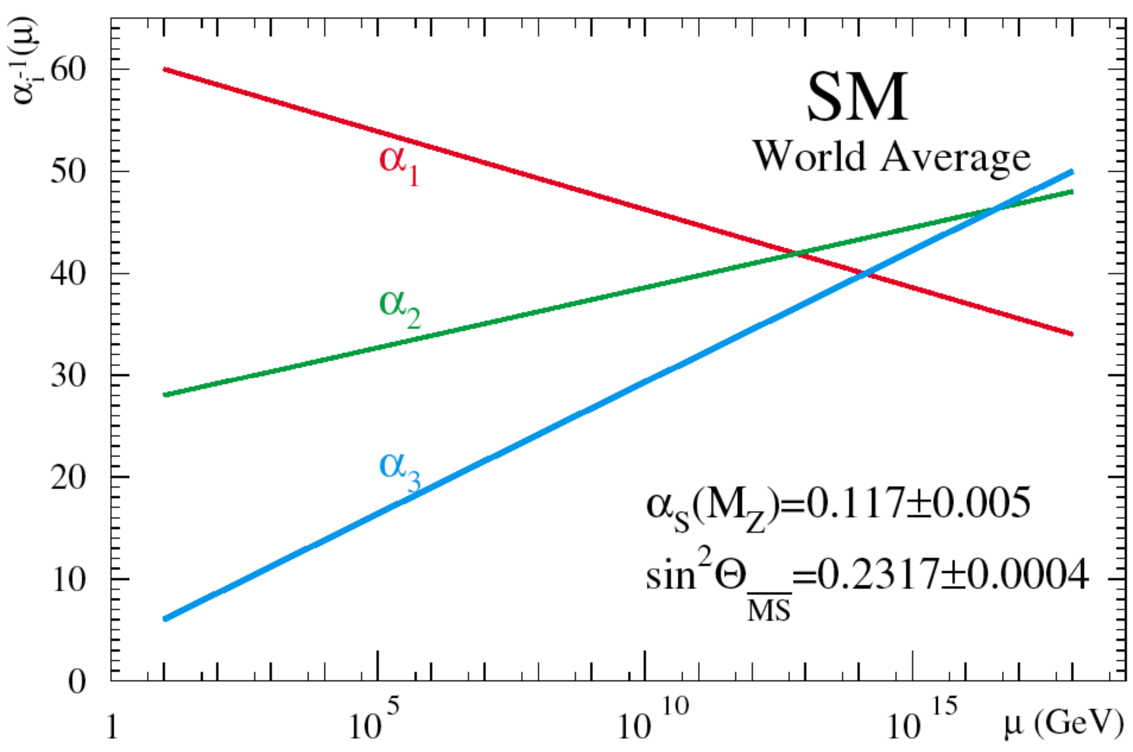
$\alpha_2 = g^2/4\pi$; $(g = e / \sin\theta_w)$

$\alpha_3 = \alpha_s$

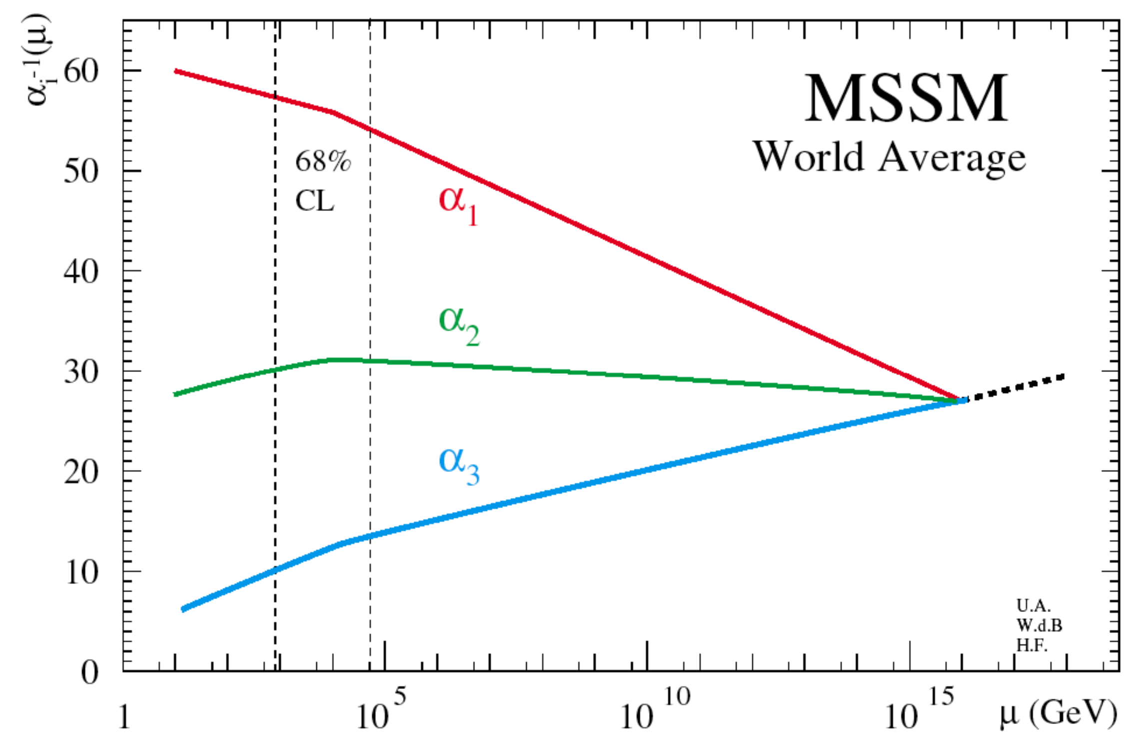
energy dependence: $$\alpha\left(q^2\right) = \frac{\alpha(\mu^2)}{1 - \beta_0 \alpha(\mu^2) \ln(q^2/\mu^2)} \;;\; \text{mit} \quad -\beta_0 = \frac{11 N_c - 4 N_f}{12\pi}$$

N_c= 0, 2, 3 für U(1), SU(2), SU(3),

N_f = 3 (Number of fermion generations)

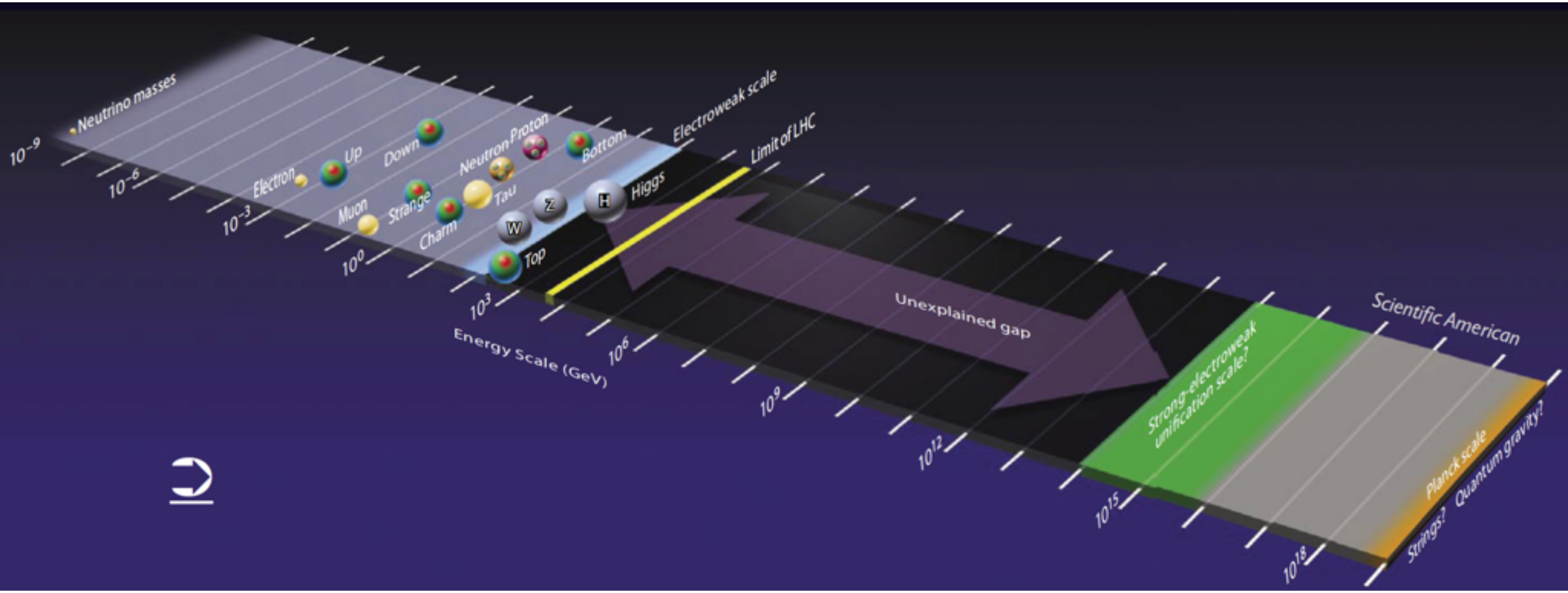


additional SUSY particles in loops:



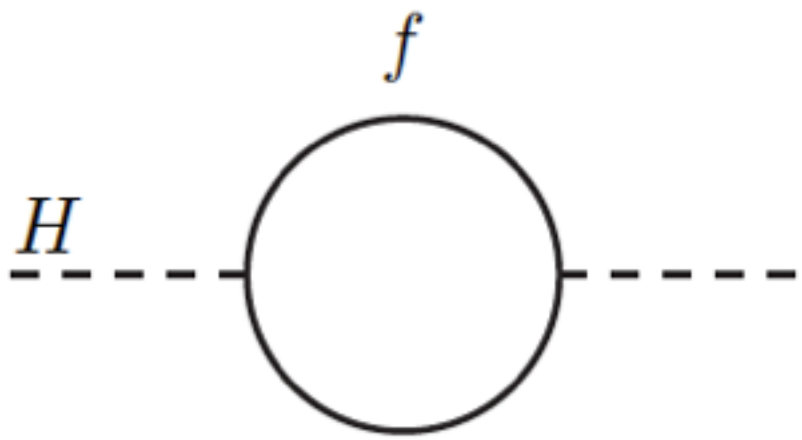
The Hierarchy Problem: A Closer Look

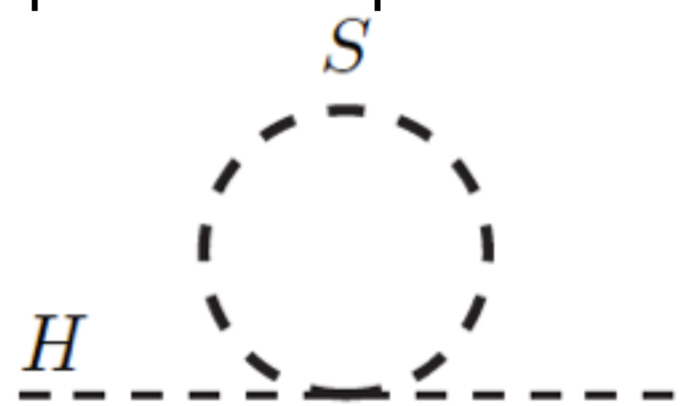
- The problem: Two mass scales: The Planck scale (~10^{19} GeV) and the electroweak scale (~10^2 GeV) - separated by 17 orders of magnitude!
  - The consequence: Gravitation is much weaker than all other interactions
  - In the Standard Model: Higgs-Mass of 125 GeV: How is this stabilized?



The Hierarchy Problem: Quantum Corrections

Quantum corrections to the Higgs mass via particle loops





Contribution of fermion loops

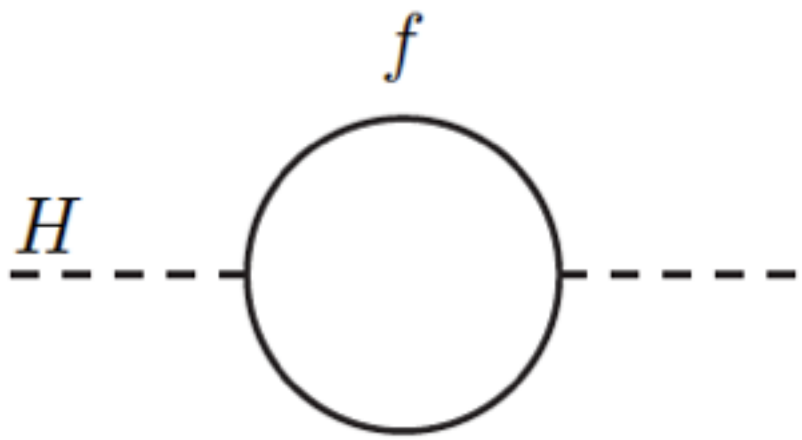
$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{\mathrm{UV}}^2 + \ldots .$$

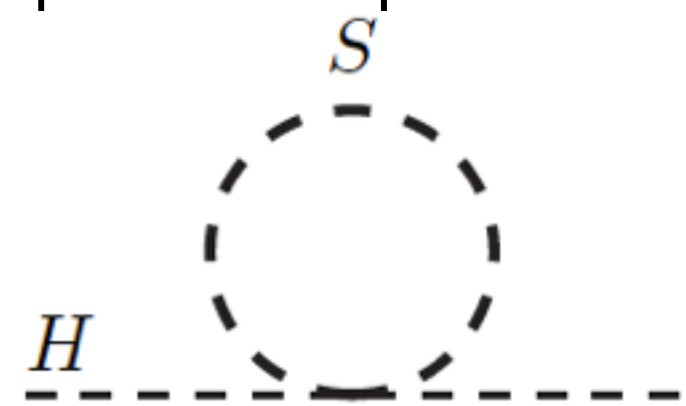
contribution of boson loops

$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}\left[\Lambda_{\mathrm{UV}}^2 - 2m_S^2 \ln(\Lambda_{\mathrm{UV}}/m_S) + \ldots\right]$$

The Hierarchy Problem: Quantum Corrections

Quantum corrections to the Higgs mass via particle loops





Contribution of fermion loops

$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{\rm UV}^2 + \ldots .$$

contribution of boson loops

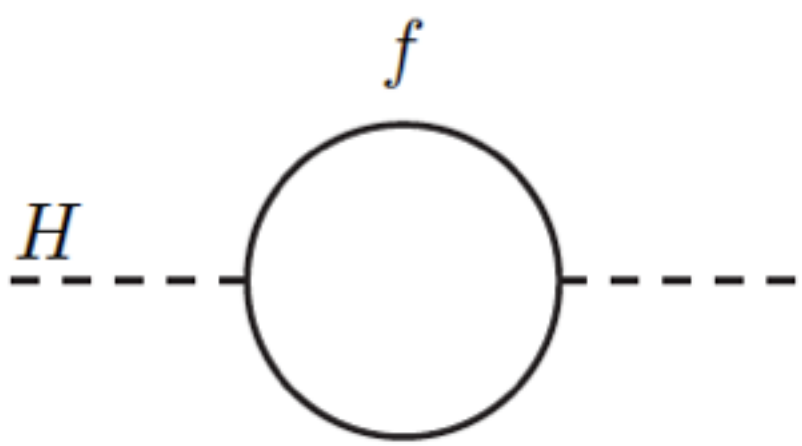
$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}\left[\Lambda_{\rm UV}^2 - 2m_S^2 \ln(\Lambda_{\rm UV}/m_S) + \ldots\right]$$

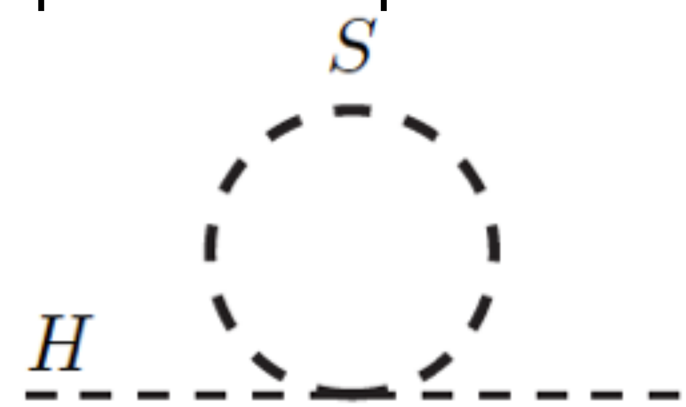
Corrections depend on the scale until which they have to be taken into account - The natural UV scale: M_P, results in enormous corrections due to the Λ^2 behavior

In the SM: Largest contribution from the top quark: Strongest coupling to the Higgs field, $\lambda_f \sim 1$

The Hierarchy Problem: Quantum Corrections

Quantum corrections to the Higgs mass via particle loops





Contribution of fermion loops

$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{\mathrm{UV}}^2 + \ldots .$$

contribution of boson loops

$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}\left[\Lambda_{\mathrm{UV}}^2 - 2m_S^2 \ln(\Lambda_{\mathrm{UV}}/m_S) + \ldots\right]$$

Corrections depend on the scale until which they have to be taken into account - The natural UV scale: M_P, results in enormous corrections due to the Λ^2 behavior

In the SM: Largest contribution from the top quark: Strongest coupling to the Higgs field, $\lambda_f \sim 1$

Also so far unknown, heavy particles contribute, the heaviest particle which couples to the Higgs field dominates!

➯ Requires unnatural fine tuning to save a small Higgs mass

A popular Idea: Supersymmetry

- The strategy for a solution is suggested by the correction terms:

$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{\mathrm{UV}}^2 + \ldots . \qquad \Delta m_H^2 = \frac{\lambda_S}{16\pi^2}\left[\Lambda_{\mathrm{UV}}^2 - 2m_S^2 \ln(\Lambda_{\mathrm{UV}}/m_S) + \ldots\right]$$

  Contributions of fermions and bosons have opposite sign!

- Cancelation of these contributions is automatic, if there is a symmetry between bosons and fermions, a so-called ***Supersymmetry***
- A SUSY - gauge transformation transforms bosons into fermions and vice versa:

$$Q|\mathrm{Boson}\rangle = |\mathrm{Fermion}\rangle, \qquad Q|\mathrm{Fermion}\rangle = |\mathrm{Boson}\rangle$$

A popular Idea: Supersymmetry

- The strategy for a solution is suggested by the correction terms:

$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{UV}^2 + \ldots . \qquad \Delta m_H^2 = \frac{\lambda_S}{16\pi^2}\left[\Lambda_{UV}^2 - 2m_S^2 \ln(\Lambda_{UV}/m_S) + \ldots\right]$$

  Contributions of fermions and bosons have opposite sign!

- Cancelation of these contributions is automatic, if there is a symmetry between bosons and fermions, a so-called ***Supersymmetry***
- A SUSY - gauge transformation transforms bosons into fermions and vice versa:

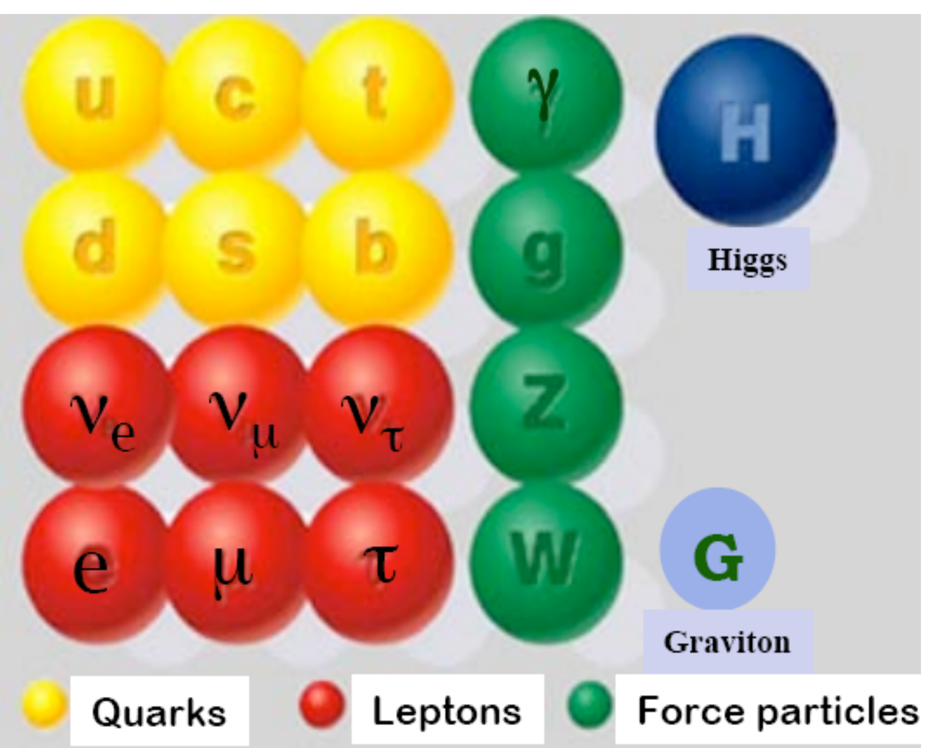
$$Q|\text{Boson}\rangle = |\text{Fermion}\rangle, \qquad Q|\text{Fermion}\rangle = |\text{Boson}\rangle$$

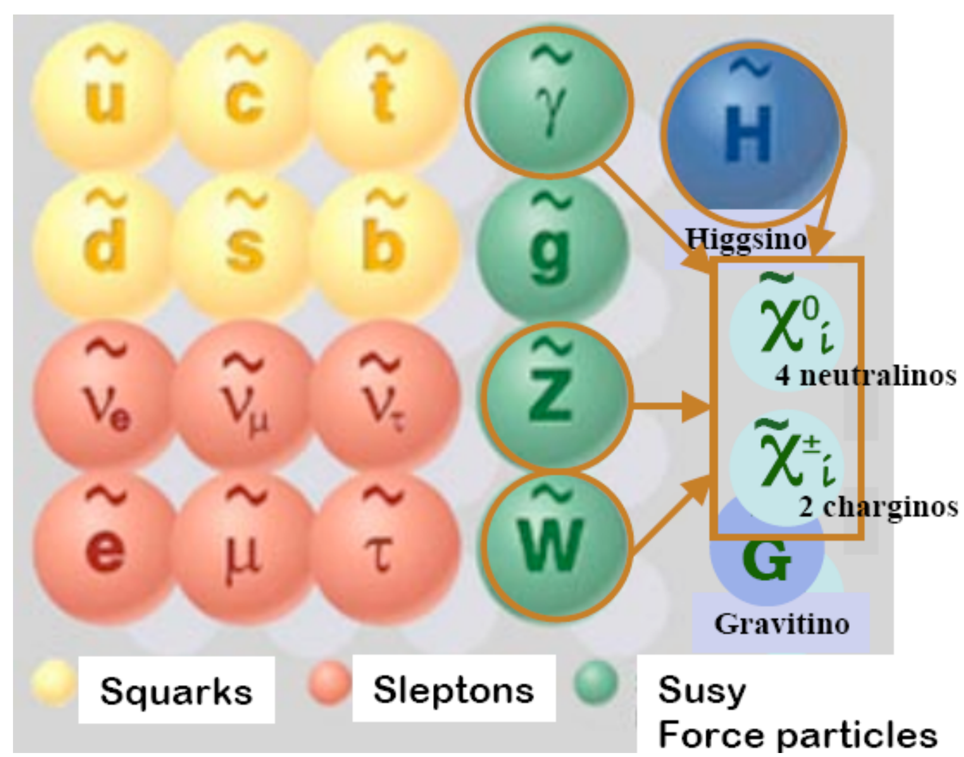
- Consequences of Supersymmetry:
  - Each fermion in the SM has a bosonic “superpartner” with 1/2 different spin, analoguous for every boson
  - The partners are arranged in so-called “super-multipletts”
  - For an exact symmetry, the masses of particles and their superpartners are identical

Supersymmetry: Particles & Forces

- Each SM particle gets a supersymmetric partner

Higgs structure gets more complex: 2 complex doublets, results in 5 physical Higgs fields - Gauginos and Higgsinos mix to form Charginos and Neutralinos



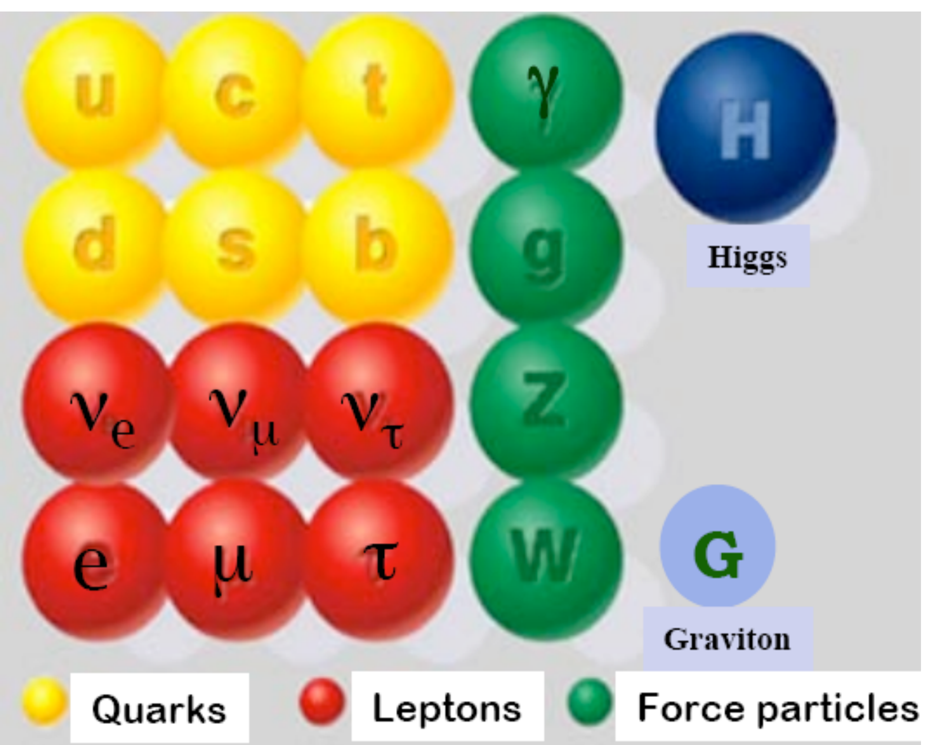


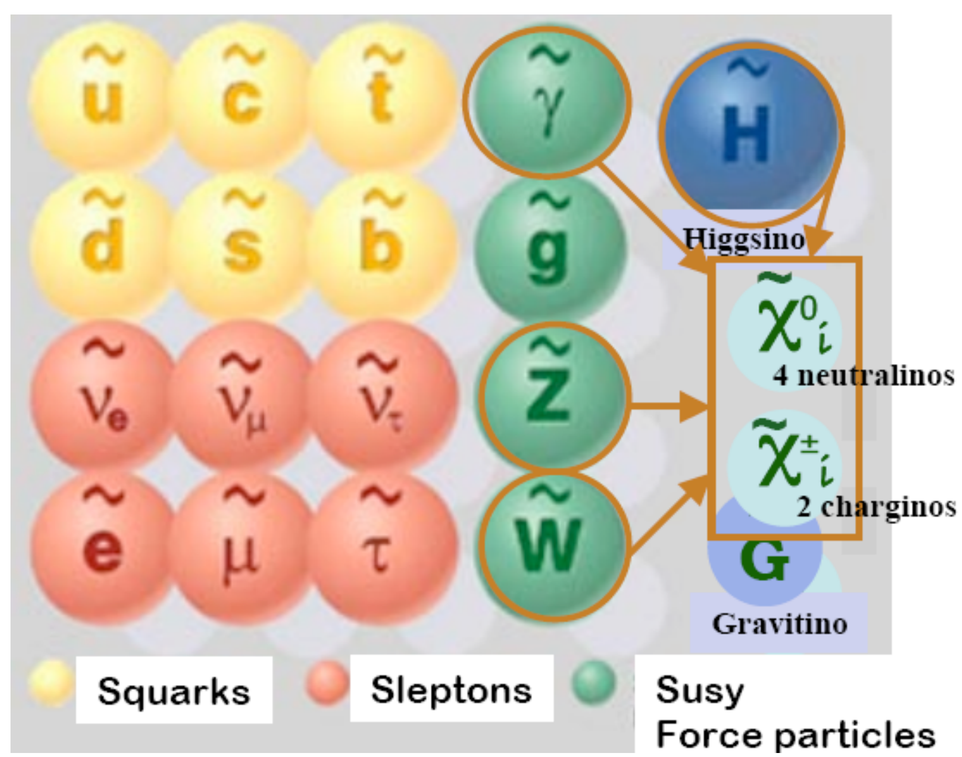
Supersymmetry: Particles & Forces

- Each SM particle gets a supersymmetric partner

Teilchen	Spin	S-Teilchen	Spin
Quark Q	1/2	Squark $\tilde{Q}$	0
Lepton l	1/2	Slepton $\tilde{l}$	0
Photon γ	1	Photino $\tilde{\gamma}$	1/2
Gluon g	1	Gluino $\tilde{g}$	1/2
$W^{\pm}$	1	Wino $\tilde{W}^{\pm}$	1/.2
Z^0	1	Zino $\tilde{Z}^0$	1/2

Higgs structure gets more complex: 2 complex doublets, results in 5 physical Higgs fields - Gauginos and Higgsinos mix to form Charginos and Neutralinos





Supersymmetry: Models & Phenomenology

- 128 free parameters to describe masses and couplings of all SUSY particles
  - reduced to a few by adding additional assumptions on breaking mechanism etc.
- New conserved quantity: ***R - Parity*** - a multiplicative quantity

  $R = (-1)^{3(B-L)+2S}$ (B/L: baryon, lepton number, S: spin)

  R = 1 for "normal" particles, = -1 for SUSY particles

R parity conservation implies that the lightest SUSY particle (LSP) has to be stable => a good Dark Matter candidate!

N.B.: Also models with
R - Parity violation exist…

Supersymmetry: Models & Phenomenology

- 128 free parameters to describe masses and couplings of all SUSY particles
  - reduced to a few by adding additional assumptions on breaking mechanism etc.
- New conserved quantity: ***R - Parity*** - a multiplicative quantity

  $R = (-1)^{3(B-L)+2S}$ (B/L: baryon, lepton number, S: spin)

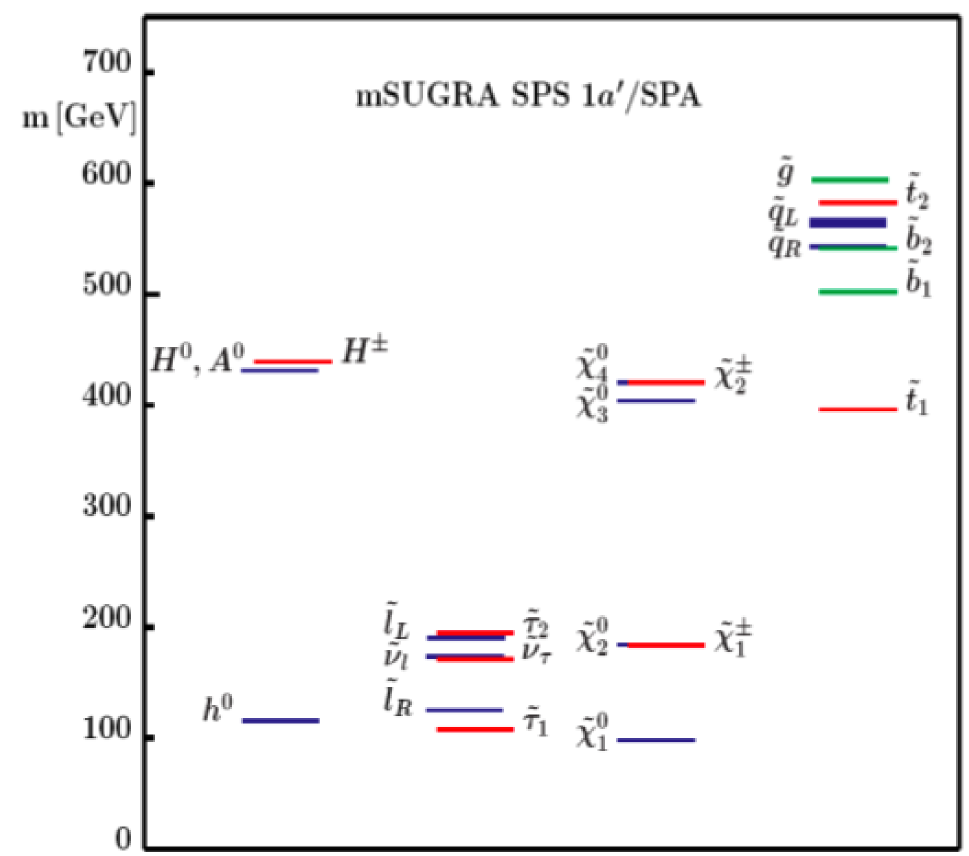
  R = 1 for "normal" particles, = -1 for SUSY particles

R parity conservation implies that the lightest SUSY particle (LSP) has to be stable => a good Dark Matter candidate!

N.B.: Also models with R - Parity violation exist…

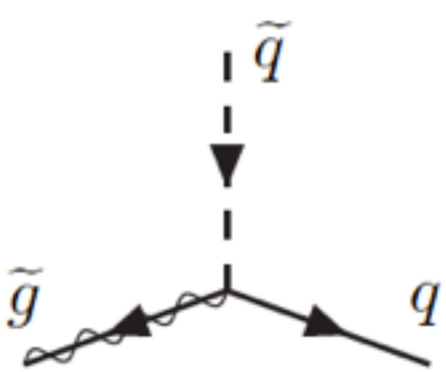
one example of a SUSY particle spectrum
… excluded by LHC after a few month of running

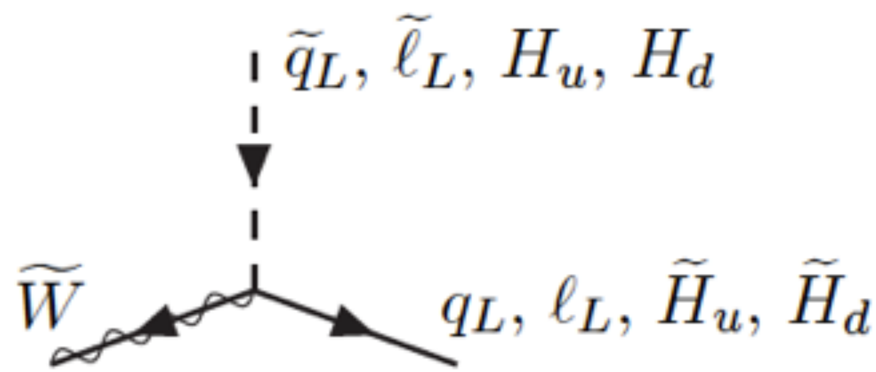
- m_0 = 100 GeV
- $m_{\frac{1}{2}}$ = 250 GeV
- A_0 = -100 GeV
- $\tan\beta$ = 10
- $\mathrm{sgn}(\mu)$ = +1

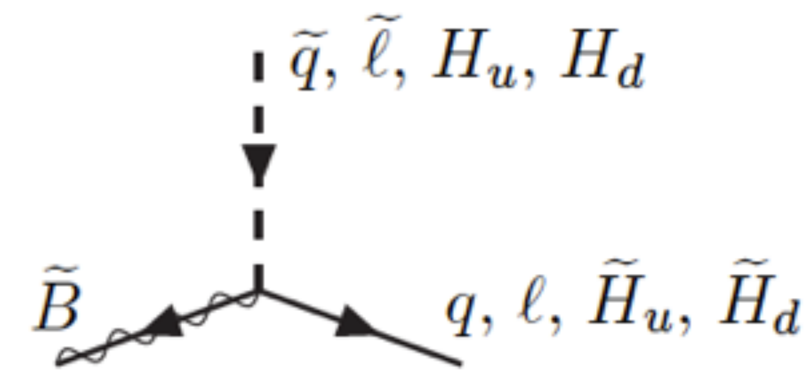


Interaction of SUSY Particles

- SUSY particles interact just as SM particles according to their quantum numbers
  - Right-sfermions (handedness here refers to the SM partners, since the sfermions have spin 0) do not carry weak isospin and therefore do not couple to W bosons
- Coupling to SUSY gauge bosons:

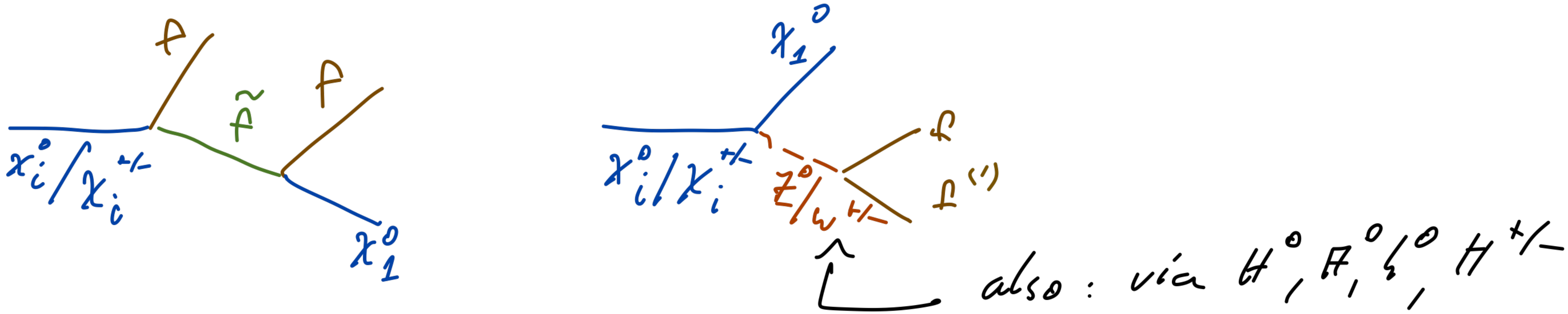






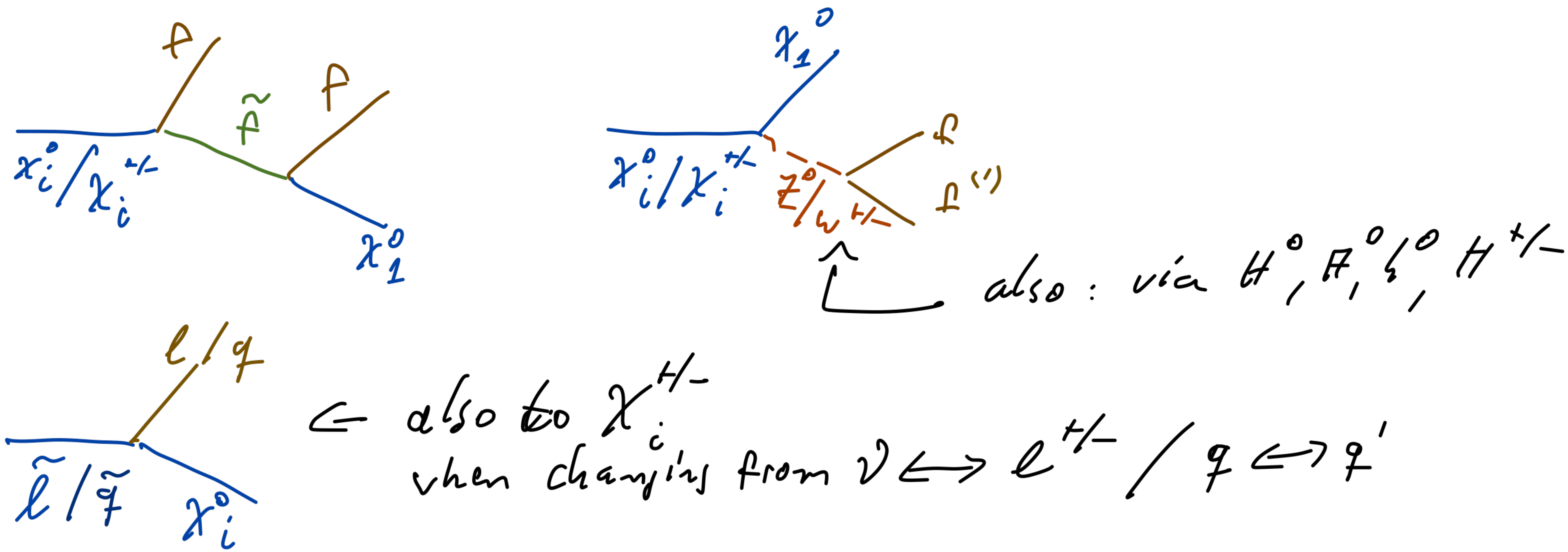
Decay of SUSY Particles

- Depends on spectrum: Ordering of masses - in general:



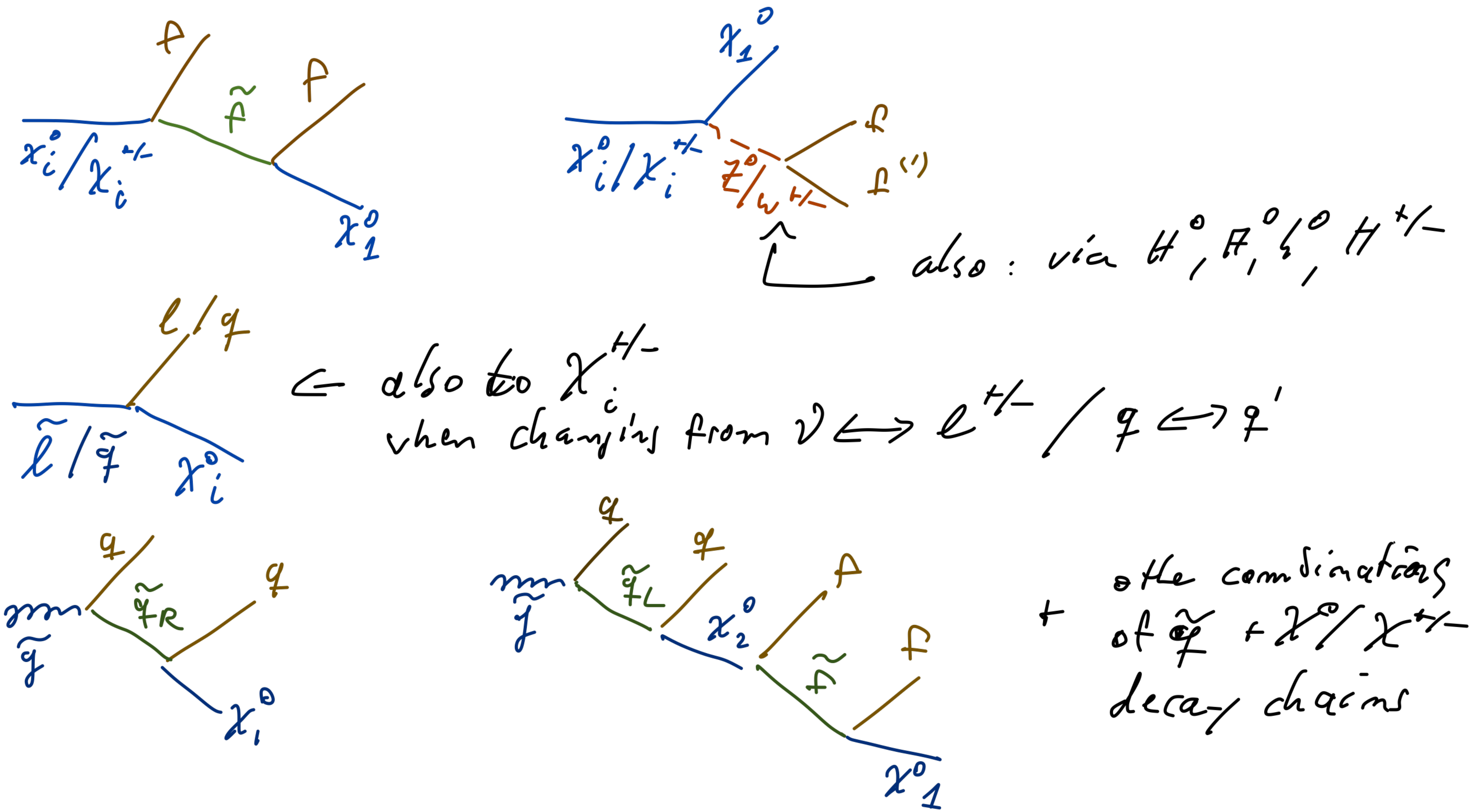
Decay of SUSY Particles

- Depends on spectrum: Ordering of masses - in general:



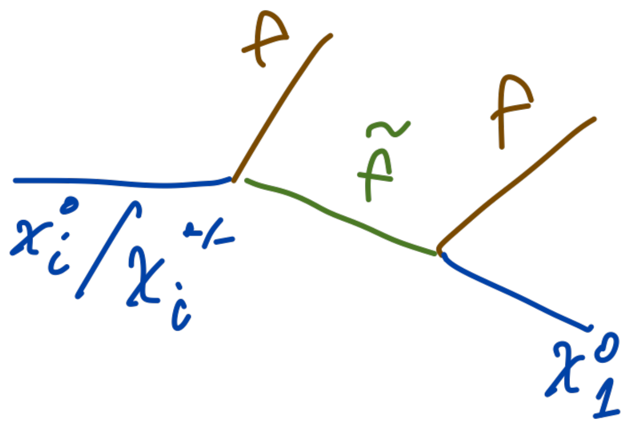
Decay of SUSY Particles

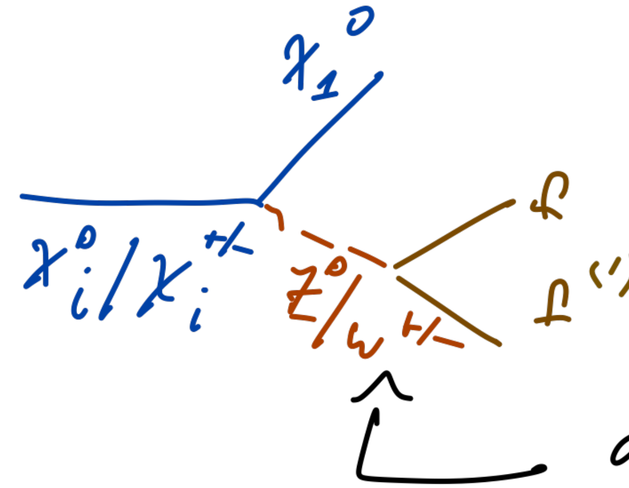
- Depends on spectrum: Ordering of masses - in general:



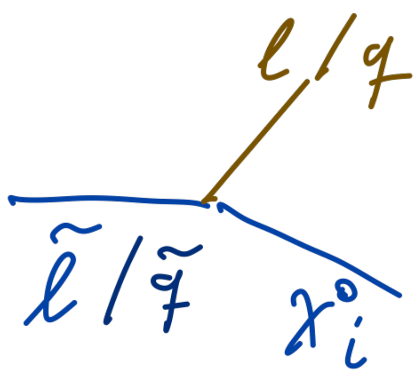
Decay of SUSY Particles

- Depends on spectrum: Ordering of masses - in general:

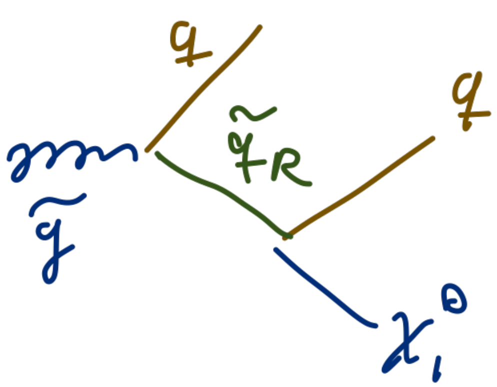


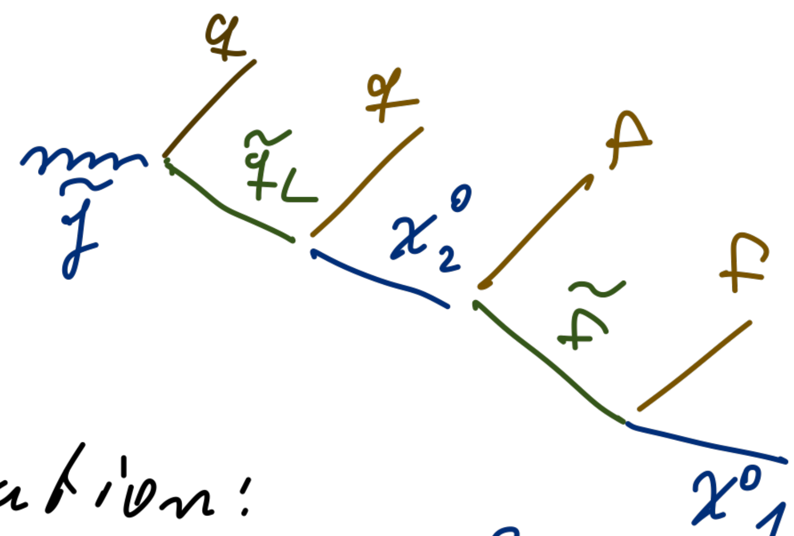


also: via $H^0, A^0, h^0, H^{+/-}$



← also to $\chi_i^{+/-}$ when changing from $\nu \leftrightarrow \ell^{+/-}$ / $q \leftrightarrow q'$



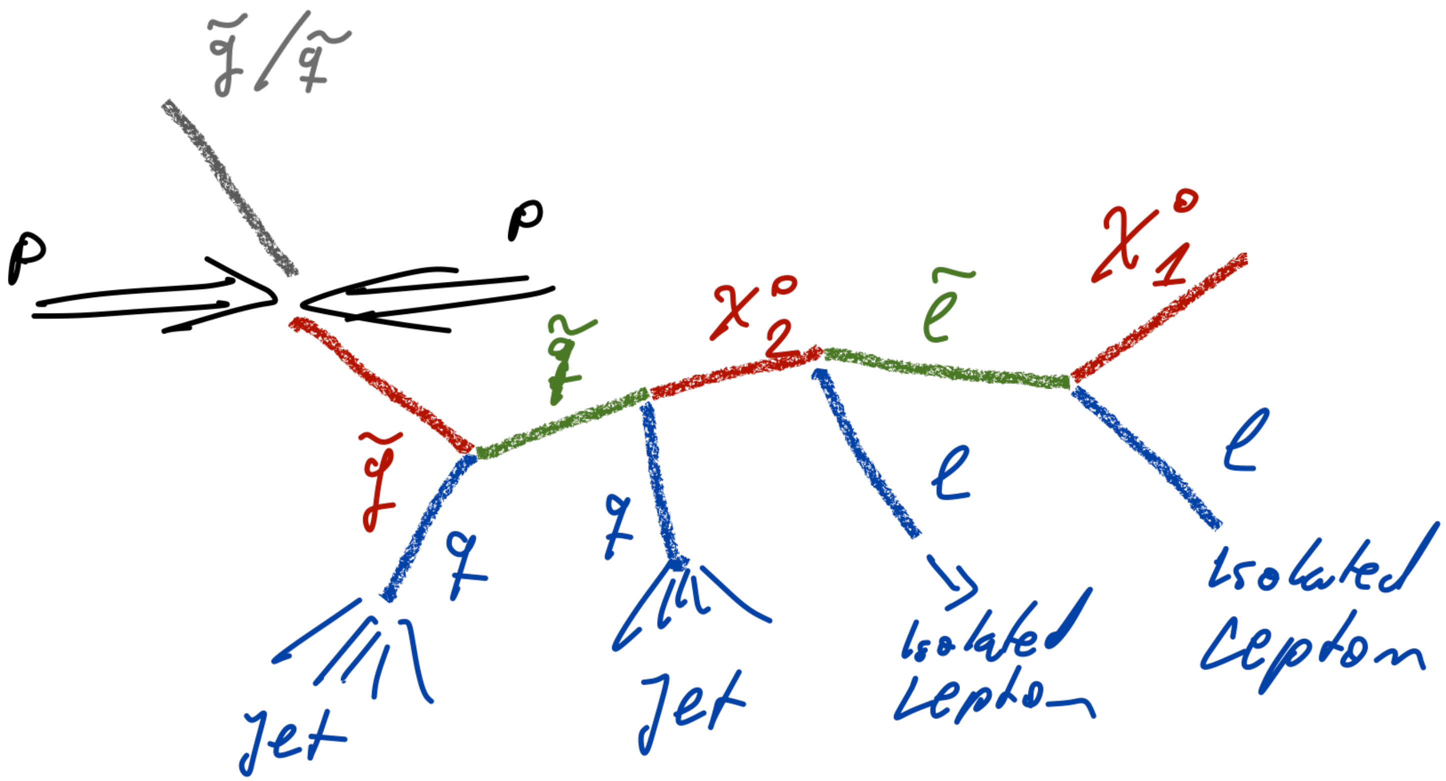


+ other combinations of $\tilde{q}$ + $\chi^0/\chi^{+/-}$ decay chains

For R-parity conservation:
Final particles always include χ_1^0 (LSP)

Experimental Searches for SUSY - Principles

- Based on typical production and decay scenarios



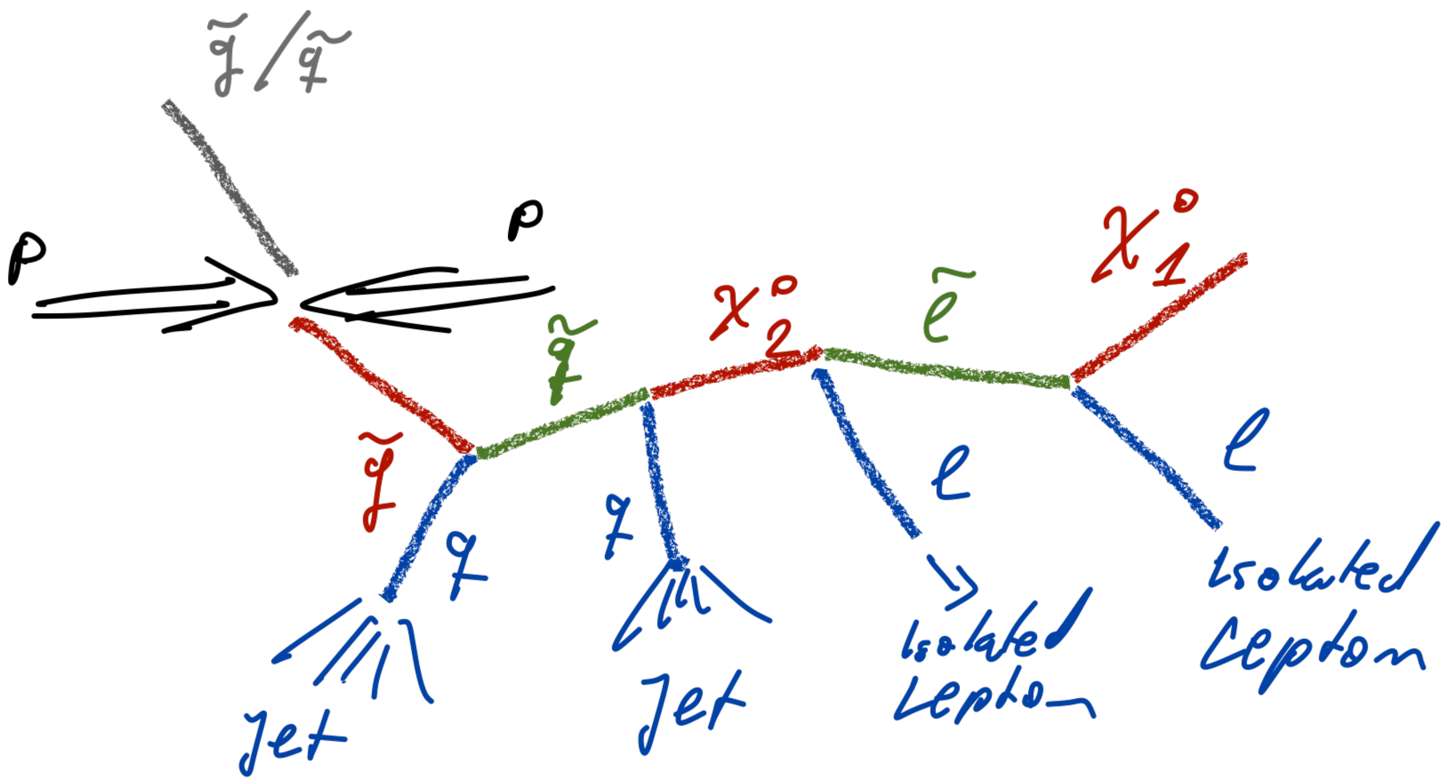
Typical signatures:

- several high-energy jets
- several high-energy leptons
- missing transverse energy

if R-parity is not conserved:
missing energy replaced by endpoints in momentum distributions giving mass differences in decay chains

Experimental Searches for SUSY - Principles

- Based on typical production and decay scenarios



Typical signatures:

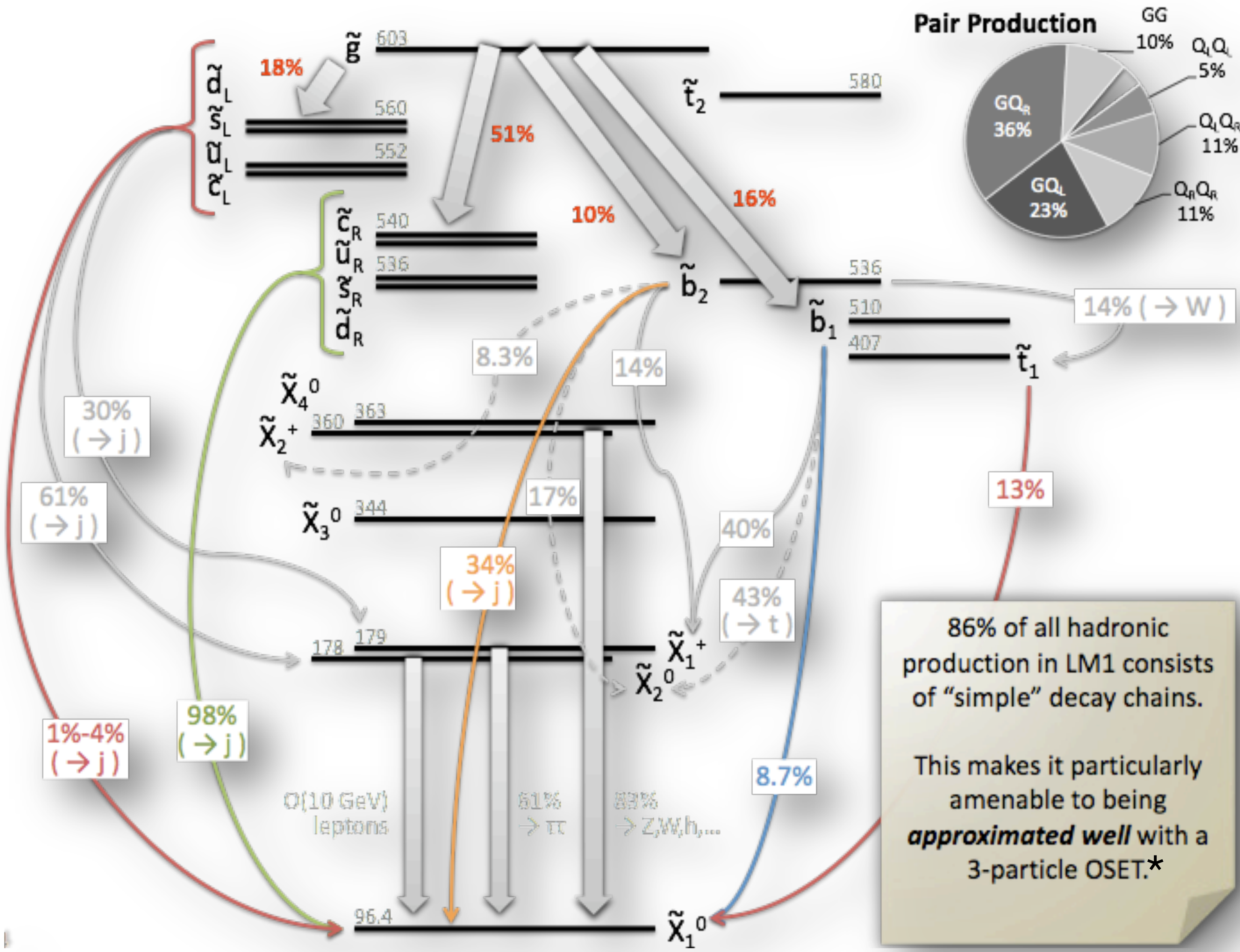
- several high-energy jets
- several high-energy leptons
- missing transverse energy

if R-parity is not conserved: missing energy replaced by endpoints in momentum distributions giving mass differences in decay chains

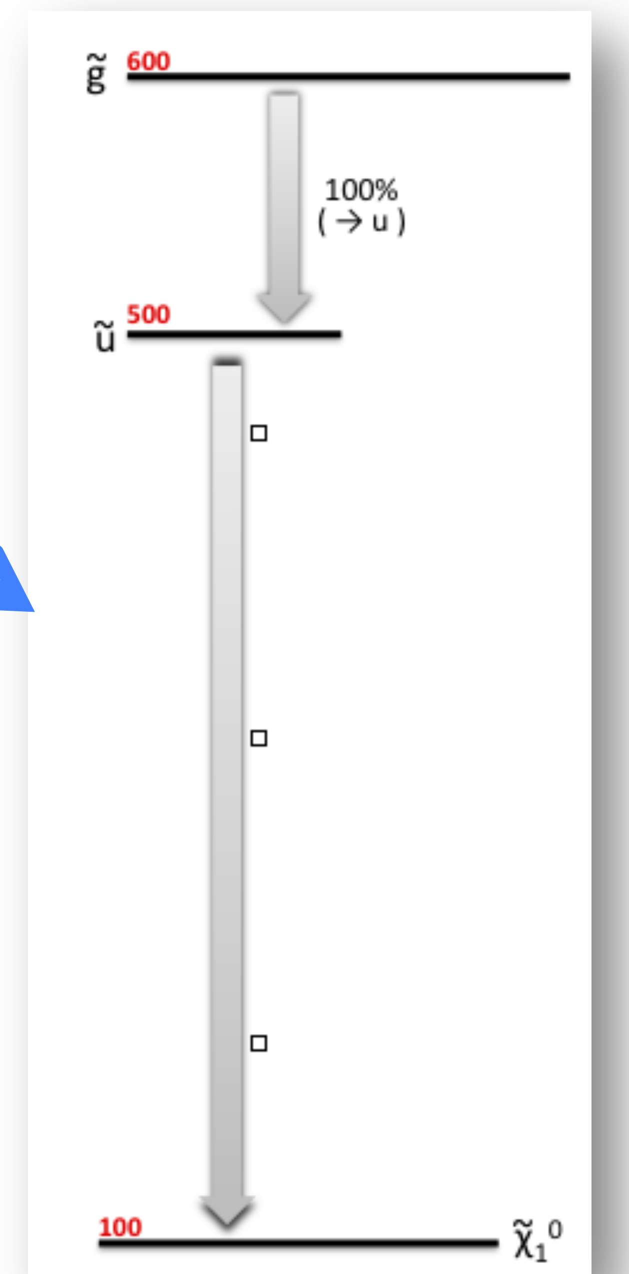
- Analysis typically performed in “simplified models”:
  Generic features - limits expressed for assumed couplings, masses and particle types, without concrete SUSY parameter assumptions

Interpretation of Results - Simplified Models

CMSSM



What the individual searches are sensitive to is much more simple…



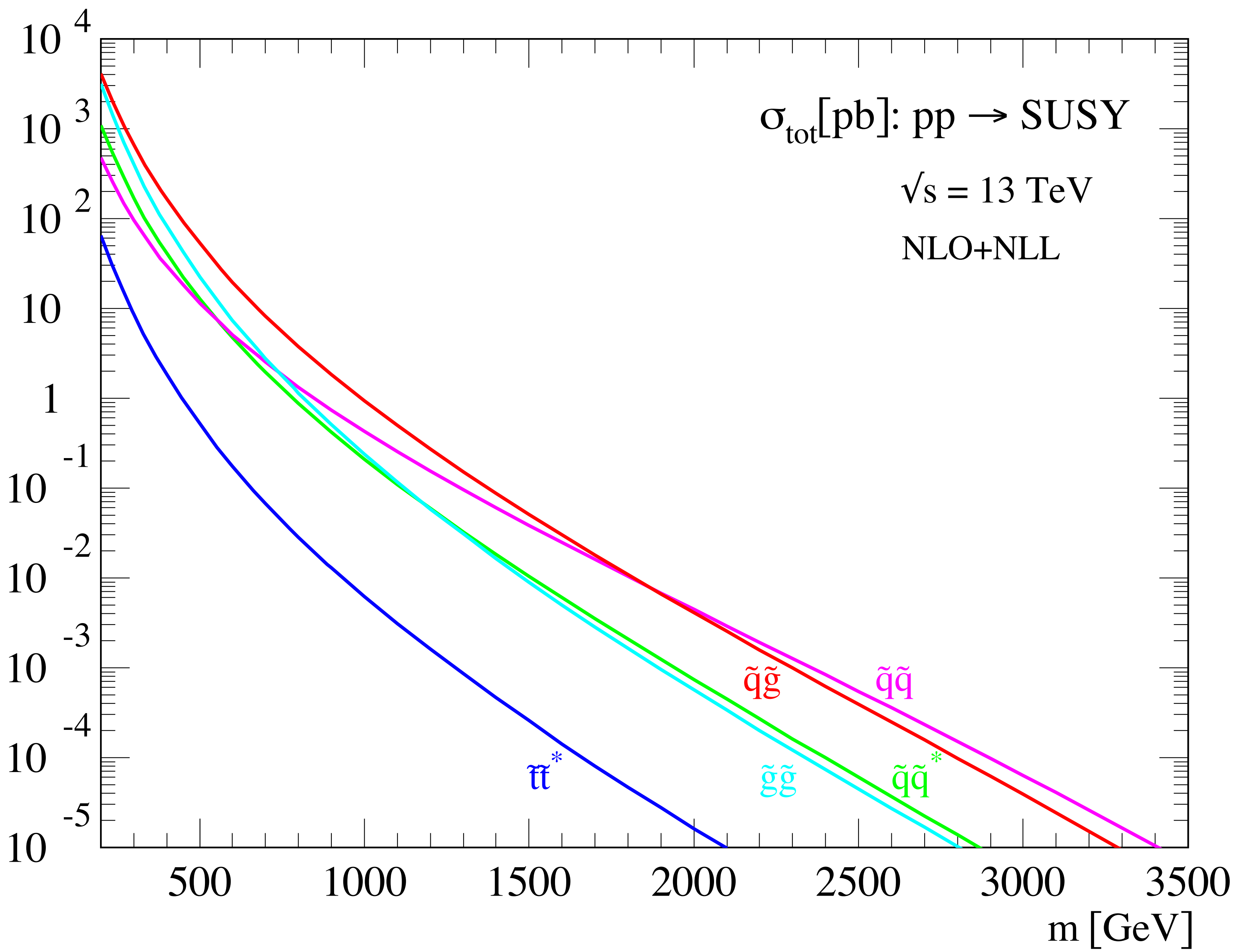
Simplified model spectrum (SMS)
with 3 particles, 2 decay modes

* OSET = On-Shell Effective Theory

O. Buchmüller, EPS-HEP 2013

Production of SUSY Particles: General Features

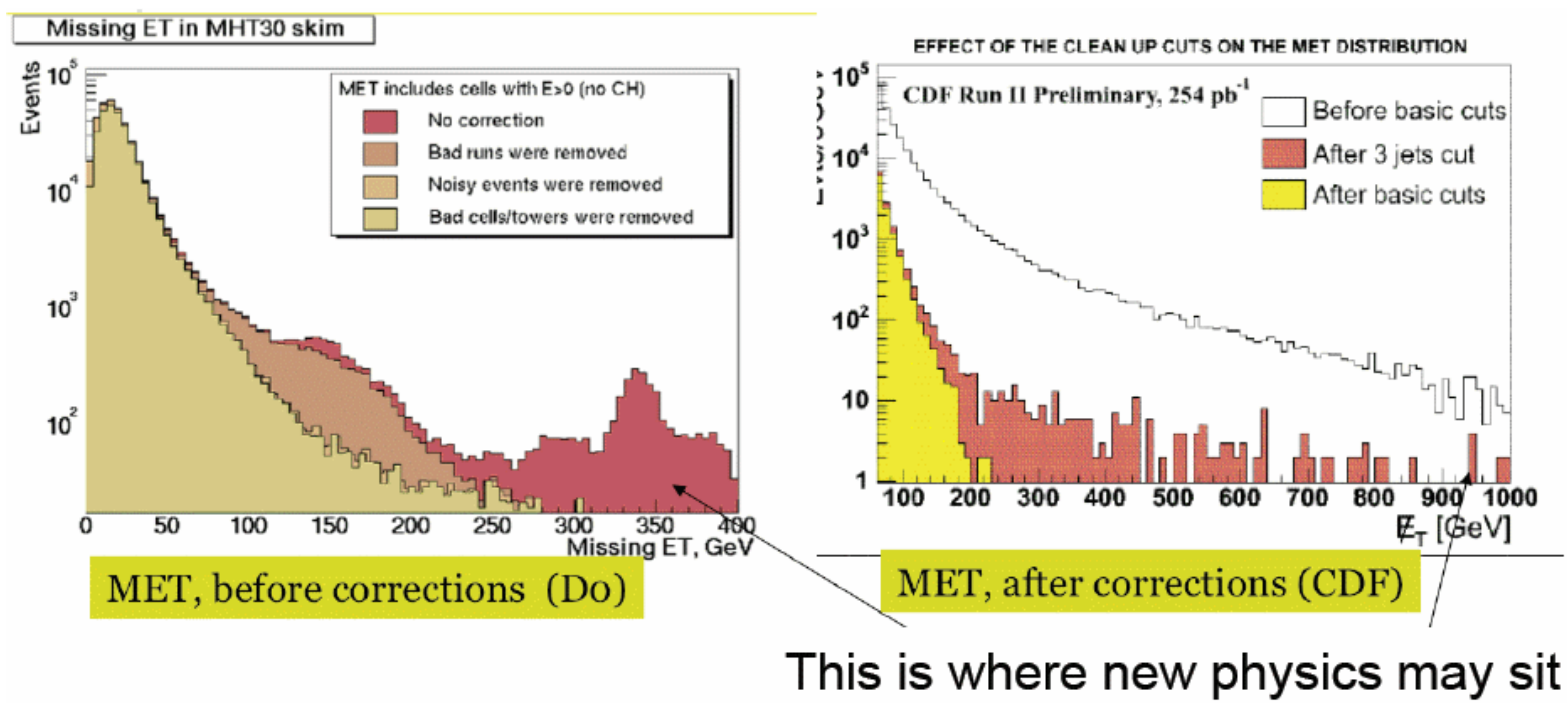
- Cross sections (and with that the mass reach at the LHC) depend strongly on the production mechanism: Highest reach via the strong interaction: New particles carrying color charge - gluinos, squarks



EPJ C74, 3174 (2014)

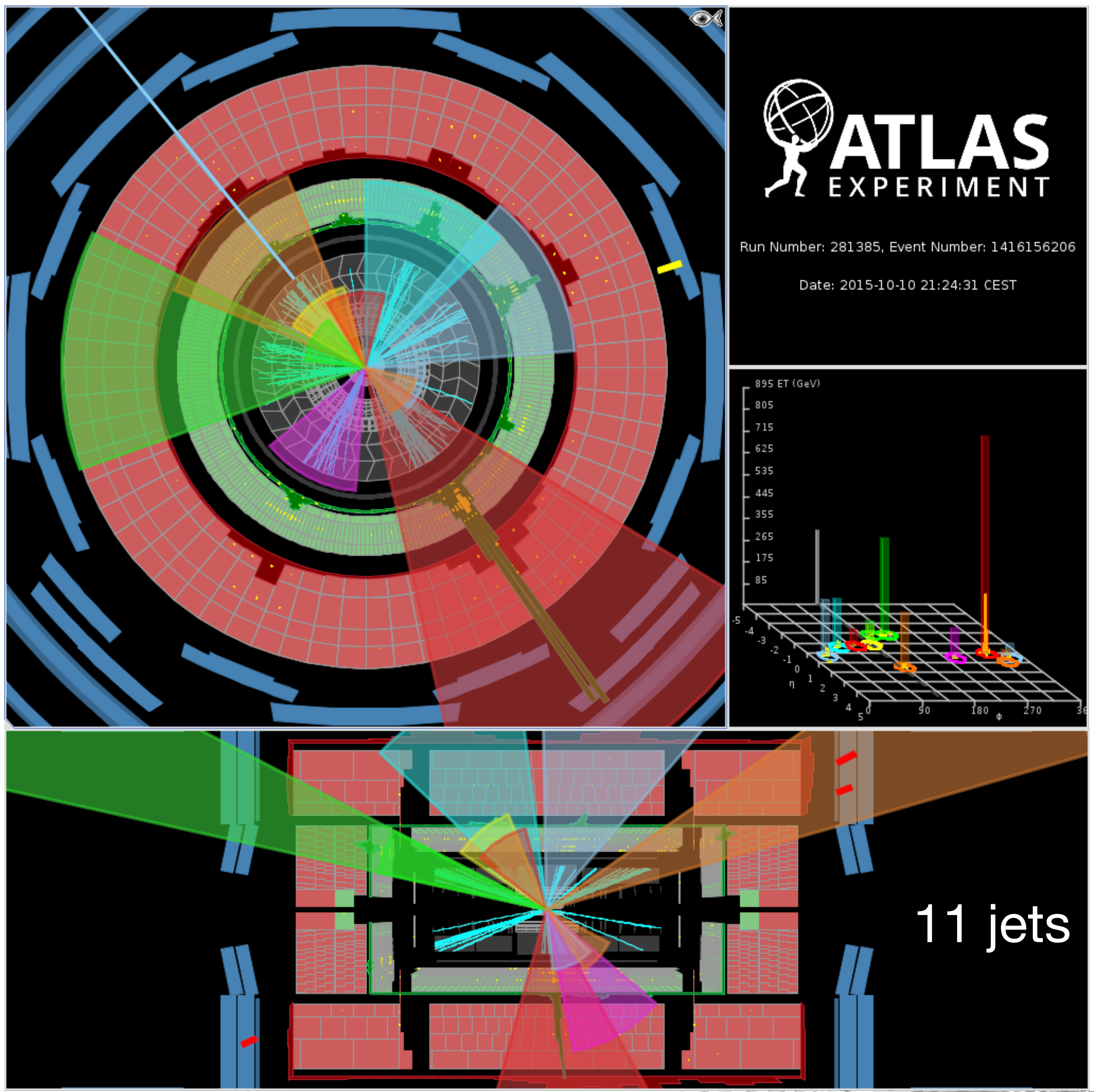
Experimental Searches for SUSY - Requirements

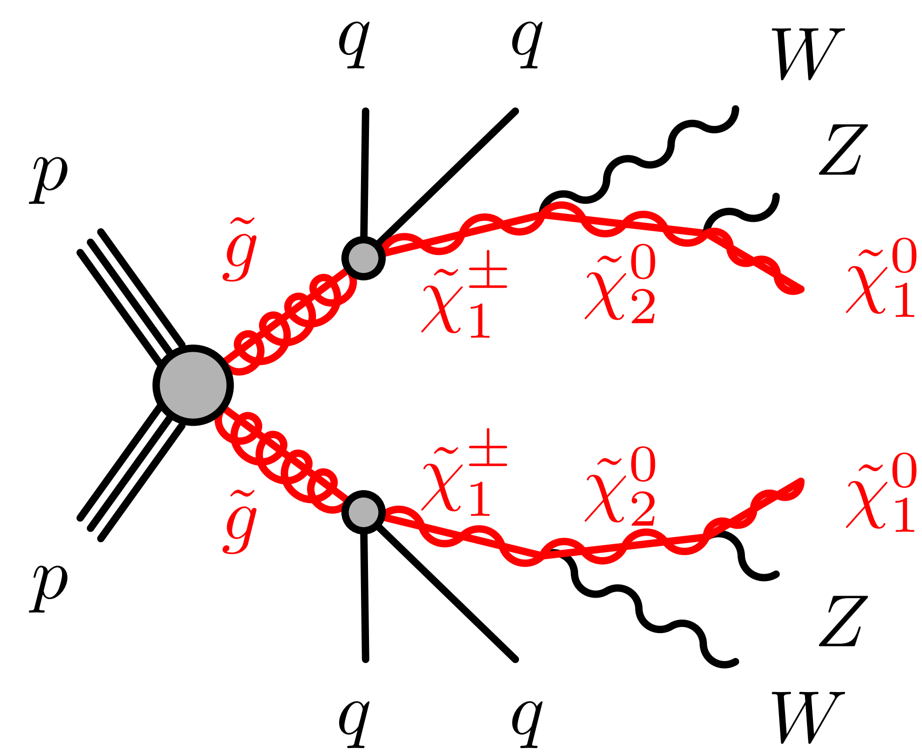
- Key experimental capabilities (and uncertainties) for new physics searches:
  - Jet and lepton reconstruction
  - Hermetic coverage of the events
  - Control of backgrounds an pile-up
  - reconstruction and resolution of missing (transverse) energy

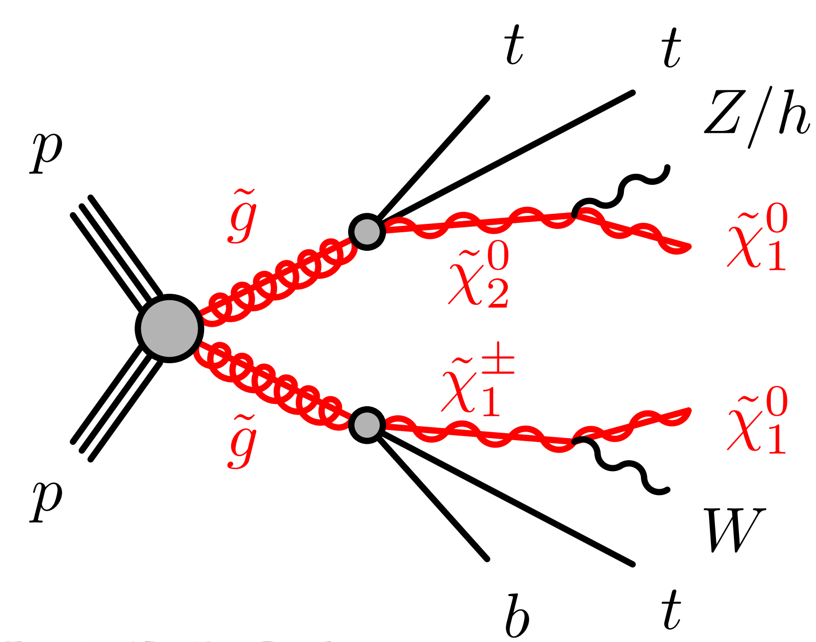


Experimental Searches for SUSY - Examples

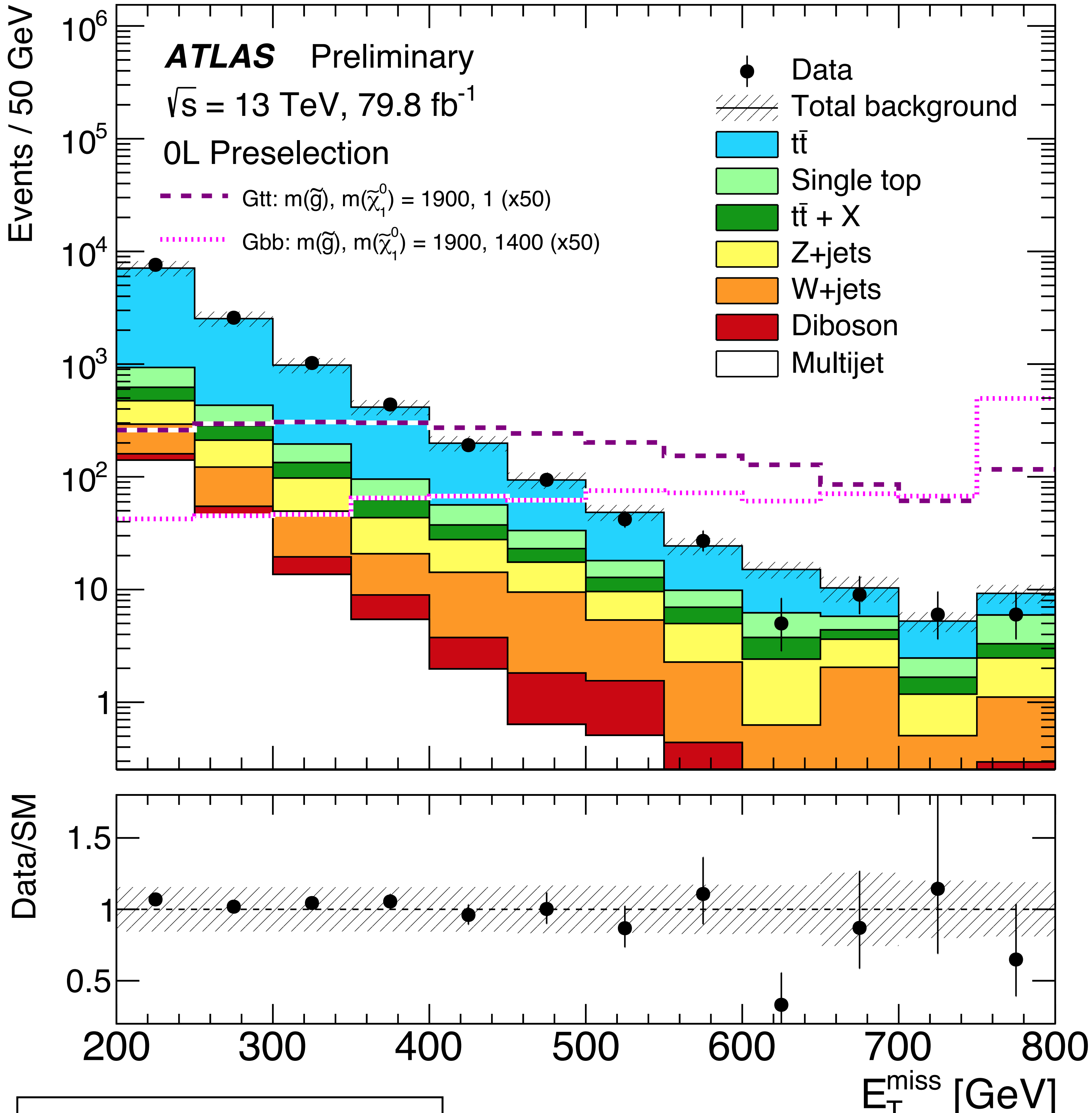
- Search for strongly interacting SUSY: Characterized by multi-jet final states from cascade decays





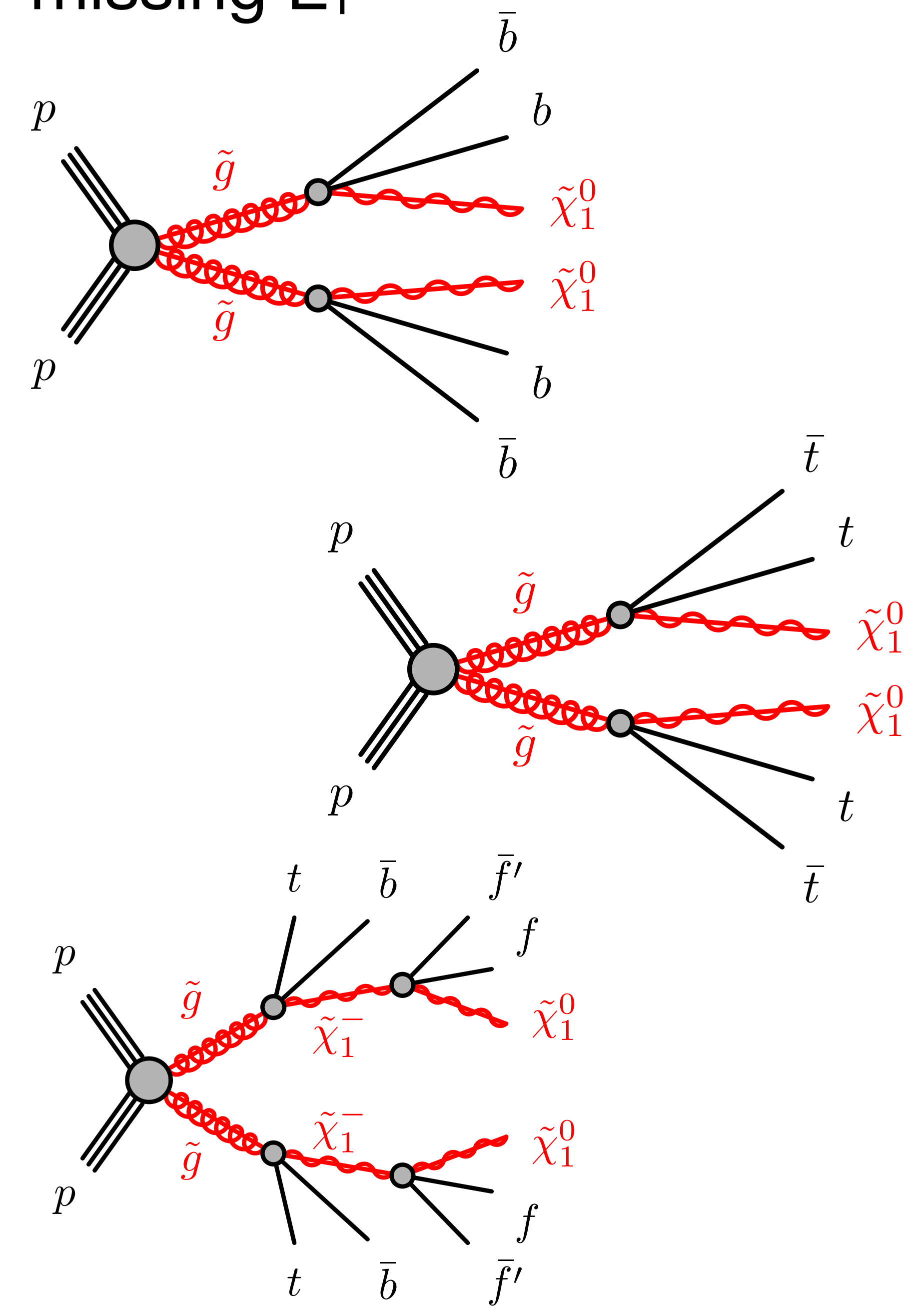


Experimental Searches for SUSY - Examples

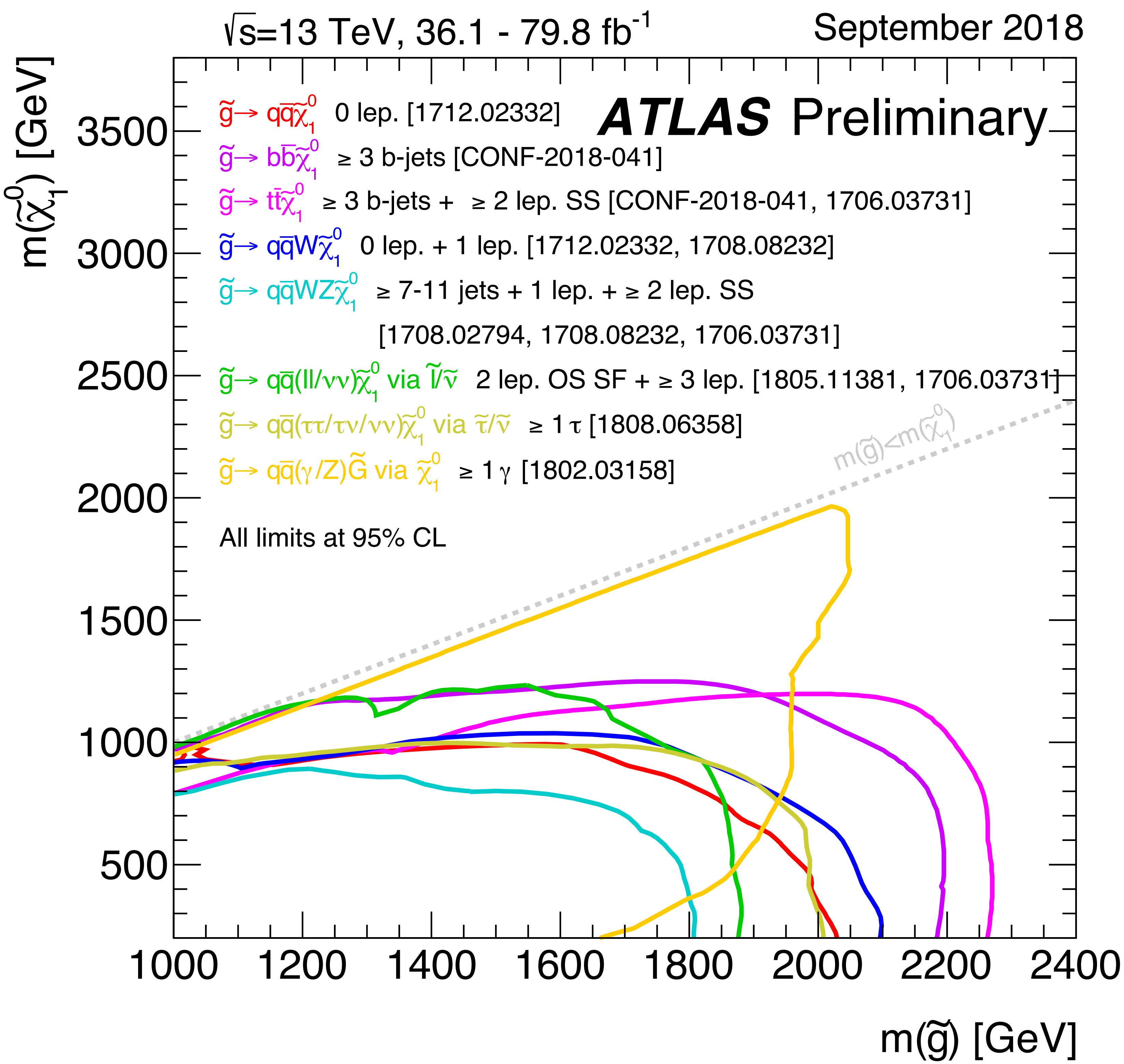


ATLAS-CONF-2018-041

- Looking for a signal excess in different distributions - such as missing E_T



Experimental Searches for SUSY - Examples

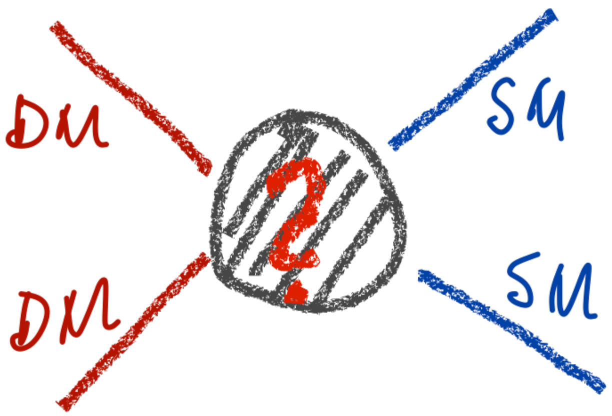


- Exclusion curves for a number of different analyses - as a function of gluino and neutralino (LSP) mass:

  Limits beyond 2 TeV for some scenarios for gluinos

Searching for Dark Matter at Colliders - Principles

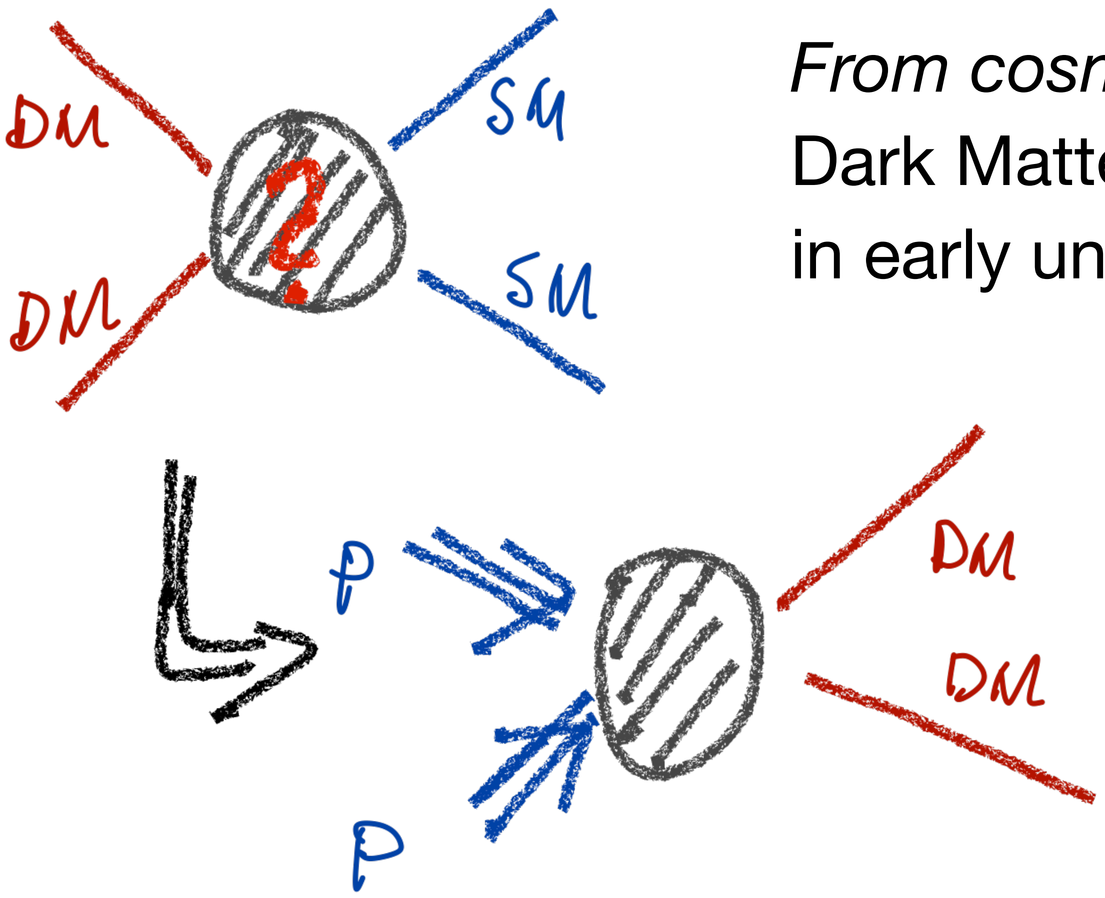
- Related to SUSY searches - but also more general



From cosmology: Expect some interaction between Dark Matter and SM particles - thermal equilibrium in early universe, followed by freeze-out

Searching for Dark Matter at Colliders - Principles

- Related to SUSY searches - but also more general

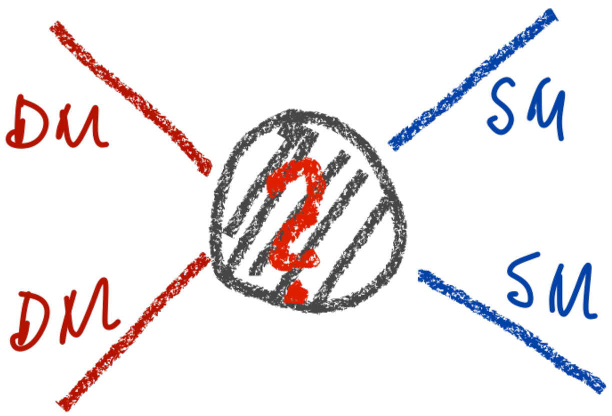


From cosmology: Expect some interaction between Dark Matter and SM particles - thermal equilibrium in early universe, followed by freeze-out

Could produce DM at colliders:
3 different search approaches

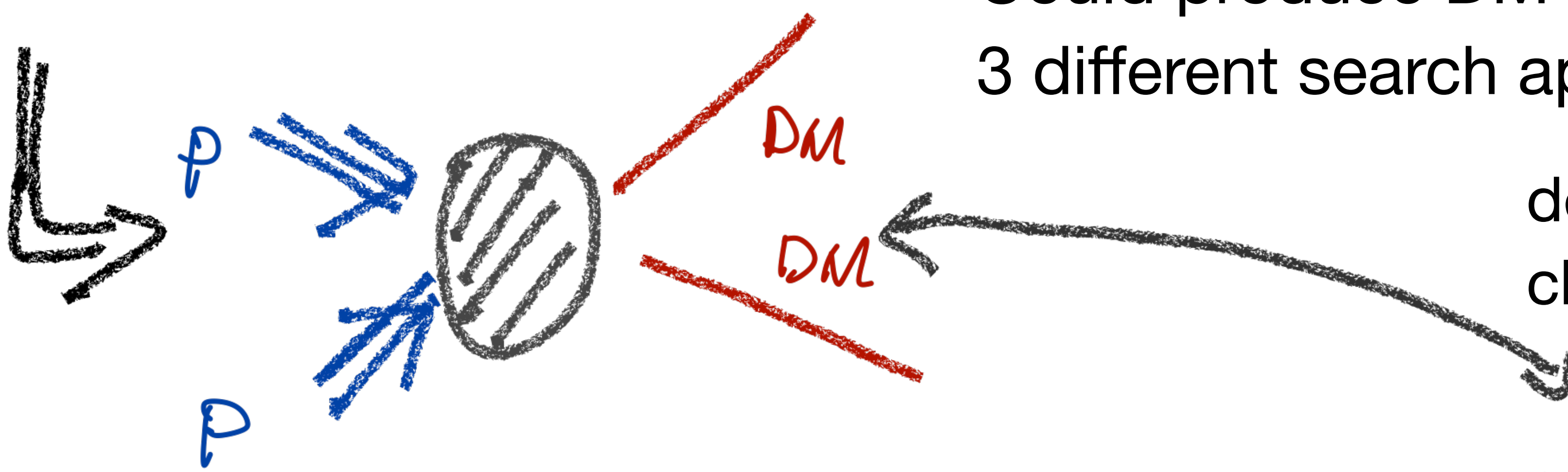
Searching for Dark Matter at Colliders - Principles

- Related to SUSY searches - but also more general

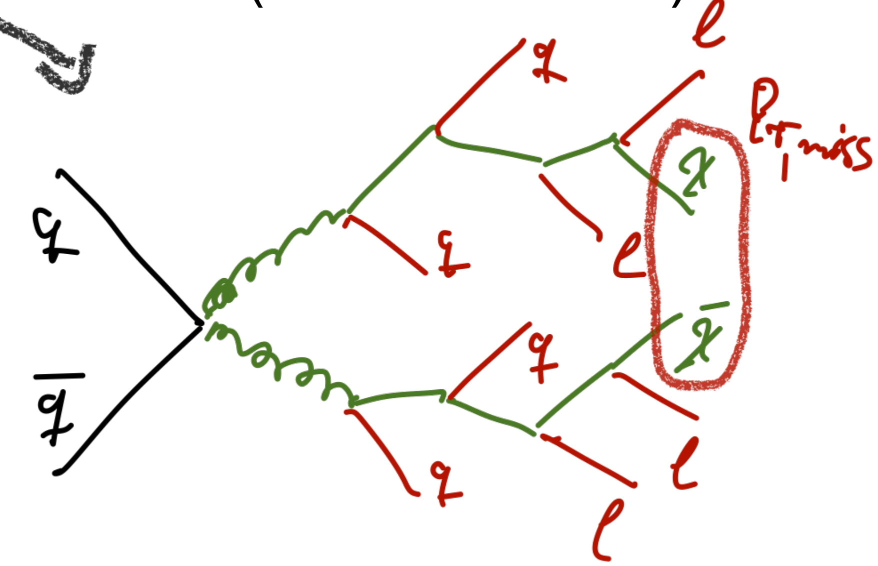


From cosmology: Expect some interaction between Dark Matter and SM particles - thermal equilibrium in early universe, followed by freeze-out

Could produce DM at colliders:
3 different search approaches

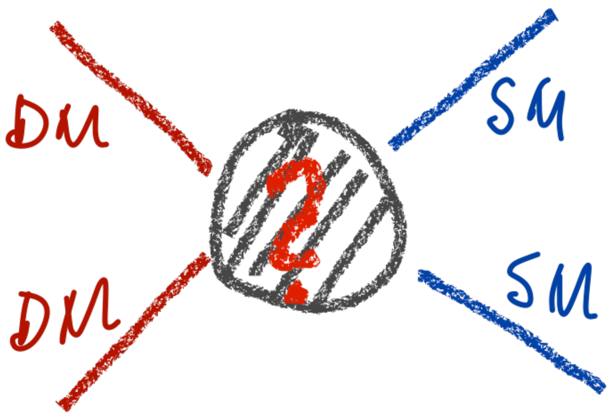


detection in complex decay chains (such as SUSY)

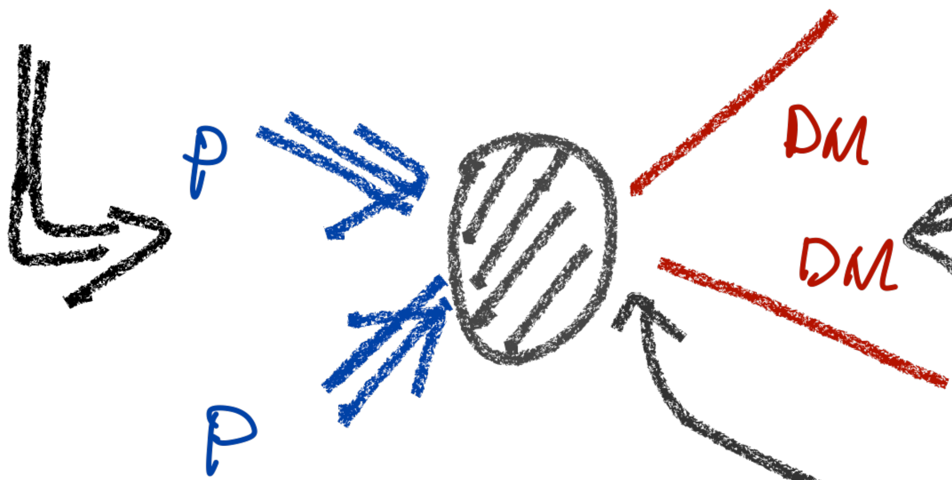


Searching for Dark Matter at Colliders - Principles

- Related to SUSY searches - but also more general

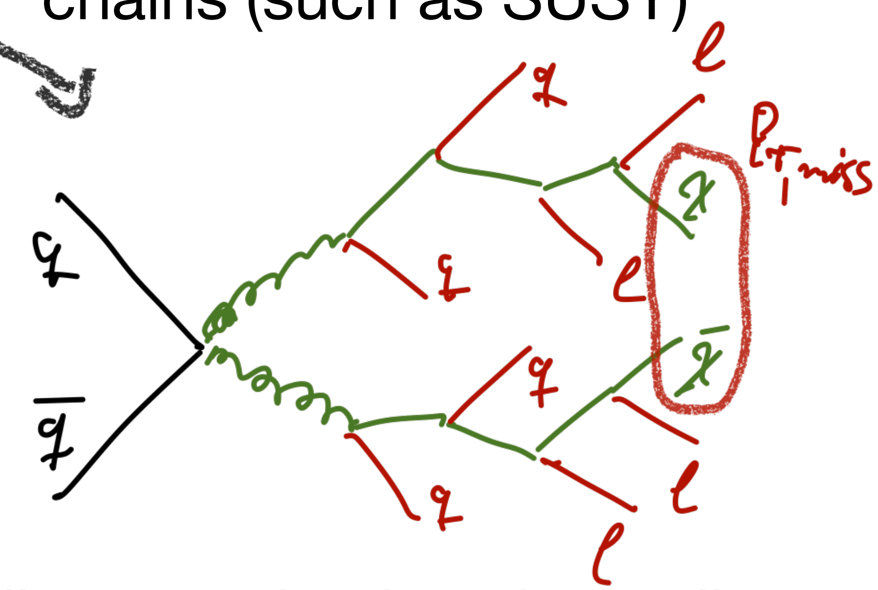


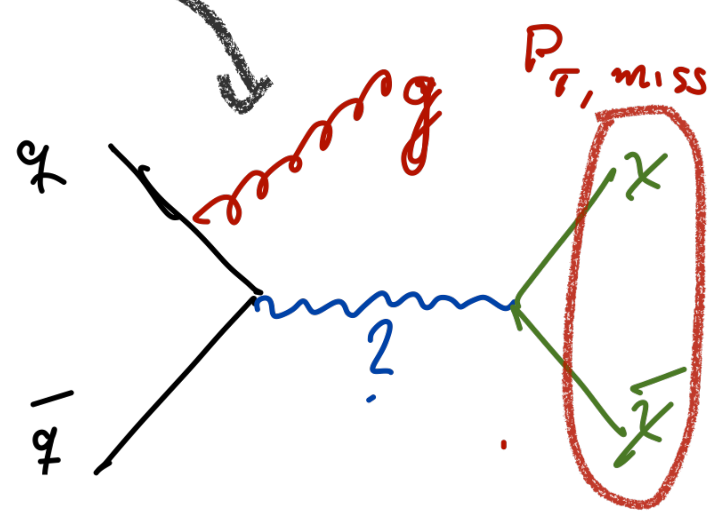
From cosmology: Expect some interaction between Dark Matter and SM particles - thermal equilibrium in early universe, followed by freeze-out



Could produce DM at colliders:
3 different search approaches

detection in complex decay chains (such as SUSY)

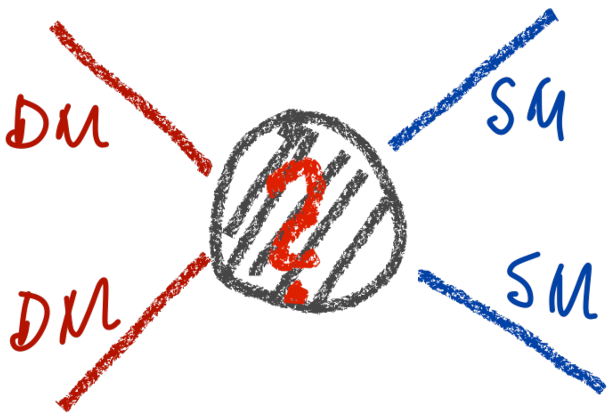




direct production via mediators, tagging of interaction

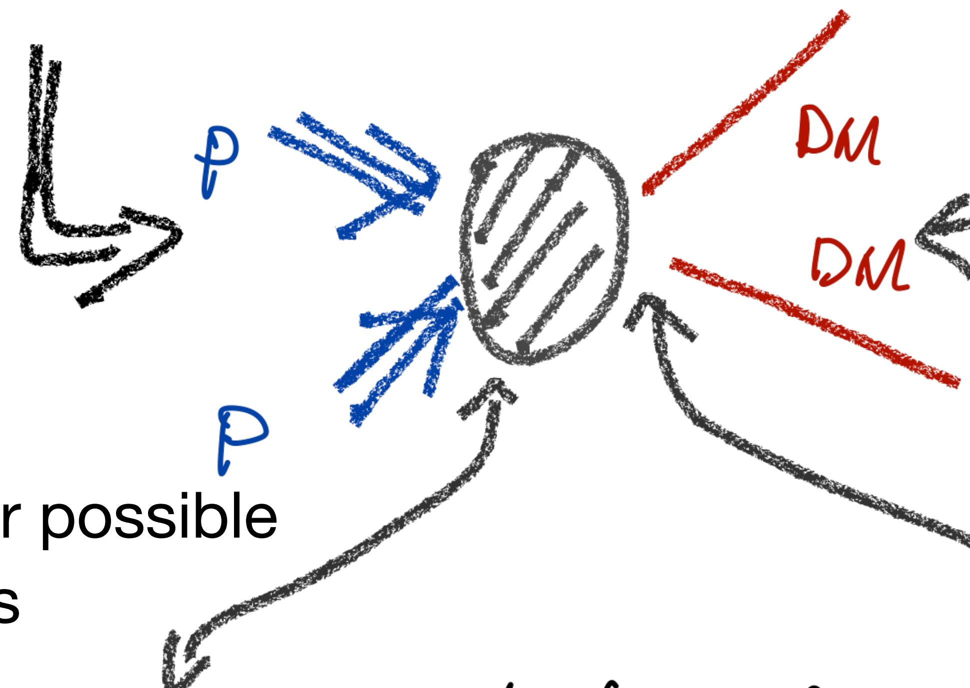
Searching for Dark Matter at Colliders - Principles

- Related to SUSY searches - but also more general

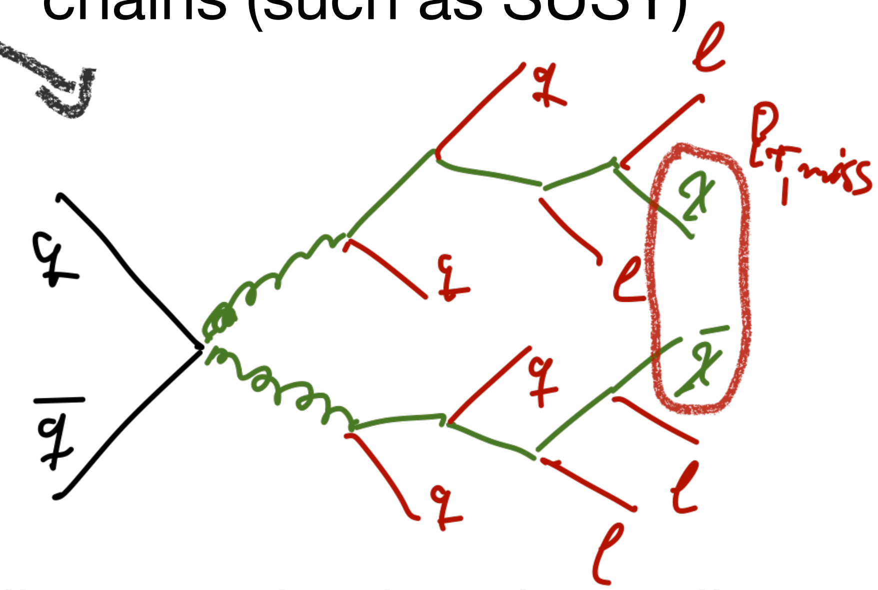


From cosmology: Expect some interaction between Dark Matter and SM particles - thermal equilibrium in early universe, followed by freeze-out

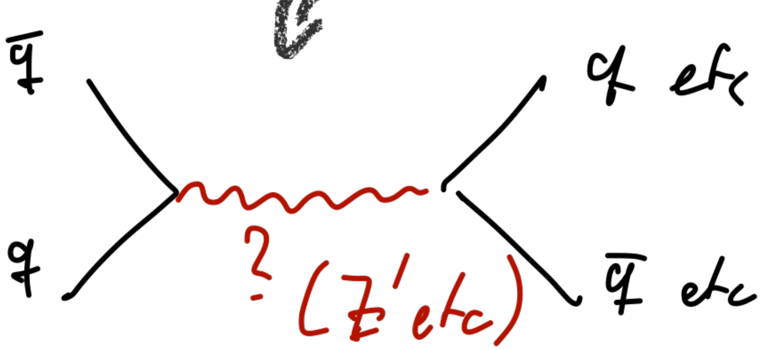
Could produce DM at colliders:
3 different search approaches

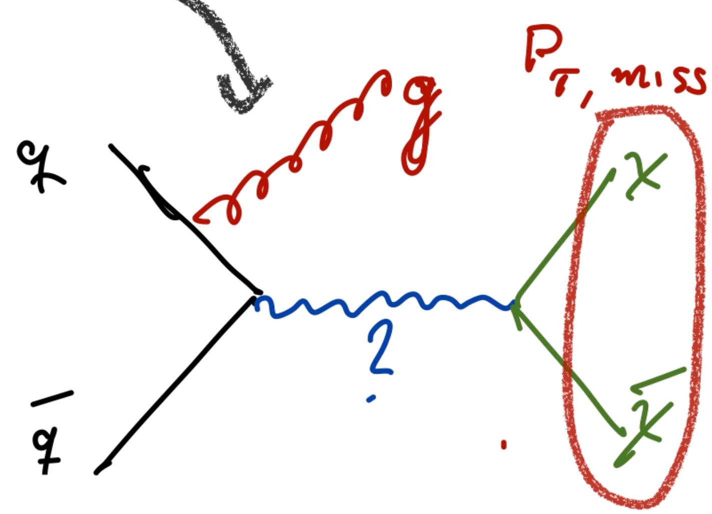


detection in complex decay chains (such as SUSY)



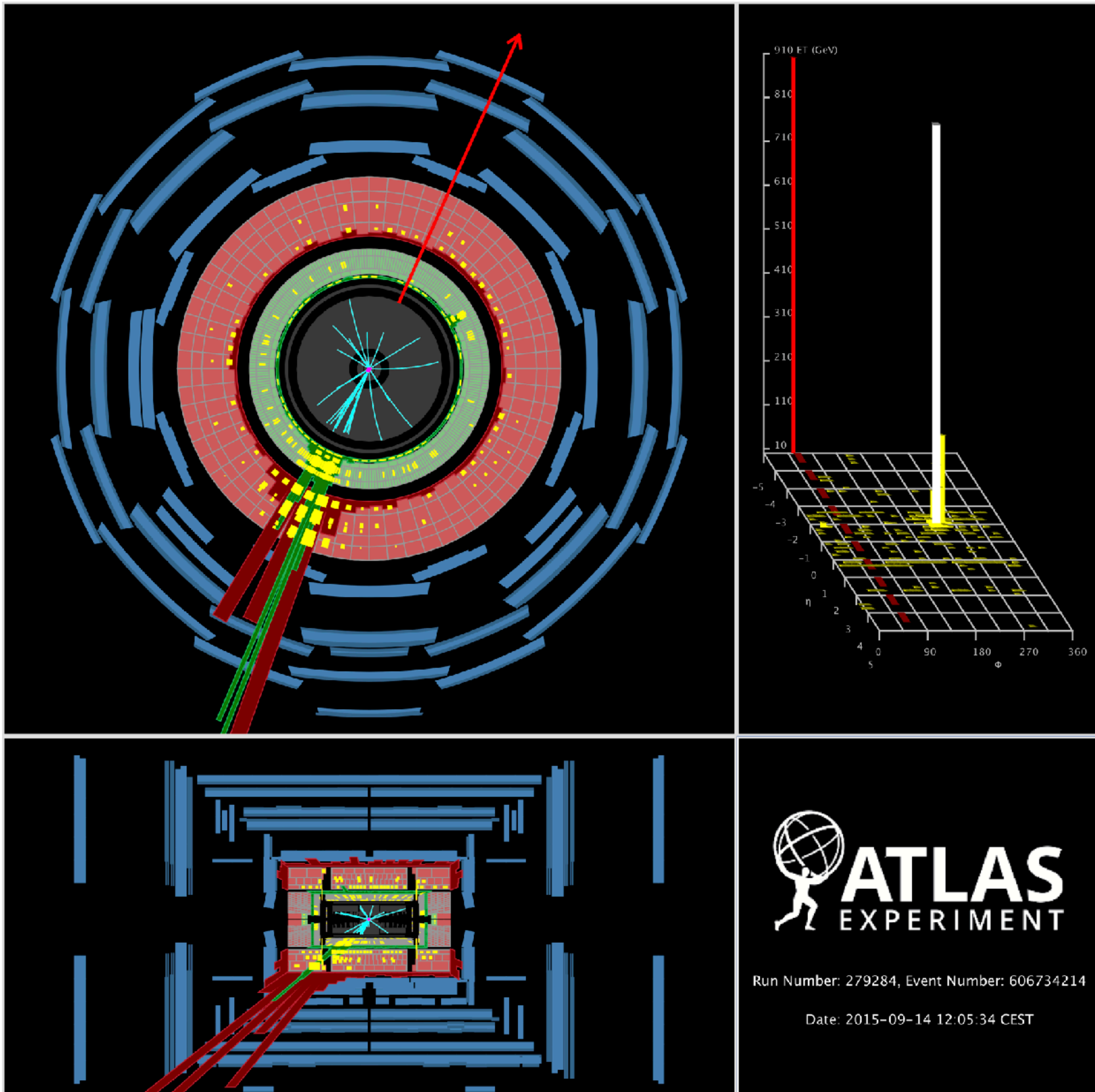
search for possible mediators



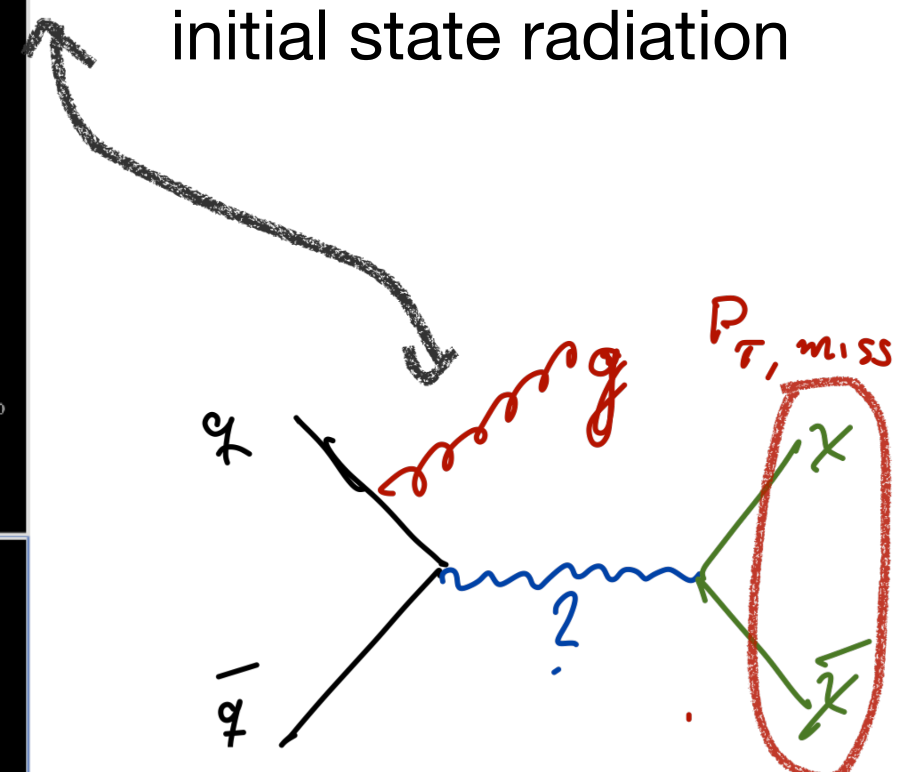


direct production via mediators, tagging of interaction

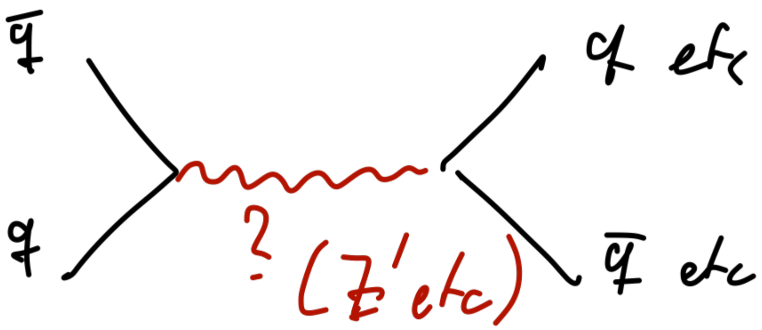
Dark Matter / SUSY Searches: Monojets



- Mono-jet (or mono-photon) signatures: Detecting the production of invisible final states through initial state radiation

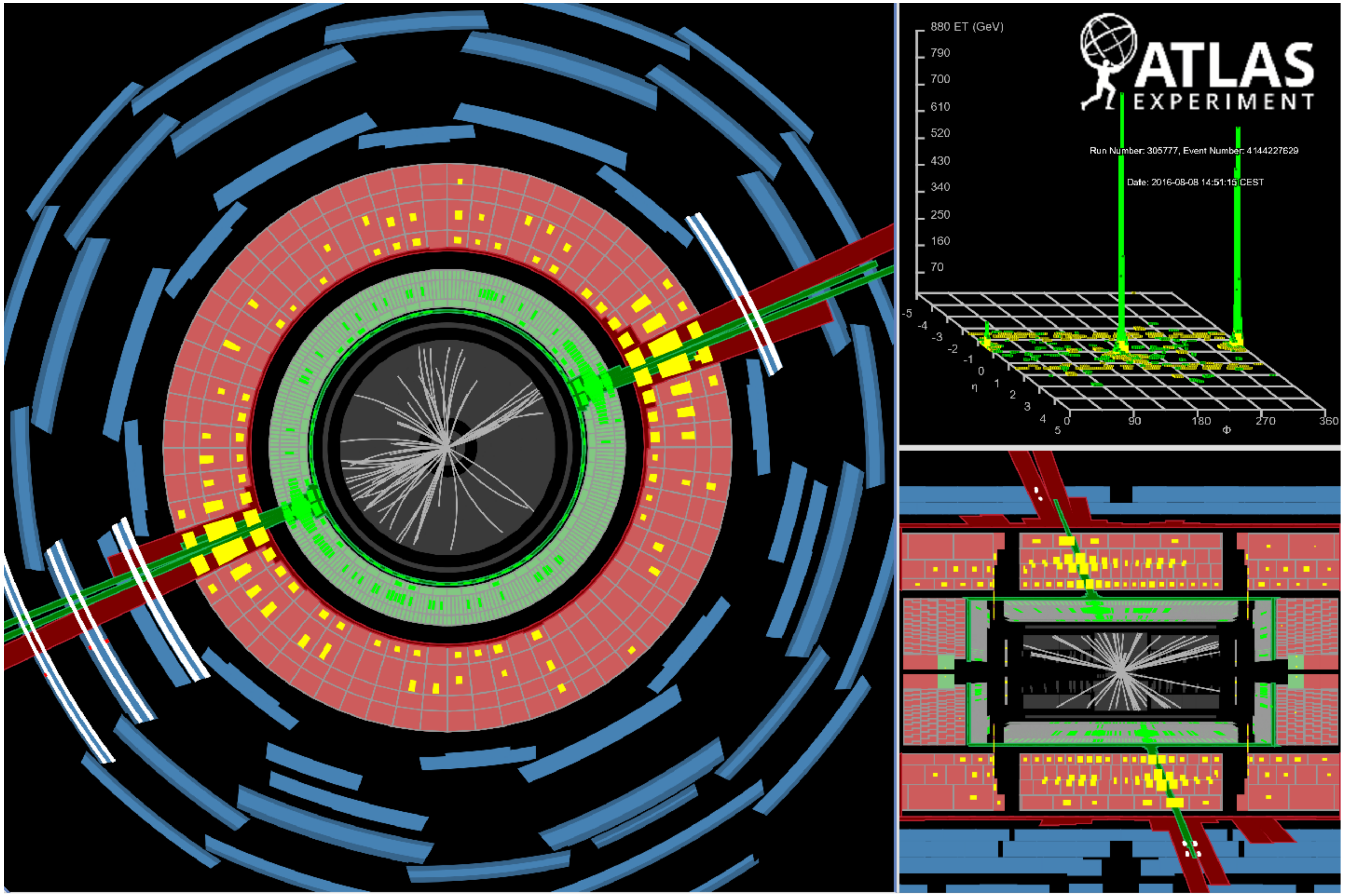


Searching for Dark Matter at Colliders - Mediators



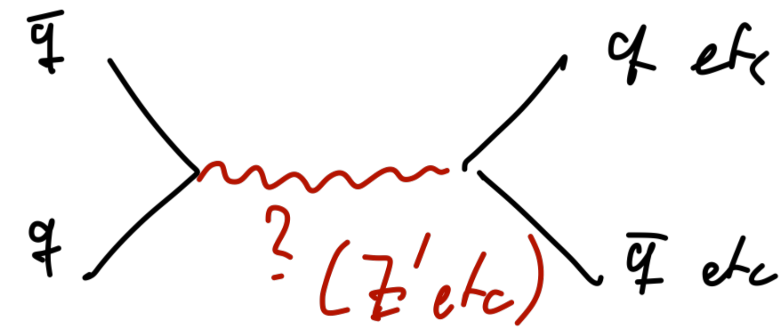
- A search for new force carriers - looking for high-mass resonances

Jet p_T 3.8 TeV, di-jet invariant mass 8.12 TeV

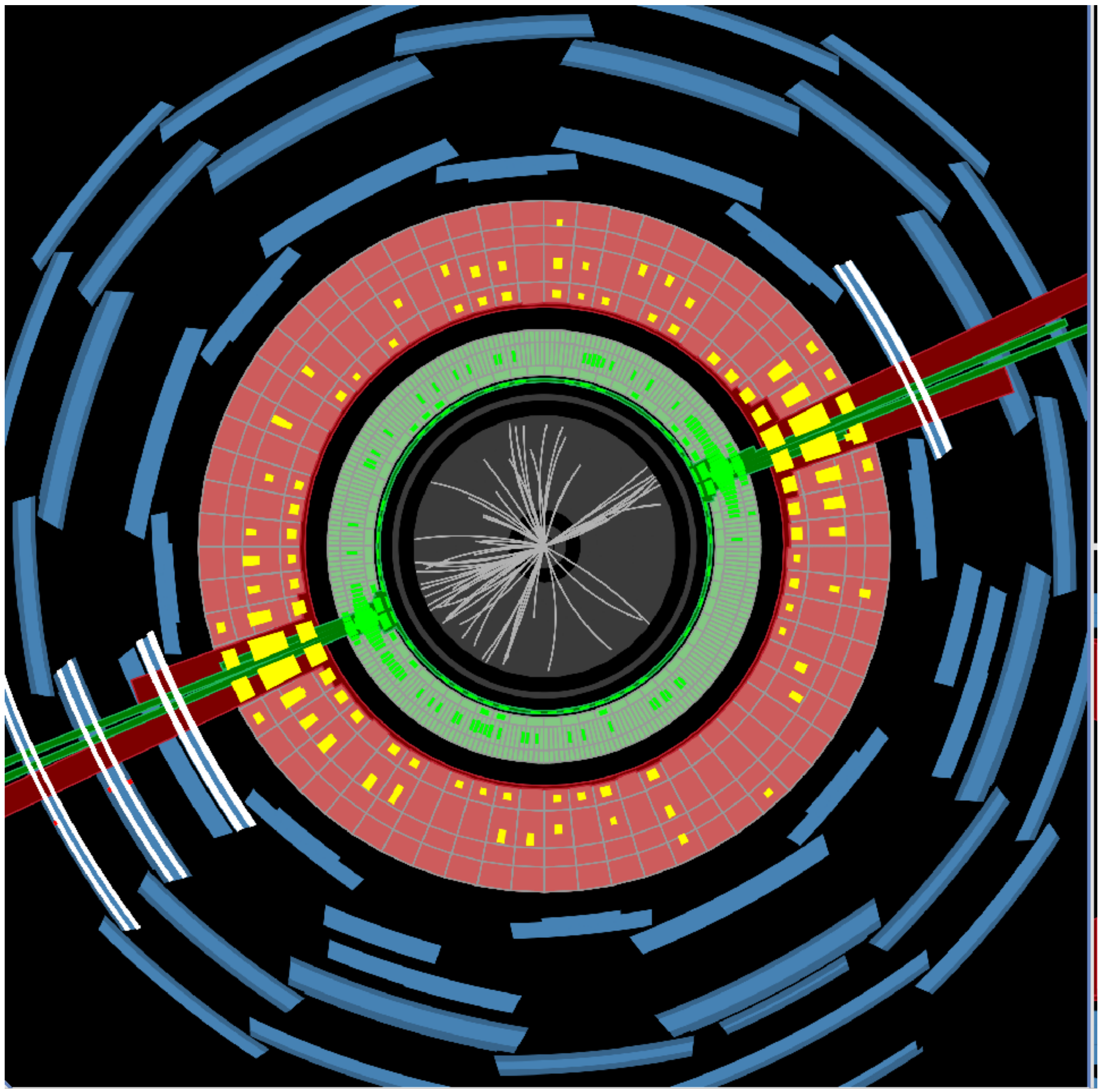


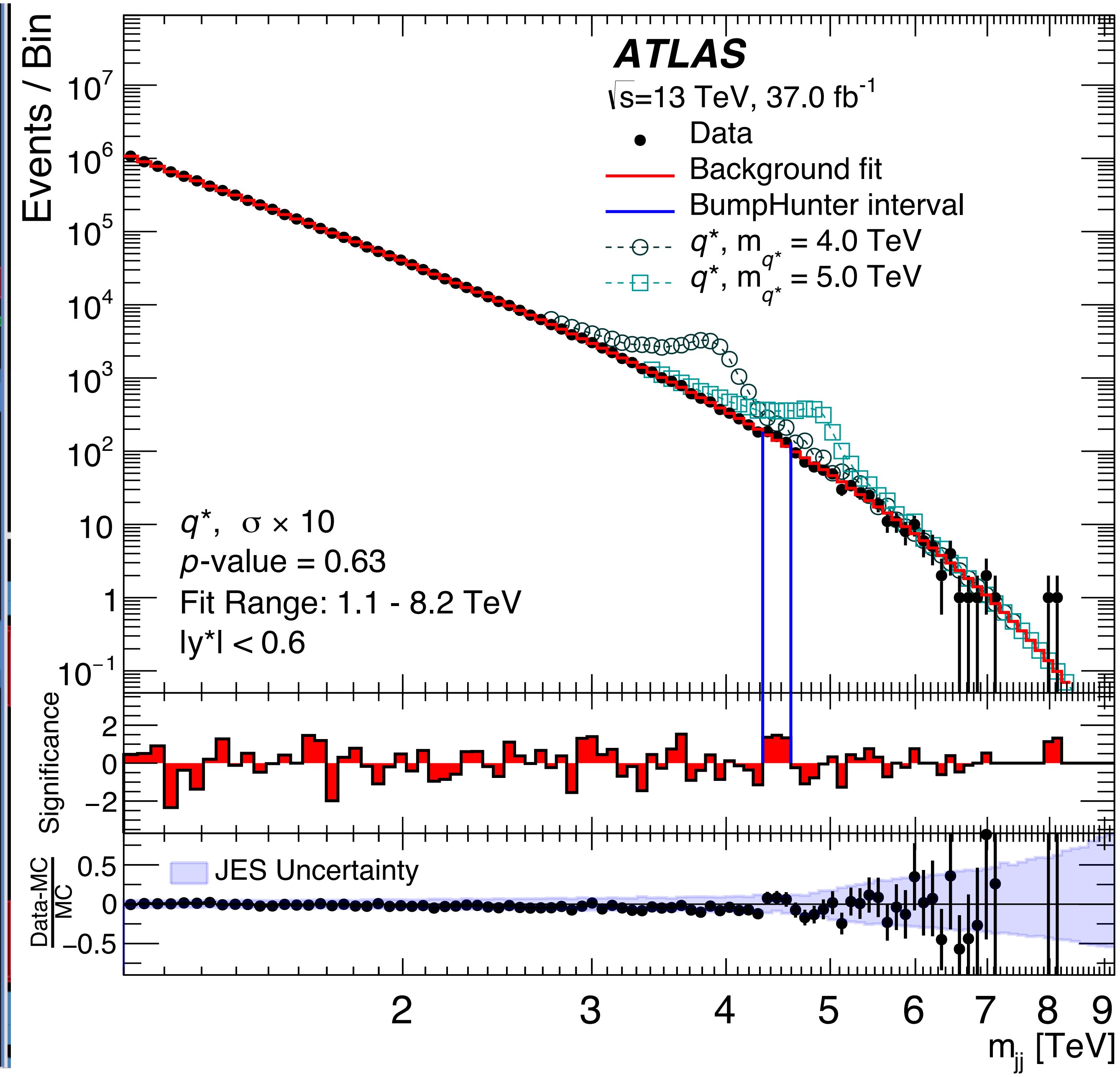
Searching for Dark Matter at Colliders - Mediators

- A search for new force carriers - looking for high-mass resonances



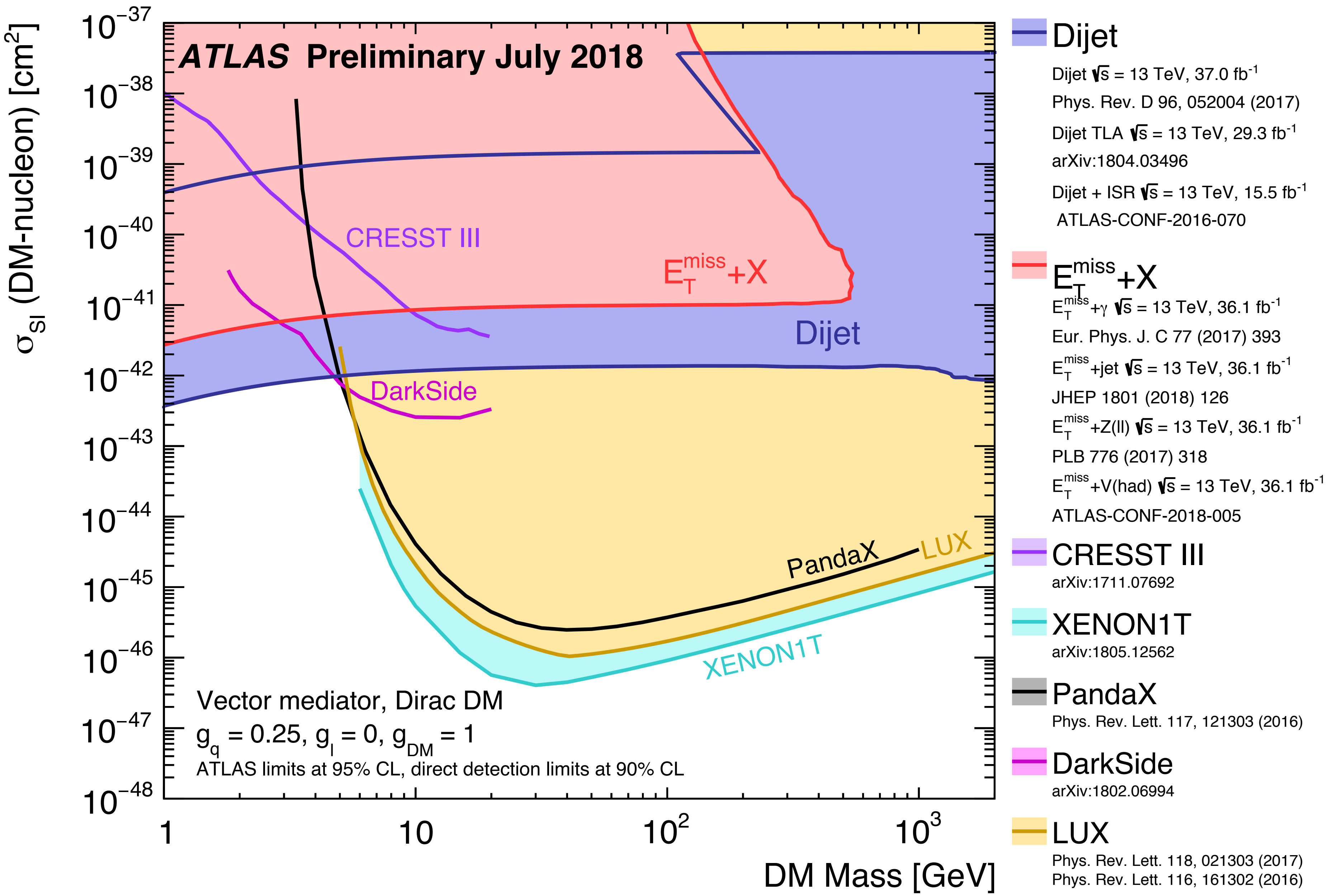
Jet p_T 3.8 TeV, di-jet invariant mass 8.12 TeV





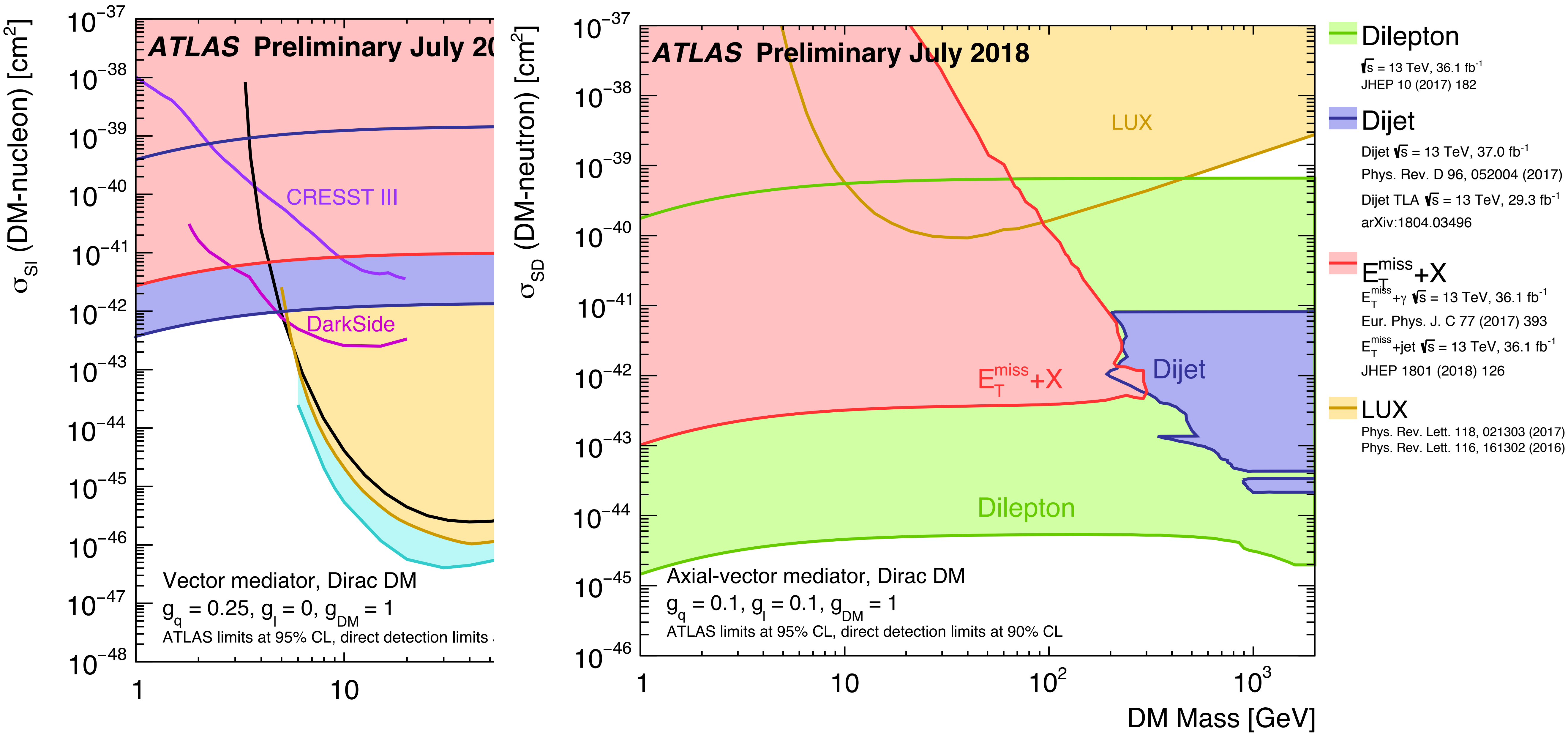
Dark Matter Searches - Limits

- Limits of collider searches are model-dependent: Assumptions on couplings between DM particles, mediators and SM particles, form of interaction, …



Dark Matter Searches - Limits

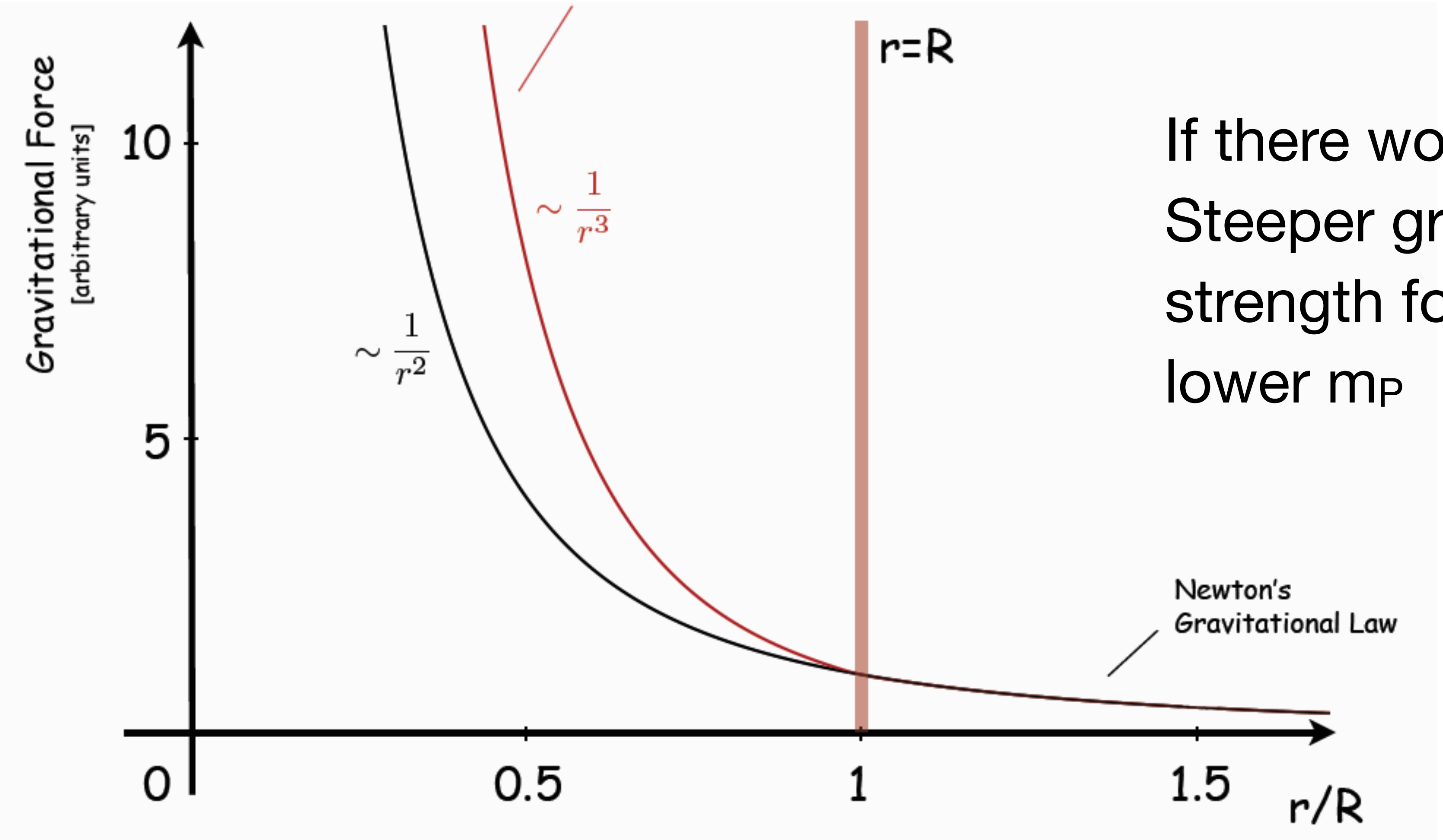
- Limits of collider searches are model-dependent: Assumptions on couplings between DM particles, mediators and SM particles, form of interaction, …



Extra Space Dimensions

- An approach to solve the hierarchy problem from the side of gravity: Lowering the Planck scale
  - Naively: The Planck scale is the mass that is required for an elementary particle such that its gravity is “strong” (comparable to other forces):

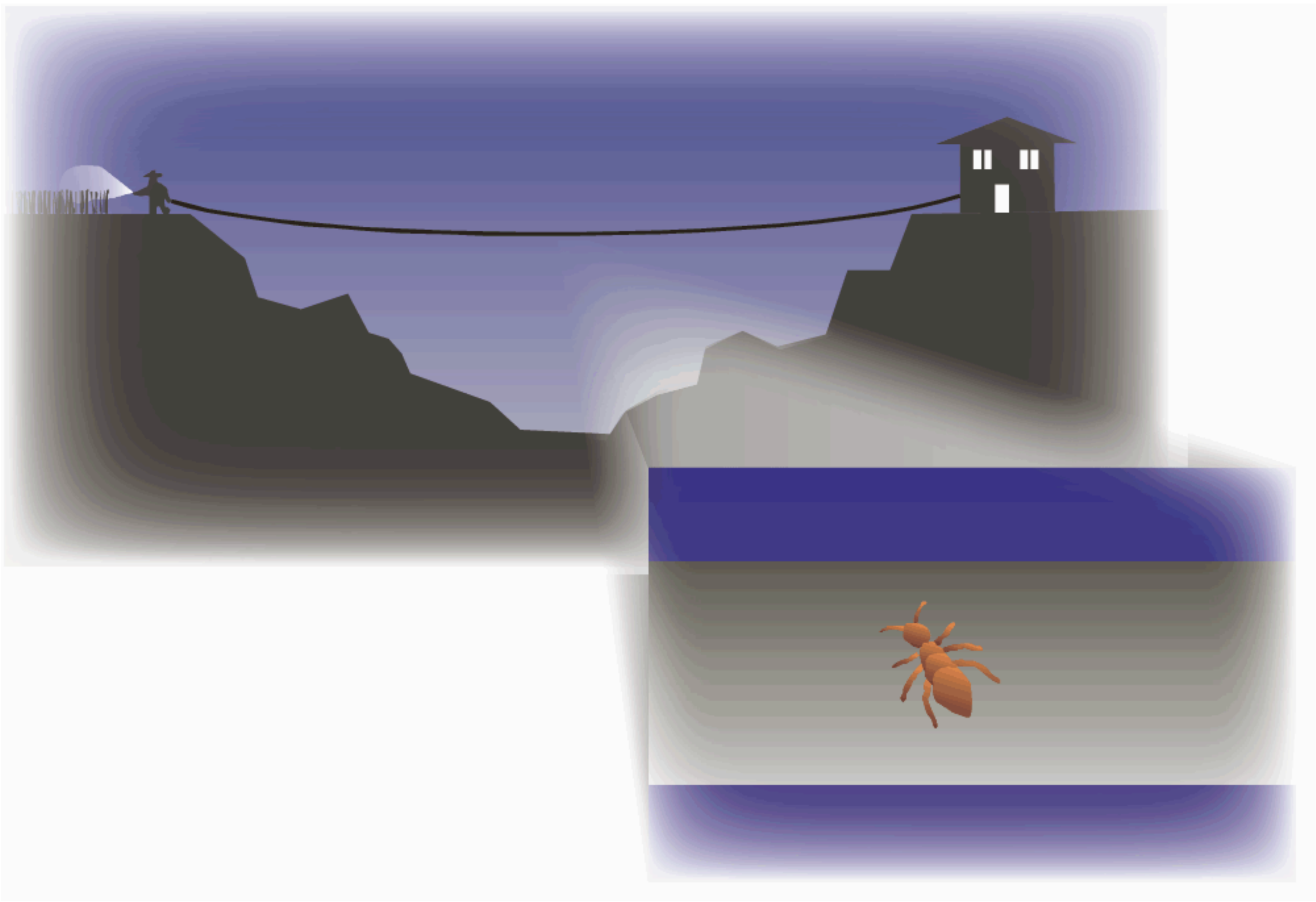
$$m_p = \sqrt{\frac{\hbar c}{G}} \sim 1 \times 10^{19} GeV$$ assuming 3 space dimensions

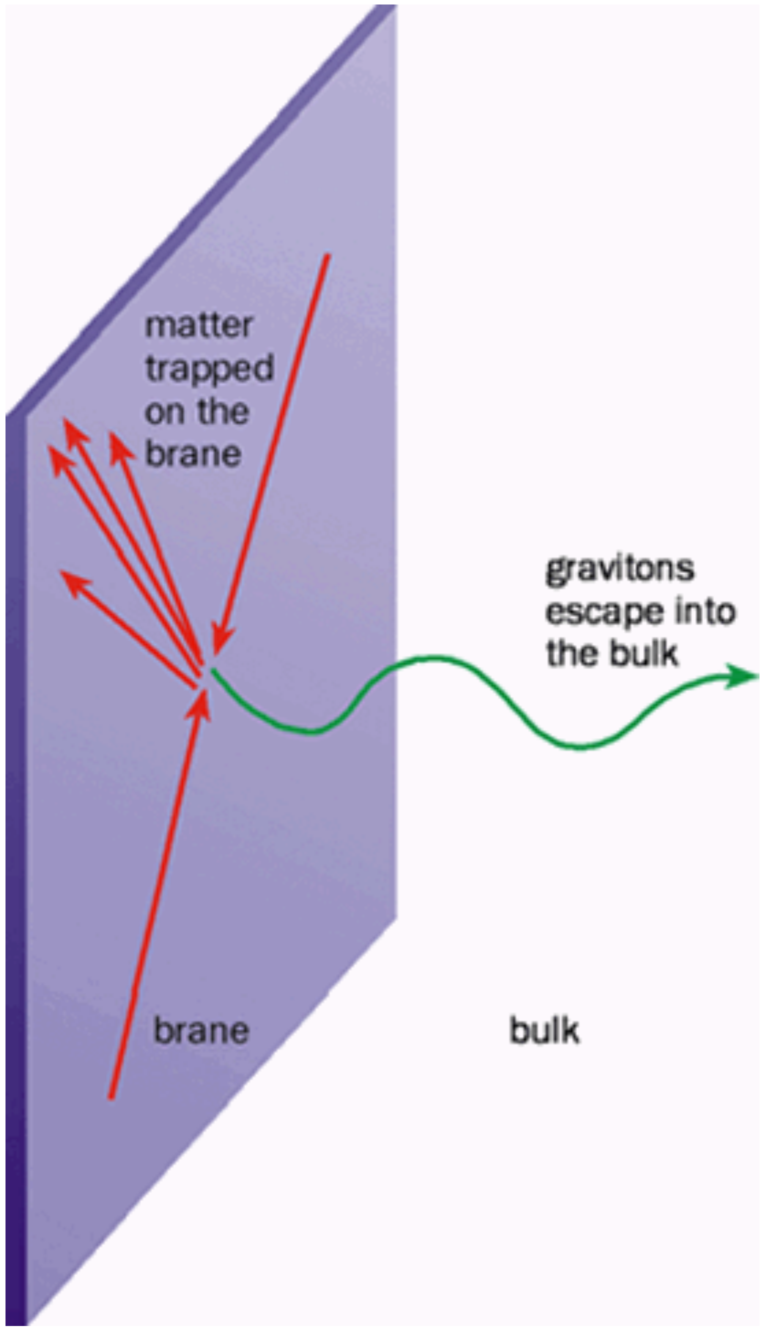


If there would be more dimensions: Steeper growth of gravitational strength for smaller separations, lower m_P

Extra Space Dimensions

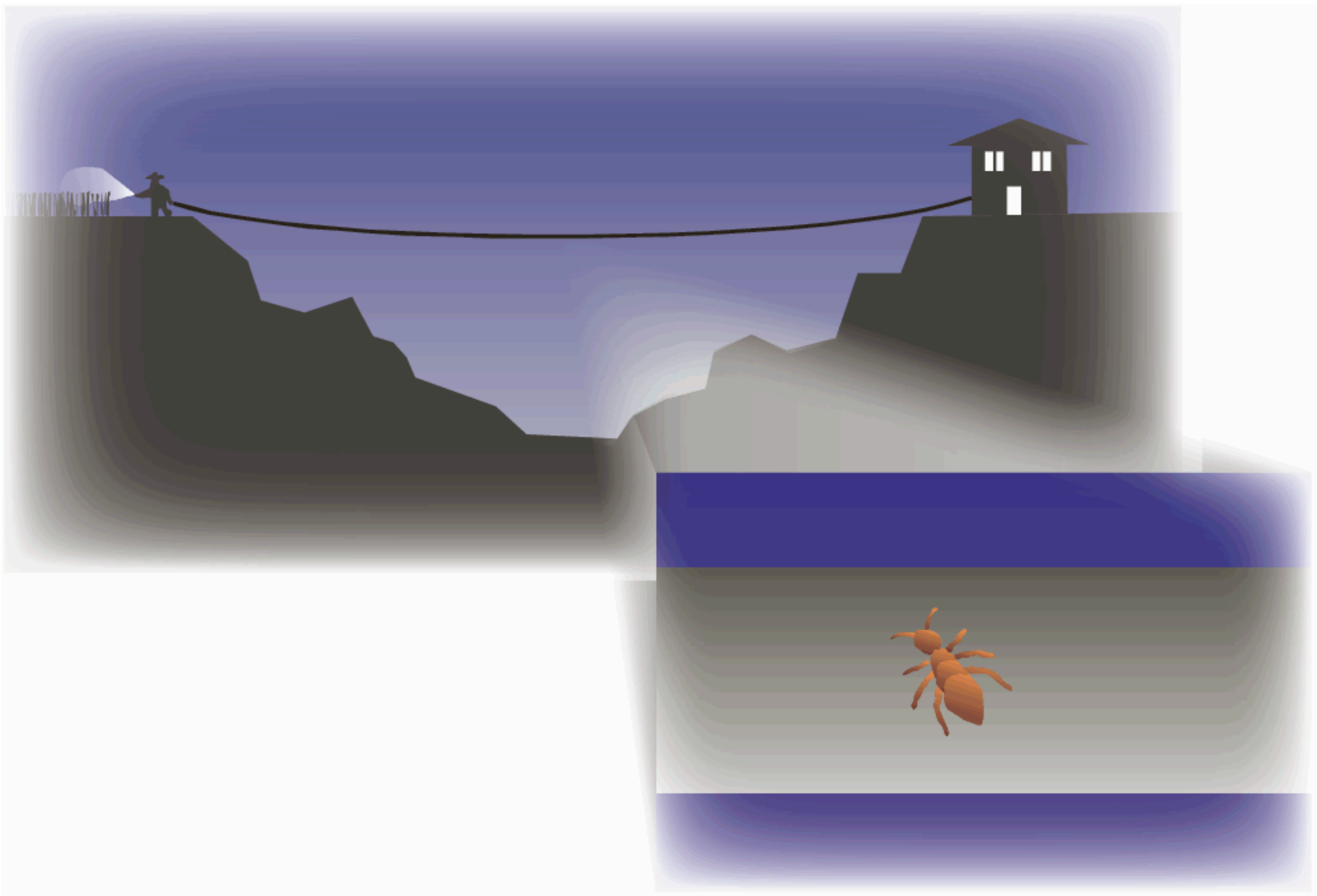
- The idea: Extra dimensions are “compactified” - only relevant at small scales, and only visible to gravity

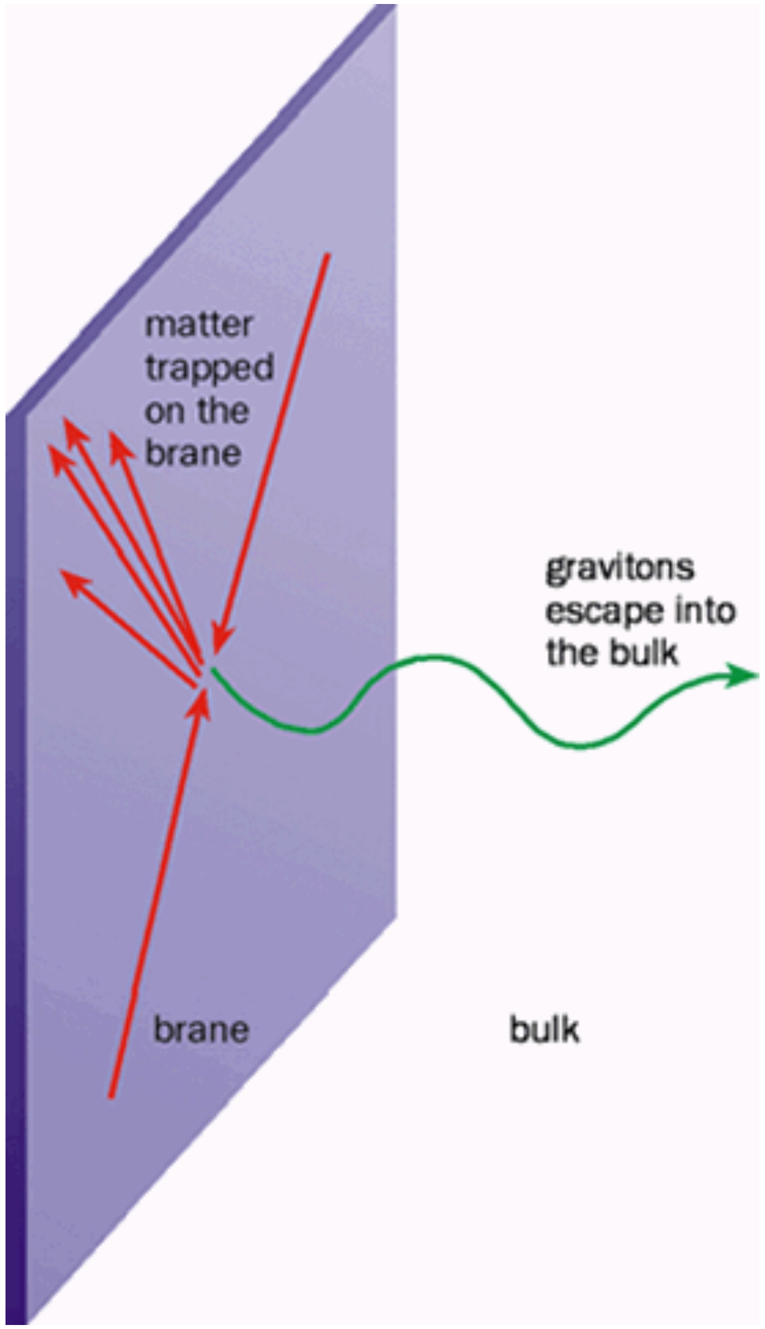




Extra Space Dimensions

- The idea: Extra dimensions are "compactified" - only relevant at small scales, and only visible to gravity





effective lowering of Planck mass by $R^{-n/2}$:

n: number of extra dimensions

R: radius

For large n and large R smaller m_P, can reach TeV scale for nm - scale extra dimensions with n > 3

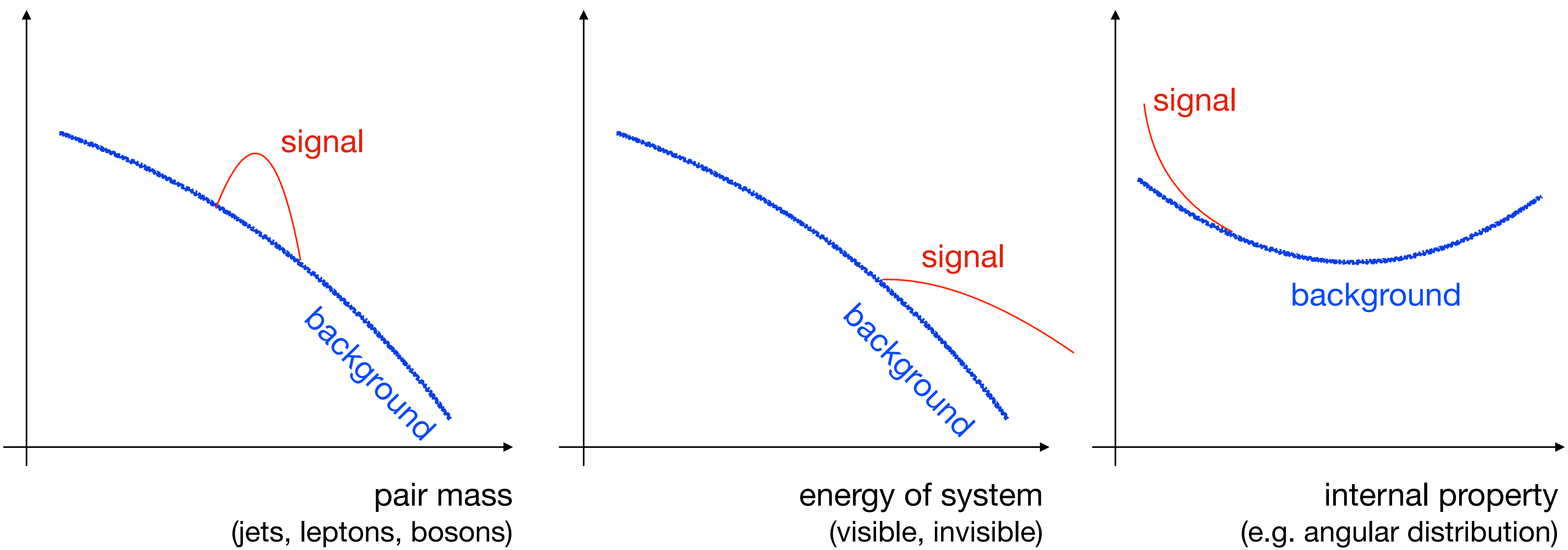
Extra Dimensions: Experimental Signatures

- Excitations in extra dimensions: High-mass resonances
- Creation and decay of micro - Black Holes: High-energy many-particle final states

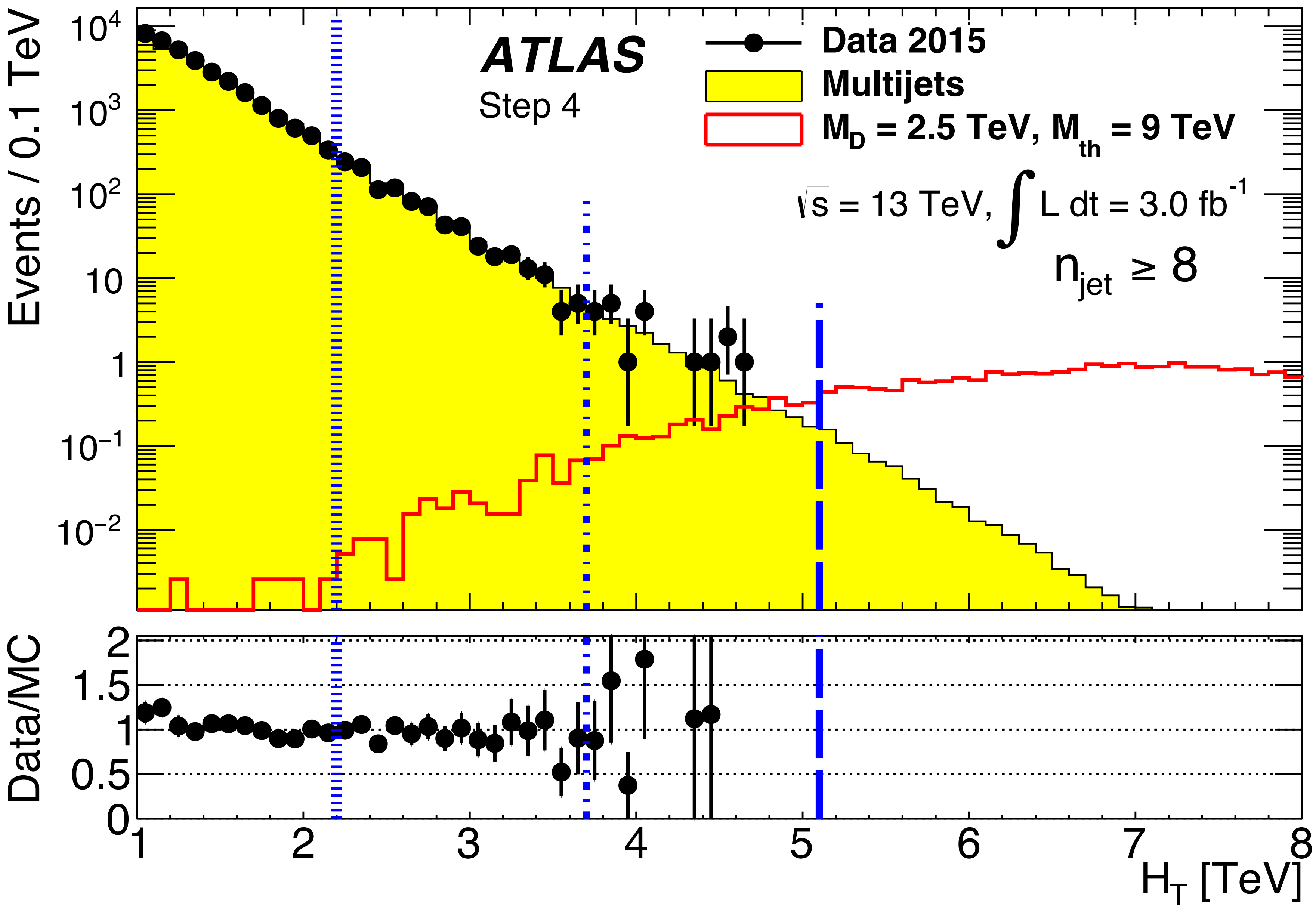
Extra Dimensions: Experimental Signatures

- Excitations in extra dimensions: High-mass resonances
- Creation and decay of micro - Black Holes: High-energy many-particle final states

Generic signatures for a number of “exotic” New Physics scenarios



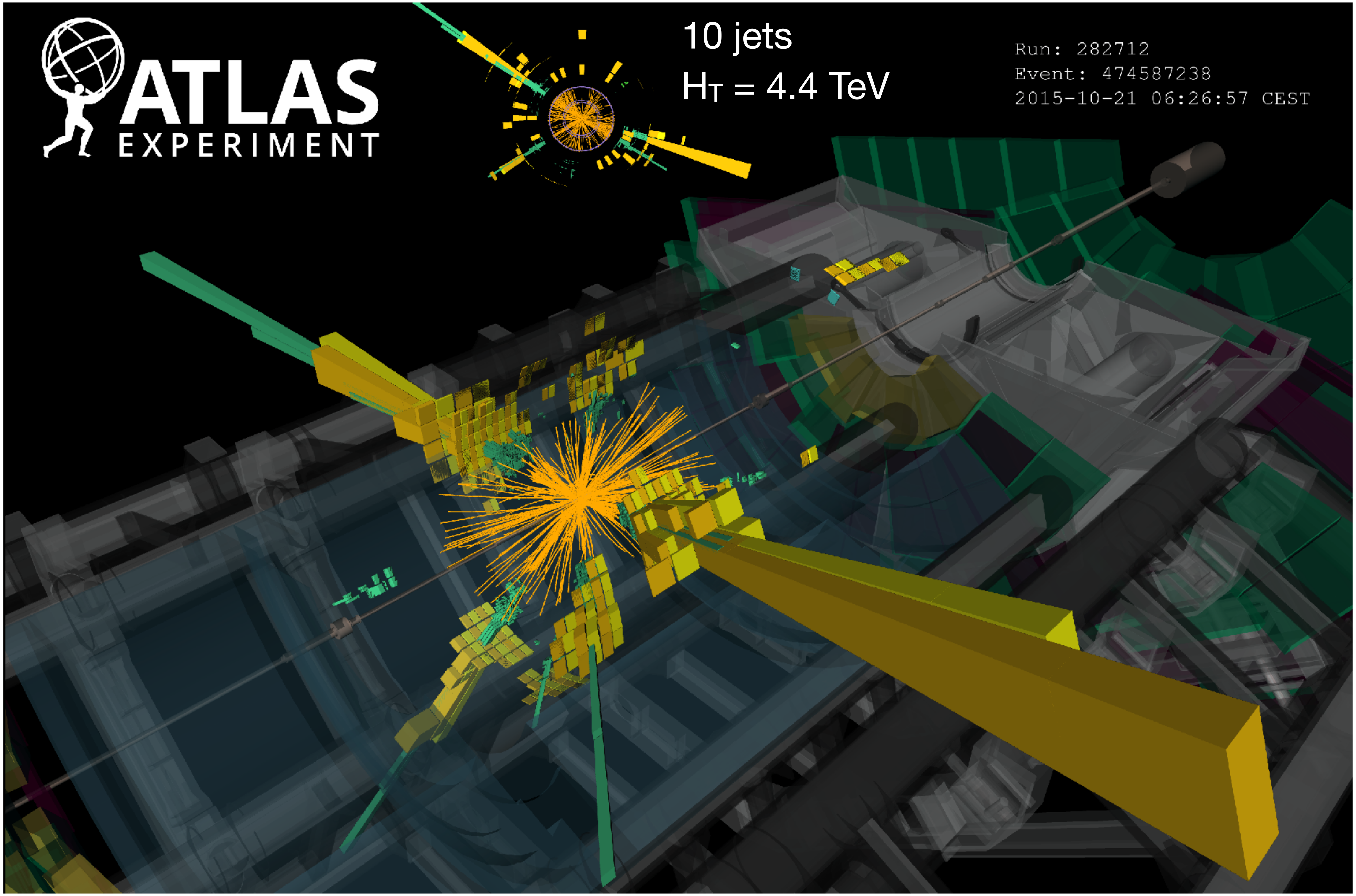
Black Hole Search: One Example



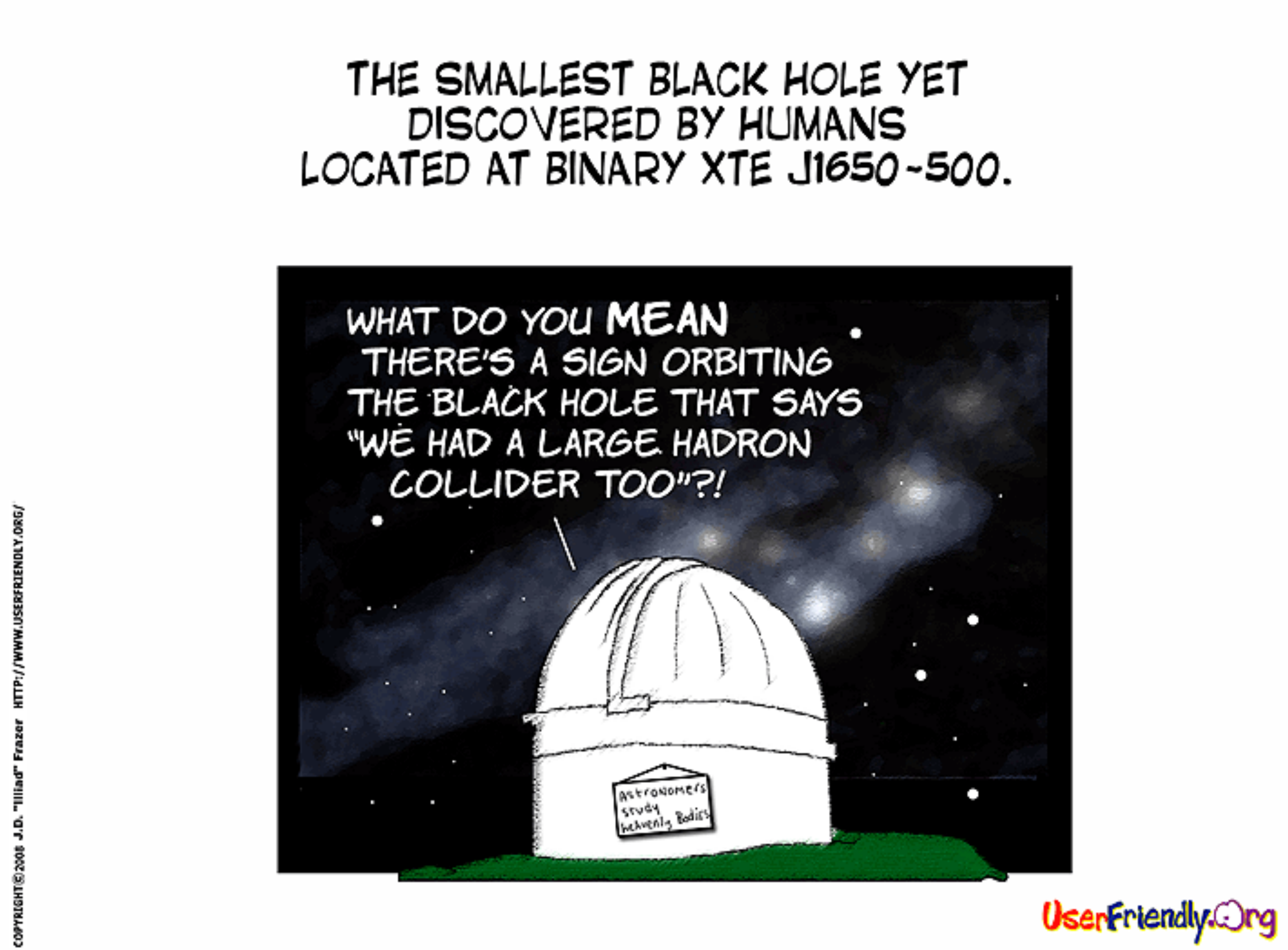
- Looking for an excess of signals in high jet multiplicities (here 8 or more jets)
- High total transverse Energy (H_T)

JHEP 03, 026 (2016)

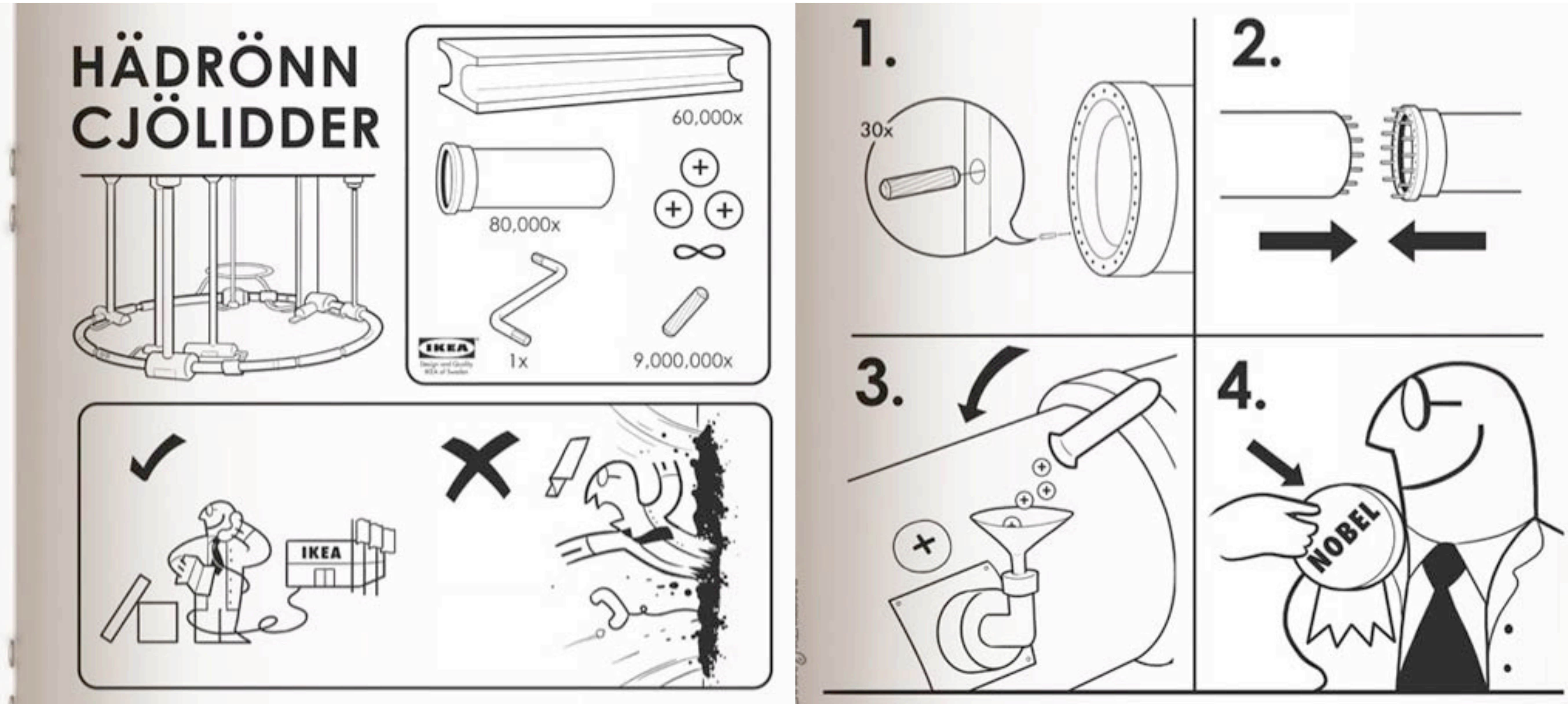
Black Hole Search: One Example



Ideas that Capture the Imagination…



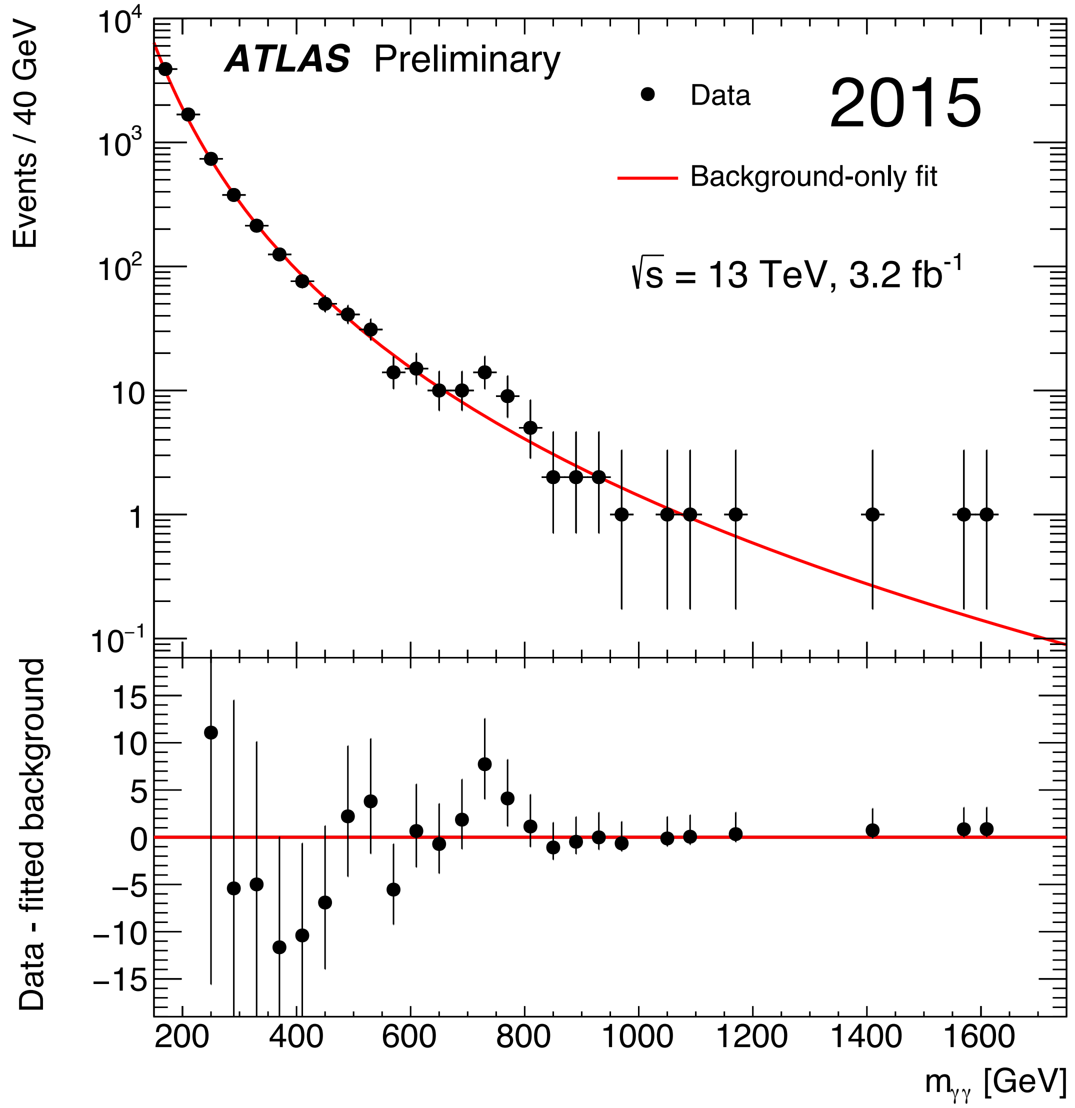
Ideas that Capture the Imagination…



Ideas that Capture the Imagination…

Ideas that Capture the Imagination…

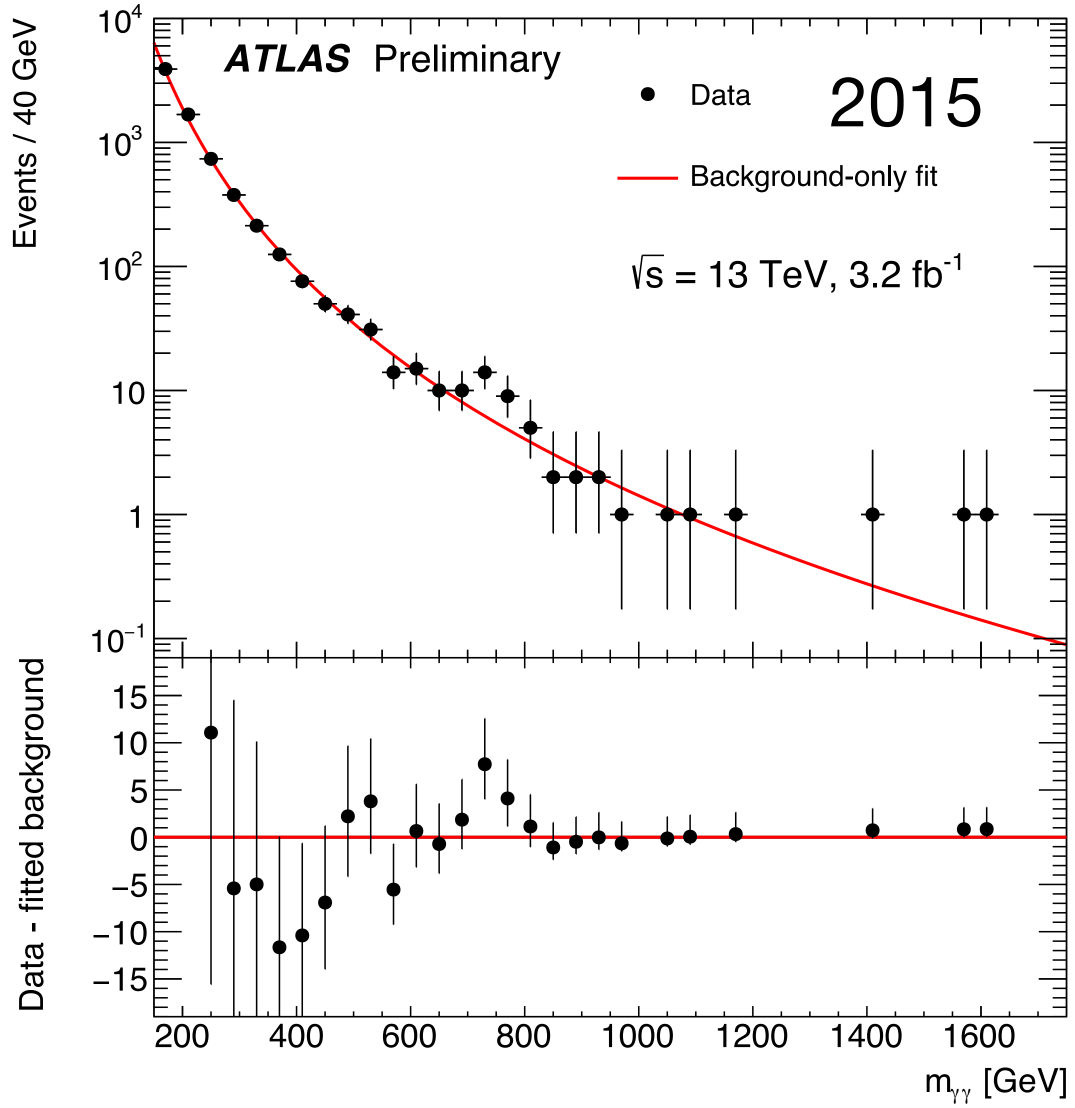
Periods of Excitement



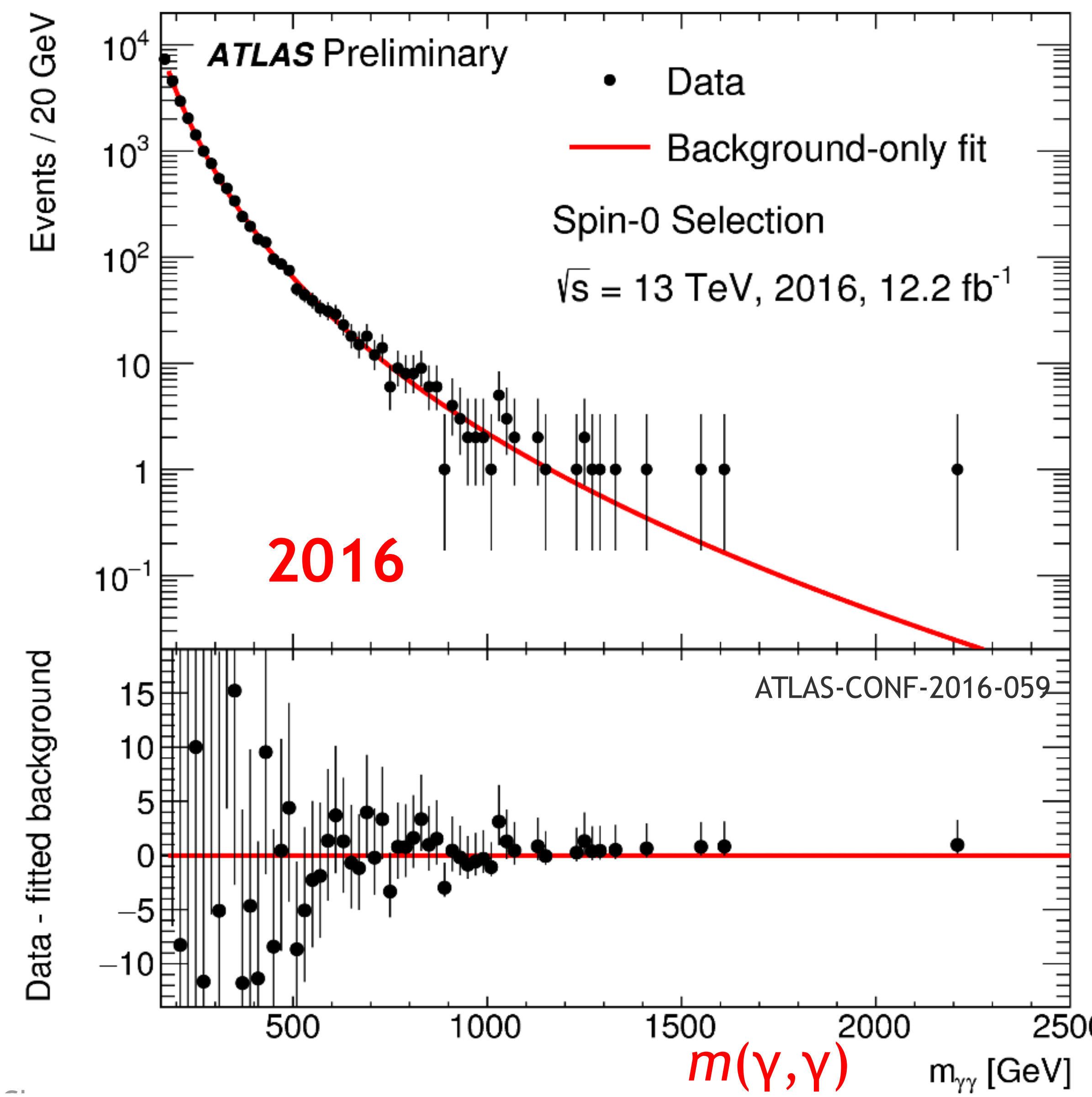
- Observed excess around 750 GeV in γγ invariant mass - a narrow resonance? also seen in similar (but not identical) mass range by CMS

2.1 σ global (3.9 σ local) significance

Periods of Excitement

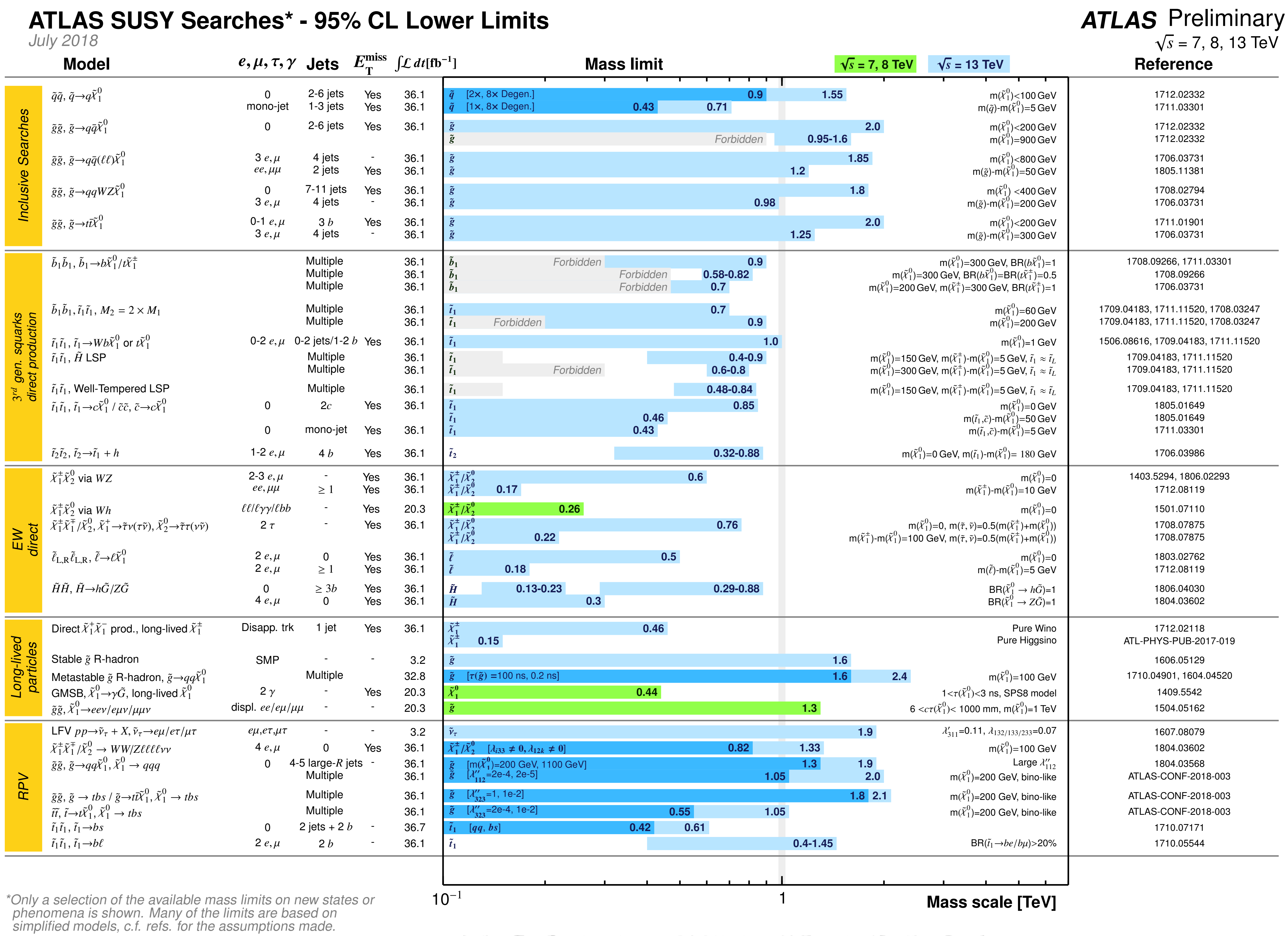


- Observed excess around 750 GeV in γγ invariant mass - a narrow resonance? also seen in similar (but not identical) mass range by CMS



… turned out to be a fluctuation.

A Broader View: Status of SUSY Searches at LHC



A Broader View: Status of BSM Searches at LHC

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2018

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.2 - 79.8)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt [\mathrm{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ	1 – 4 j	Yes	36.1	M_D 7.7 TeV	$n = 2$	1711.03301
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	M_S 8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	M_{th} 8.9 TeV	$n = 6$	1703.09217
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	3.2	M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	36.7	G_{KK} mass 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	1707.04147
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	G_{KK} mass 2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	CERN-EP-2018-179
	Bulk RS $g_{KK} \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	g_{KK} mass 3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 3 j	Yes	36.1	KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	36.1	Z' mass 4.5 TeV		1707.02424
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	Z' mass 2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z' mass 2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	Z' mass 3.0 TeV	$\Gamma/m = 1\%$	1804.10823
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	79.8	W' mass 5.6 TeV		ATLAS-CONF-2018-017
	SSM $W' \to \tau\nu$	1 τ	–	Yes	36.1	W' mass 3.7 TeV		1801.06992
	HVT $V' \to WV \to qqqq$ model B	0 e, μ	2 J	–	79.8	V' mass 4.15 TeV	$g_V = 3$	ATLAS-CONF-2018-016
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	V' mass 2.93 TeV	$g_V = 3$	1712.06518
	LRSM $W'_R \to tb$	multi-channel			36.1	W' mass 3.25 TeV		CERN-EP-2018-142
CI	CI $qqqq$	–	2 j	–	37.0	Λ 21.8 TeV η^-_{LL}		1703.09217
	CI $\ell\ell qq$	2 e, μ	–	–	36.1	Λ 40.0 TeV η^-_{LL}		1707.02424
	CI $tttt$	≥ 1 e, μ	≥ 1 b, ≥ 1 j	Yes	36.1	Λ 2.57 TeV	$\lvert C_{4t}\rvert = 4\pi$	CERN-EP-2018-174
DM	Axial-vector mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	m_{med} 1.55 TeV	g_q=0.25, g_χ=1.0, $m(\chi) = 1$ GeV	1711.03301
	Colored scalar mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	m_{med} 1.67 TeV	g=1.0, $m(\chi) = 1$ GeV	1711.03301
	$VV\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	M_* 700 GeV	$m(\chi) < 150$ GeV	1608.02372
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	3.2	LQ mass 1.1 TeV	$\beta = 1$	1605.06035
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	3.2	LQ mass 1.05 TeV	$\beta = 1$	1605.06035
	Scalar LQ 3rd gen	1 e, μ	≥ 1 b, ≥ 3 j	Yes	20.3	LQ mass 640 GeV	$\beta = 0$	1508.04735
Heavy quarks	VLQ $TT \to Ht/Zt/Wb + X$	multi-channel			36.1	T mass 1.37 TeV	SU(2) doublet	ATLAS-CONF-2018-032
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	B mass 1.34 TeV	SU(2) doublet	ATLAS-CONF-2018-032
	VLQ $T_{5/3} T_{5/3} \lvert T_{5/3} \to Wt + X$	2(SS)/≥ 3 e, μ	≥ 1 b, ≥ 1 j	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3}Wt)$= 1	CERN-EP-2018-171
	VLQ $Y \to Wb + X$	1 e, μ	≥ 1 b, ≥ 1j	Yes	3.2	Y mass 1.44 TeV	$\mathcal{B}(Y \to Wb)$= 1, $c(YWb)$= $1/\sqrt{2}$	ATLAS-CONF-2016-072
	VLQ $B \to Hb + X$	0 e, μ, 2 γ	≥ 1 b, ≥ 1j	Yes	79.8	B mass 1.21 TeV	κ_B= 0.5	ATLAS-CONF-2018-024
	VLQ $QQ \to WqWq$	1 e, μ	≥ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	37.0	q^* mass 6.0 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1703.09127
	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	36.7	q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	36.1	b^* mass 2.6 TeV		1805.09299
	Excited lepton ℓ^*	3 e, μ	–	–	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	Type III Seesaw	1 e, μ	≥ 2 j	Yes	79.8	N^0 mass 560 GeV		ATLAS-CONF-2018-020
	LRSM Majorana ν	2 e, μ	2 j	–	20.3	N^0 mass 2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	$H^{\pm\pm}$ mass 870 GeV	DY production	1710.09748
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Monotop (non-res prod)	1 e, μ	1 b	Yes	20.3	spin-1 invisible particle mass 657 GeV	$a_{non-res} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	multi-charged particle mass 785 GeV	DY production, $\lvert q\rvert = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	monopole mass 1.34 TeV	DY production, $\lvert g\rvert = 1 g_D$, spin 1/2	1509.08059

$\sqrt{s}$ = 8 TeV $\sqrt{s}$ = 13 TeV

10^{-1} 1   10   **Mass scale [TeV]**

*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

Finally…

Absence of evidence is not evidence of absence

meaning:

no sign of physics BSM from Run-I / Run-II data,
but unexplored phase space still large!

… and there are corners that cannot be fully explored with LHC,
even within its energy / mass reach.

Summary

- The Standard Model is incomplete - conceptual problems and failures to describe astrophysical observations. But so far experiments have not yet revealed concrete discoveries of New Physics

- A wide range of theoretical models:
  - Grand Unified Theories as an overarching theory at very high energies
  - Supersymmetry, Large Extra Dimensions, … on the electroweak scale

- A rich array of experimental searches at the LHC, looking for:
  - New particles
  - Dark Matter candidates
  - New forces and unexpected phenomena
  - …

Up to now: Nothing found!

Summary

- The Standard Model is incomplete - conceptual problems and failures to describe astrophysical observations. But so far experiments have not yet revealed concrete discoveries of New Physics
- A wide range of theoretical models:
  - Grand Unified Theories as an overarching theory at very high energies
  - Supersymmetry, Large Extra Dimensions, … on the electroweak scale
- A rich array of experimental searches at the LHC, looking for:
  - New particles
  - Dark Matter candidates
  - New forces and unexpected phenomena
  - …

Up to now: Nothing found!

Next (and final!) Lecture:
Physics beyond the Standard Model in the Early Universe - B. Majorovits, 04.02.2018

Lecture Overview

15.10.	Introduction, Particle Physics Refresher	*F. Simon*
22.10.	Introduction to Cosmology I	*B. Majorovits*
29.10.	Introduction to Cosmology II	*B. Majorovits*
05.11.	Particle Collisions at High Energy	*F. Simon*
12.11.	The Higgs Boson	*F. Simon*
19.11.	The Early Universe: Thermal Freeze-out of Particles	*B. Majorovits*
26.11.	The Universe as a High Energy Laboratory: BBN	*B. Majorovits*
03.12.	The Universe as a High Energy Laboratory: CMB	*B. Majorovits*
10.12.	Particle Colliders	*F. Simon*
17.12.	Detectors for Particle Colliders I	*F. Simon*
	Christmas Break	
07.01.	Detectors for Particle Colliders II	*F. Simon*
14.01.	Cosmic Rays: Acceleration Mechanisms and Possible Sources	*B. Majorovits*
21.01.	Supernovae Accelerators for Charged Particles and Neutrinos	*B. Majorovits*
28.01.	Searching for New Physics at the Energy Frontier	*F. Simon*
04.02.	Physics beyond the Standard Model in the Early Universe	*B. Majorovits*