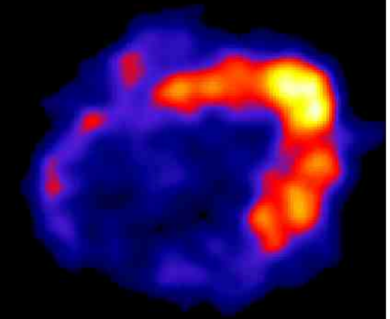
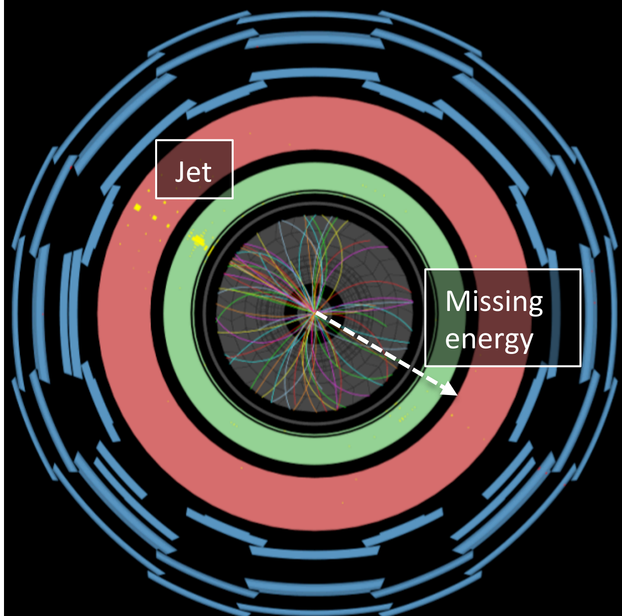
Going after the Dark at the LHC

David Berge (CERN)

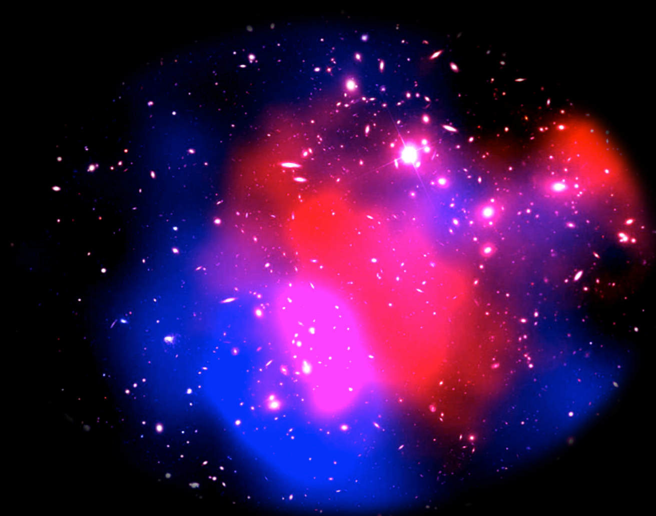
Supernova remnant RX J1713





H.E.S.S. experiment

ATLAS mono-jet event display



Galaxy cluster Abell 2744

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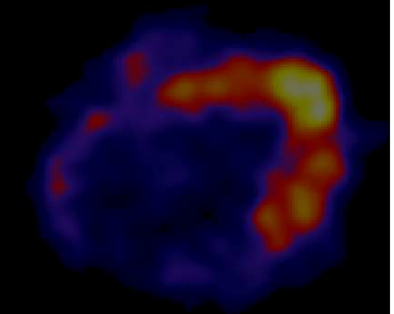

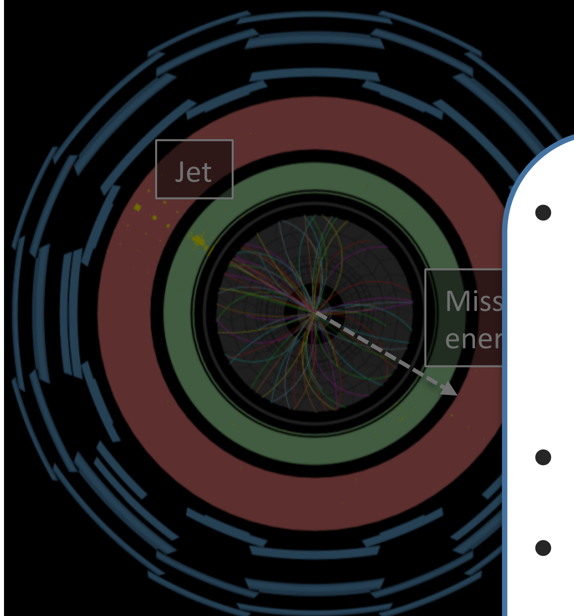

- Setting the stage
  - The need for new physics
  - The need for a hadron collider
- ATLAS searches and Dark Matter
- Future plans

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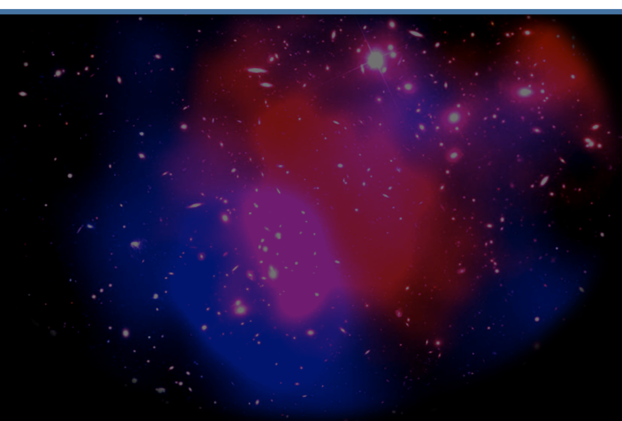
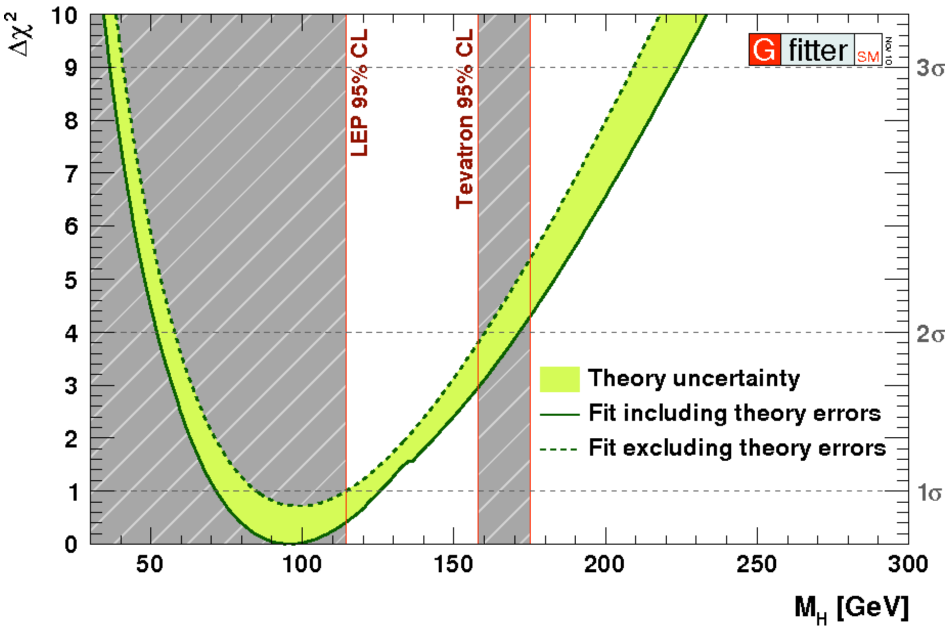


Galaxy cluster Abell 2744

Arguments for new physics (at the TeV scale)

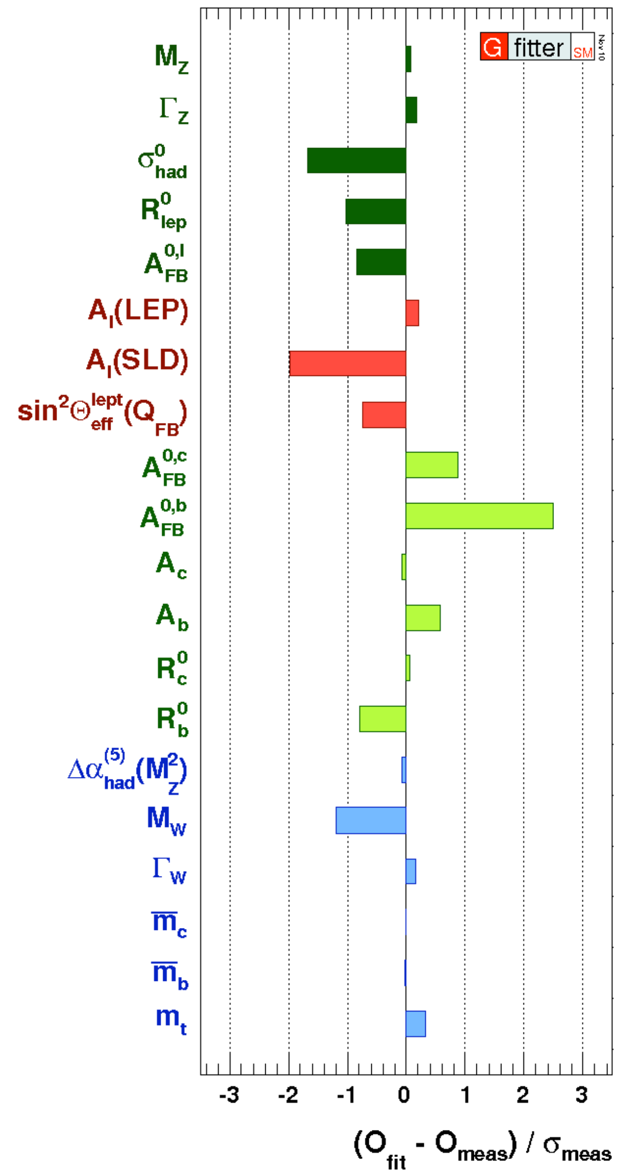
No unambiguous experimental result requires new physics at the TeV scale

EW fit **not including** direct Higgs searches (LHC bands missing)



Central value ±1σ: $M_H = 96^{+31}_{-24}$ GeV

95% CL upper limit: 169 GeV

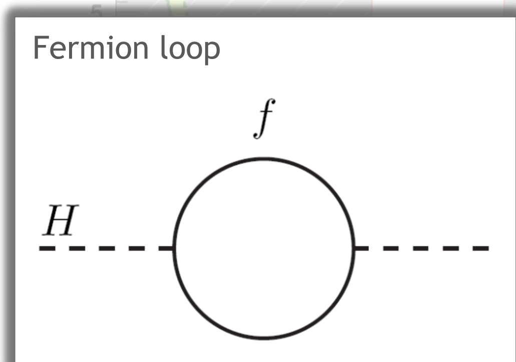


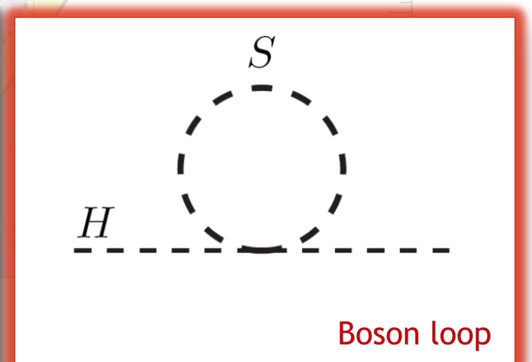
Arguments for new physics (at the TeV scale)

No unambiguous experimental result requires new physics at the TeV scale

Theoretical considerations suggestive of new (TeV) physics:

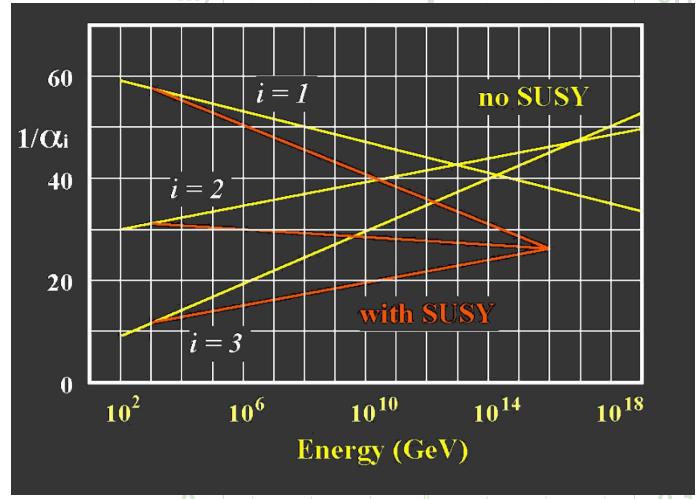
1. Gauge hierarchy problem



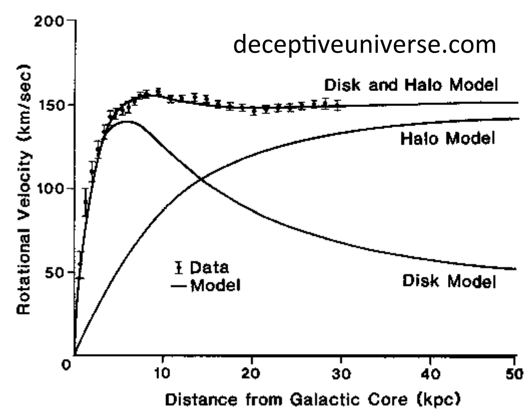


Higgs radiative corrections

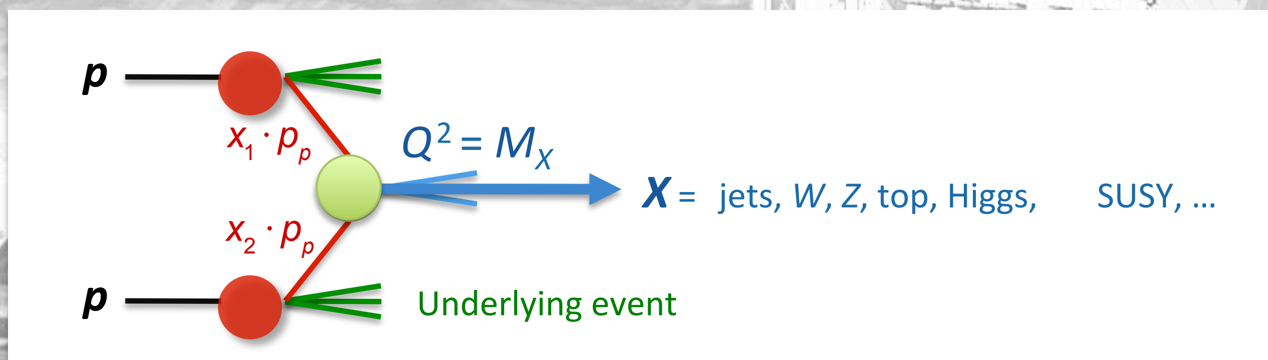
2. Unification of gauge couplings



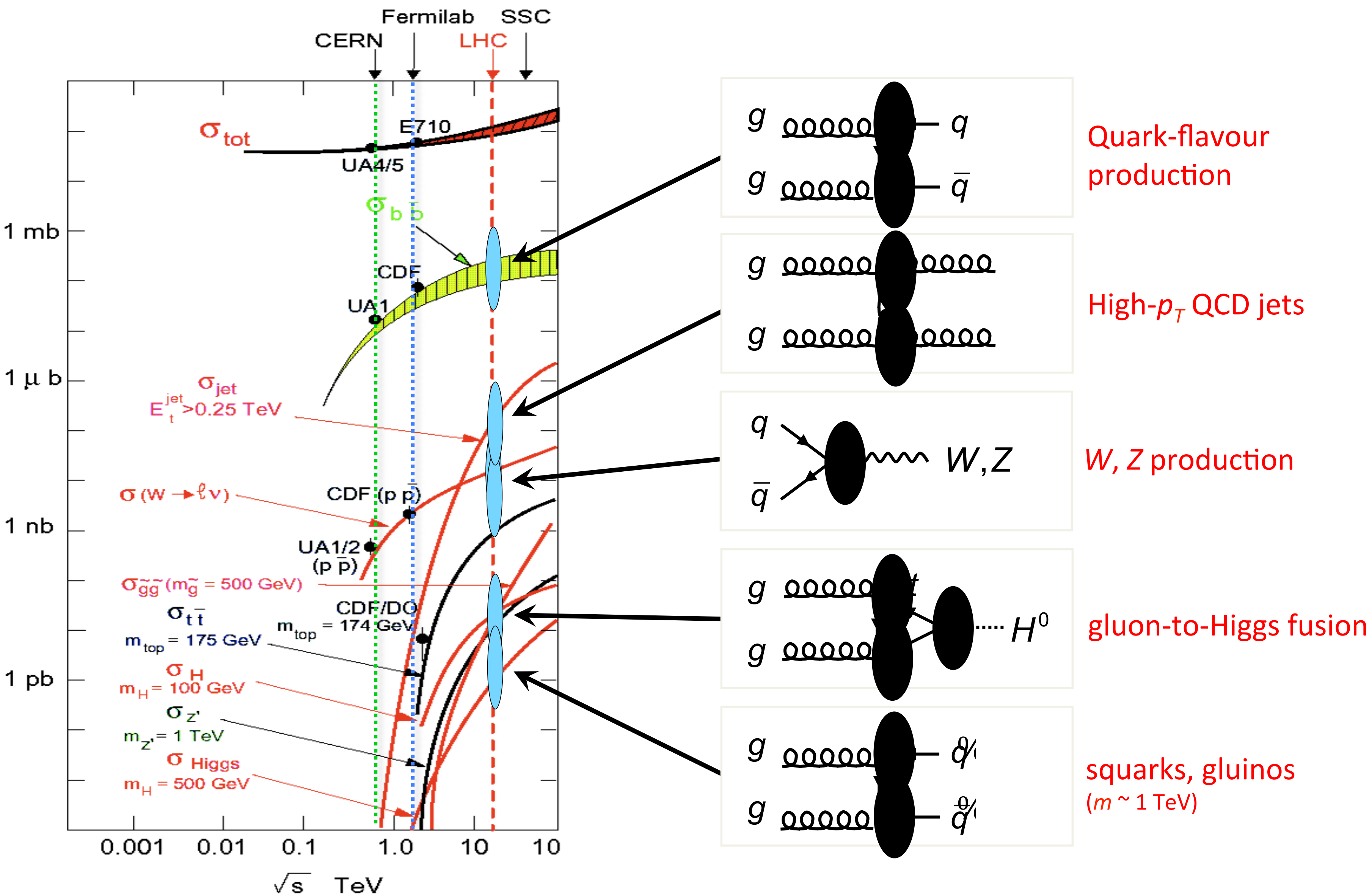
3. Existence of Dark Matter



Wanted: new particles
Needed: multi-TeV proton collider



Typical production cross sections at a hadron collider



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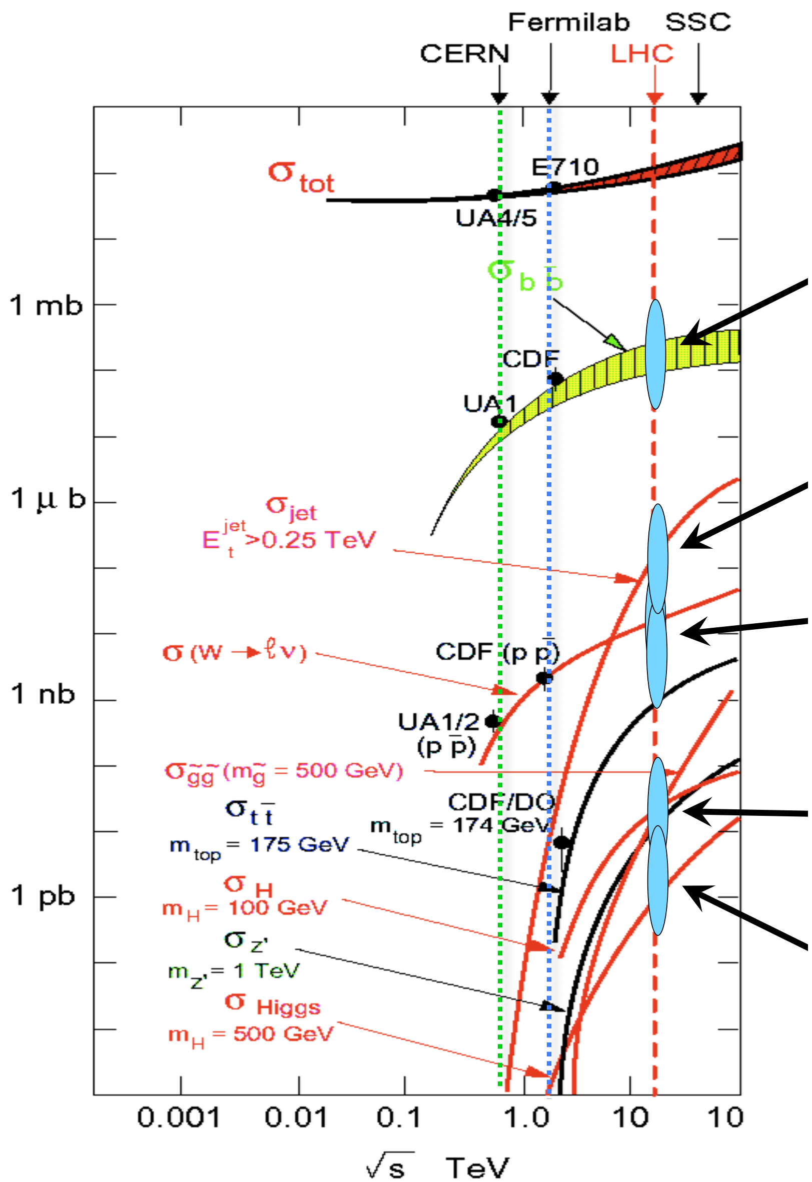


Need for discovery of new TeV scale physics:

- **A multi-TeV accelerator**
- **Very large luminosities**

$$N_{obs} = \text{cross section} \times \text{efficiency} \times \int L \cdot dt$$

"Cross section" given by Nature

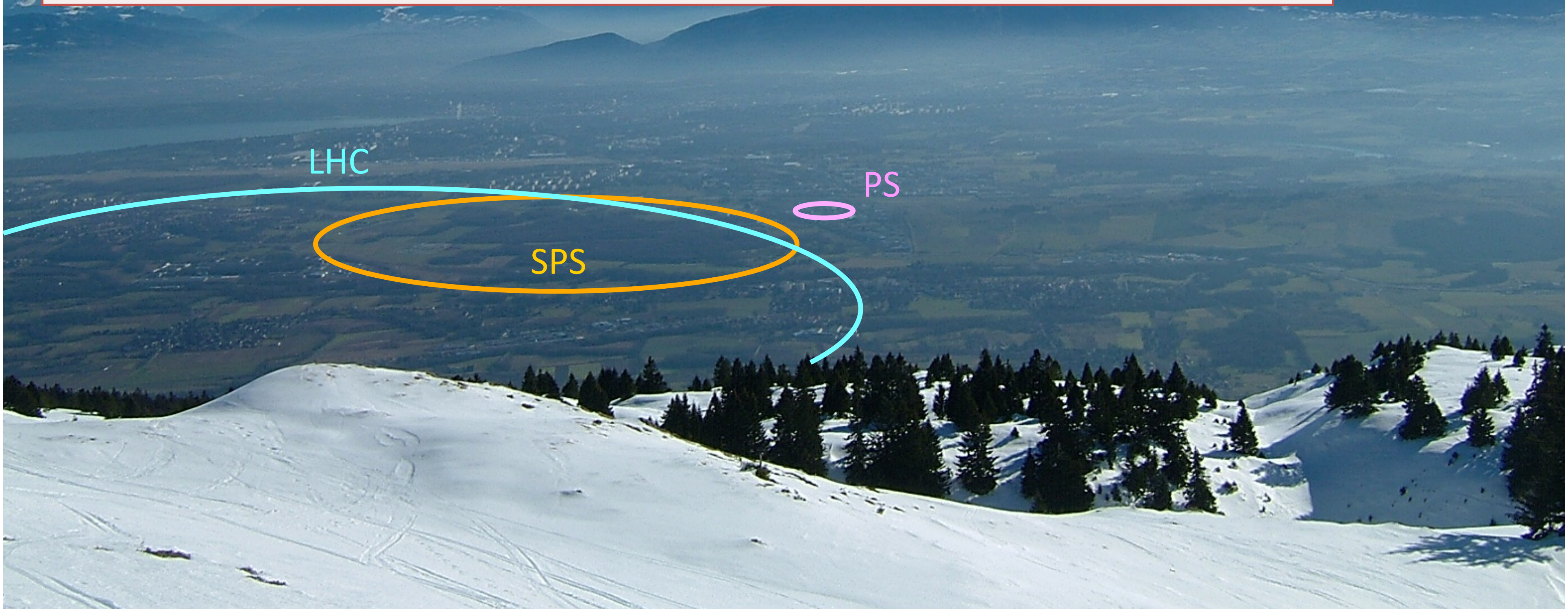
"Efficiency" of detection optimised by experimentalist

"Luminosity" – how bright are we?

- **An experiment to measure high-pt physics**

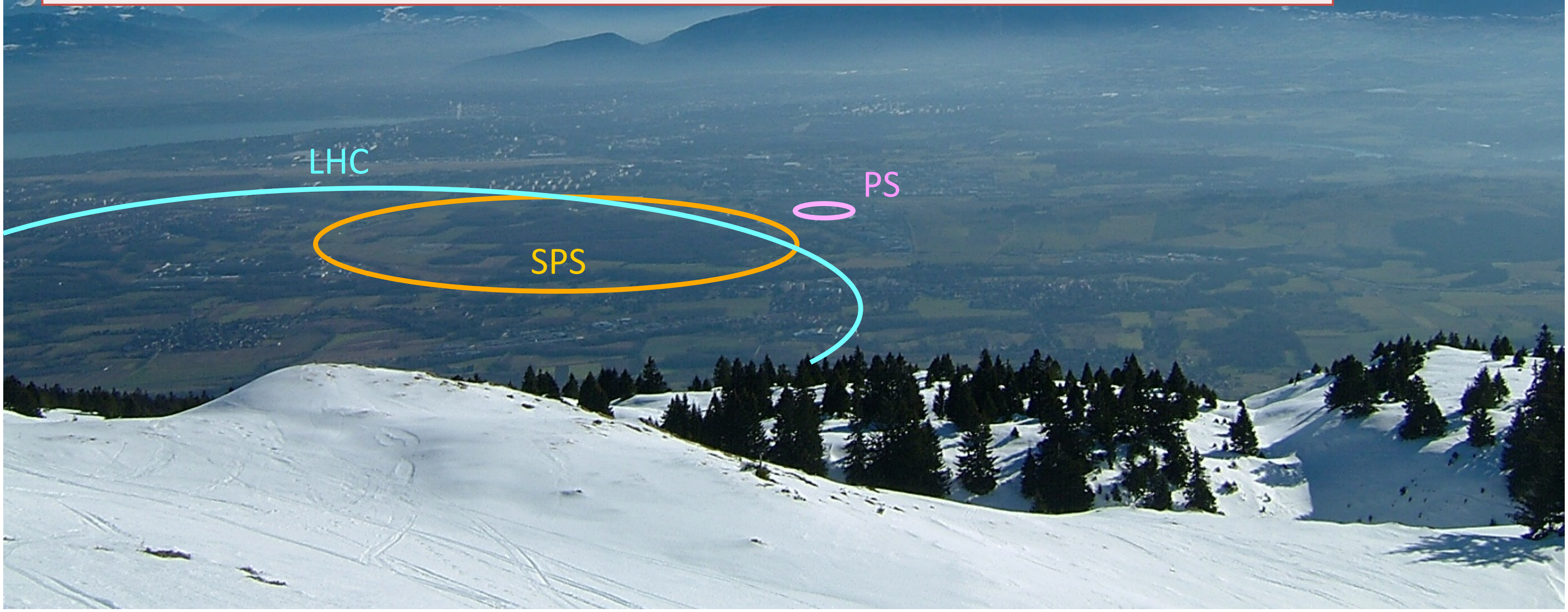
The Large Hadron Collider

	2011 performance	Design performance
Colliding bunches	1331	2808
Energy	3.5 TeV x 3.5 TeV	7 TeV x 7 TeV
Bunch spacing	50 ns	25 ns
Luminosity	3.6 x 10^{33} cm^{-2} s^{-1}	10^{34} cm^{-2} s^{-1}
Pile-up interactions	~20	~25



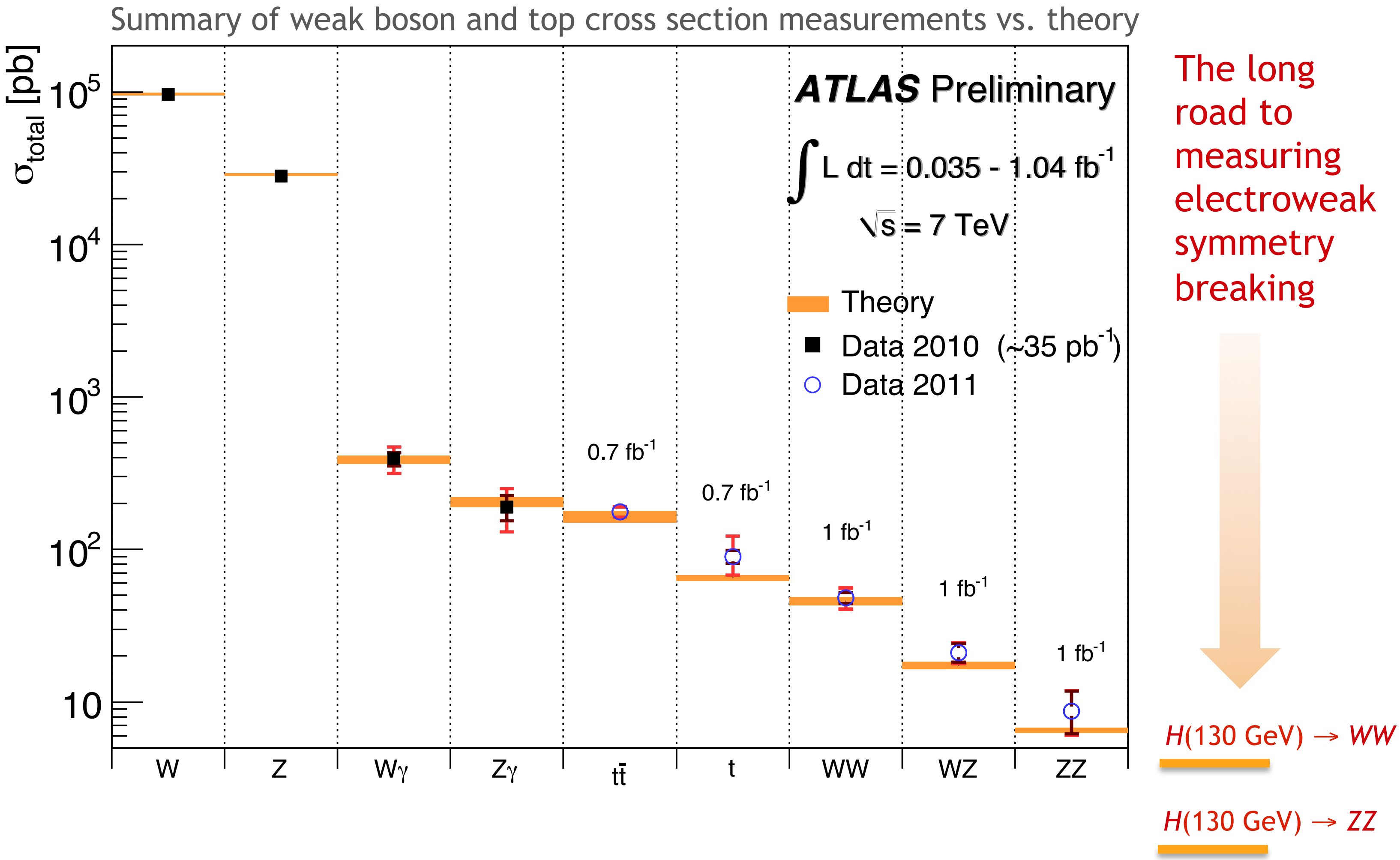
The Large Hadron Collider

	2012 performance	Design performance
Colliding bunches	1331	2808
Energy	4 TeV x 4 TeV	7 TeV x 7 TeV
Bunch spacing	50 ns	25 ns
Luminosity	6.8 x 10^{33} cm^{-2} s^{-1}	10^{34} cm^{-2} s^{-1}
Pile-up interactions	~35	~25



Two general-purpose experiments: ATLAS & CMS

Searches for the Standard Model at 7 TeV



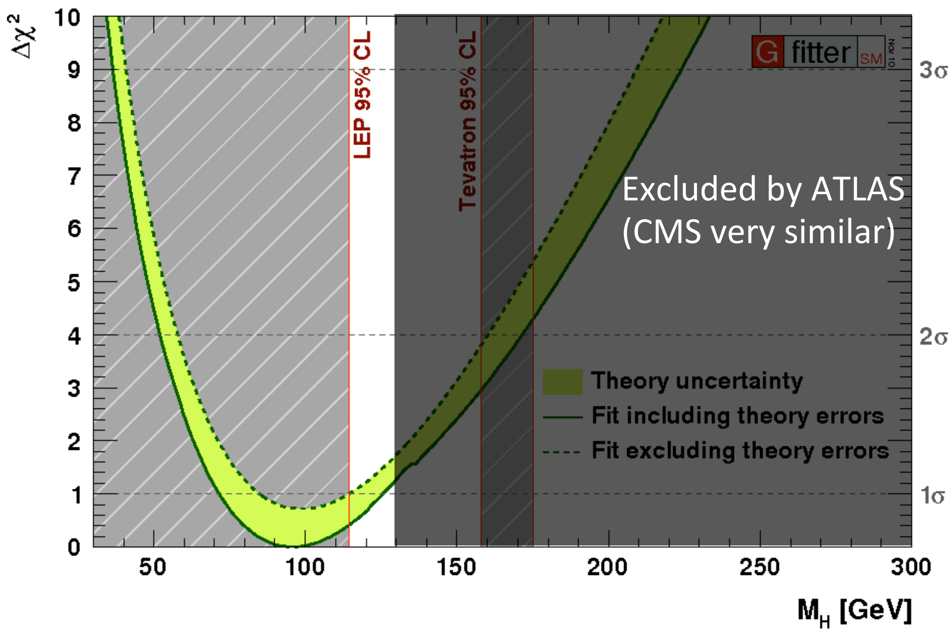
Pursue Standard Model measurements as important benchmarks!

Excellent understanding of initial performance following years and years of testbeam studies and simulation work.

Higgs Status

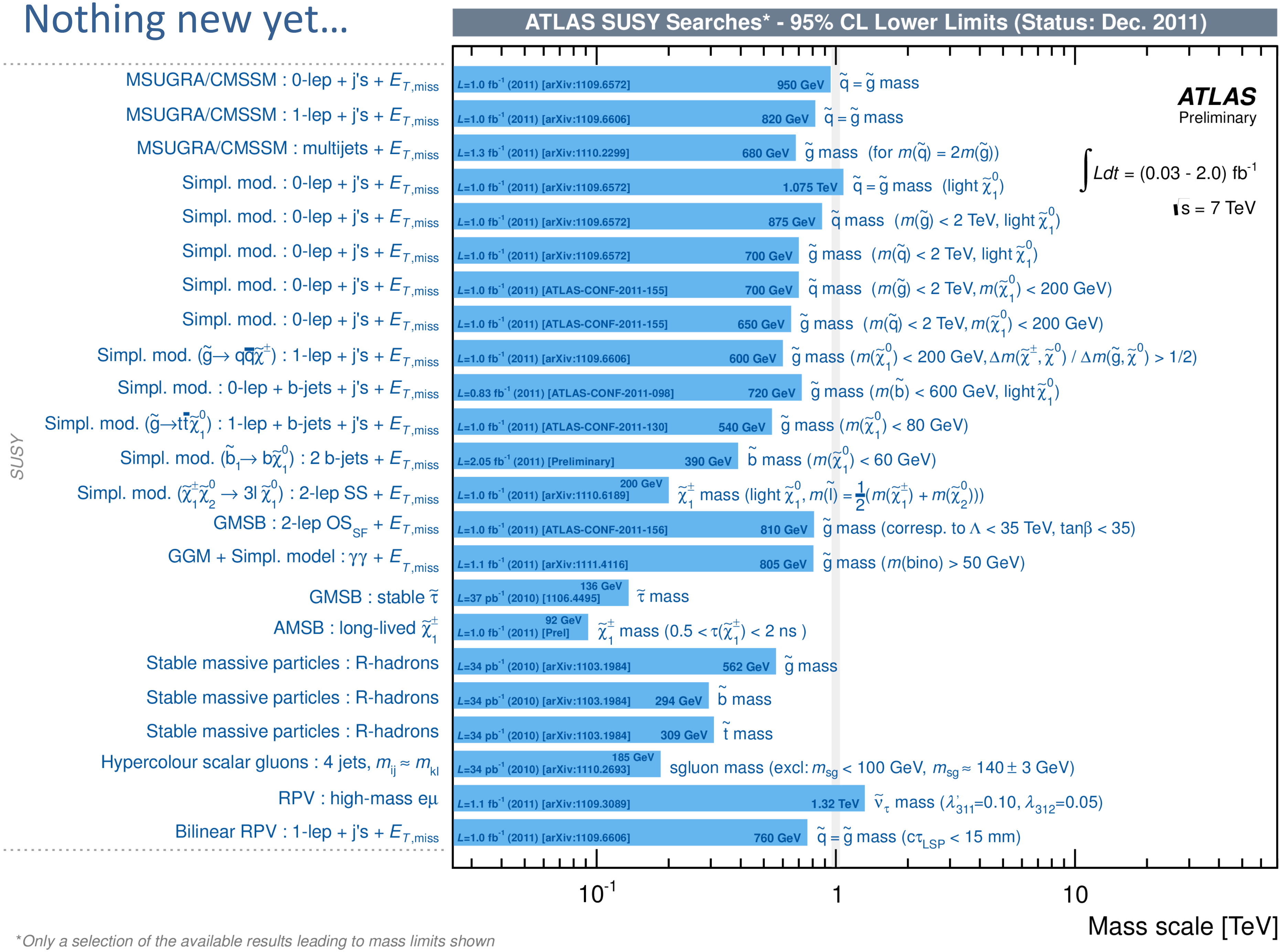
Higgs mass range narrowed down to 115.5—131 GeV
Perhaps first indications of a signal around 125 GeV

EW fit **not including** direct Higgs searches

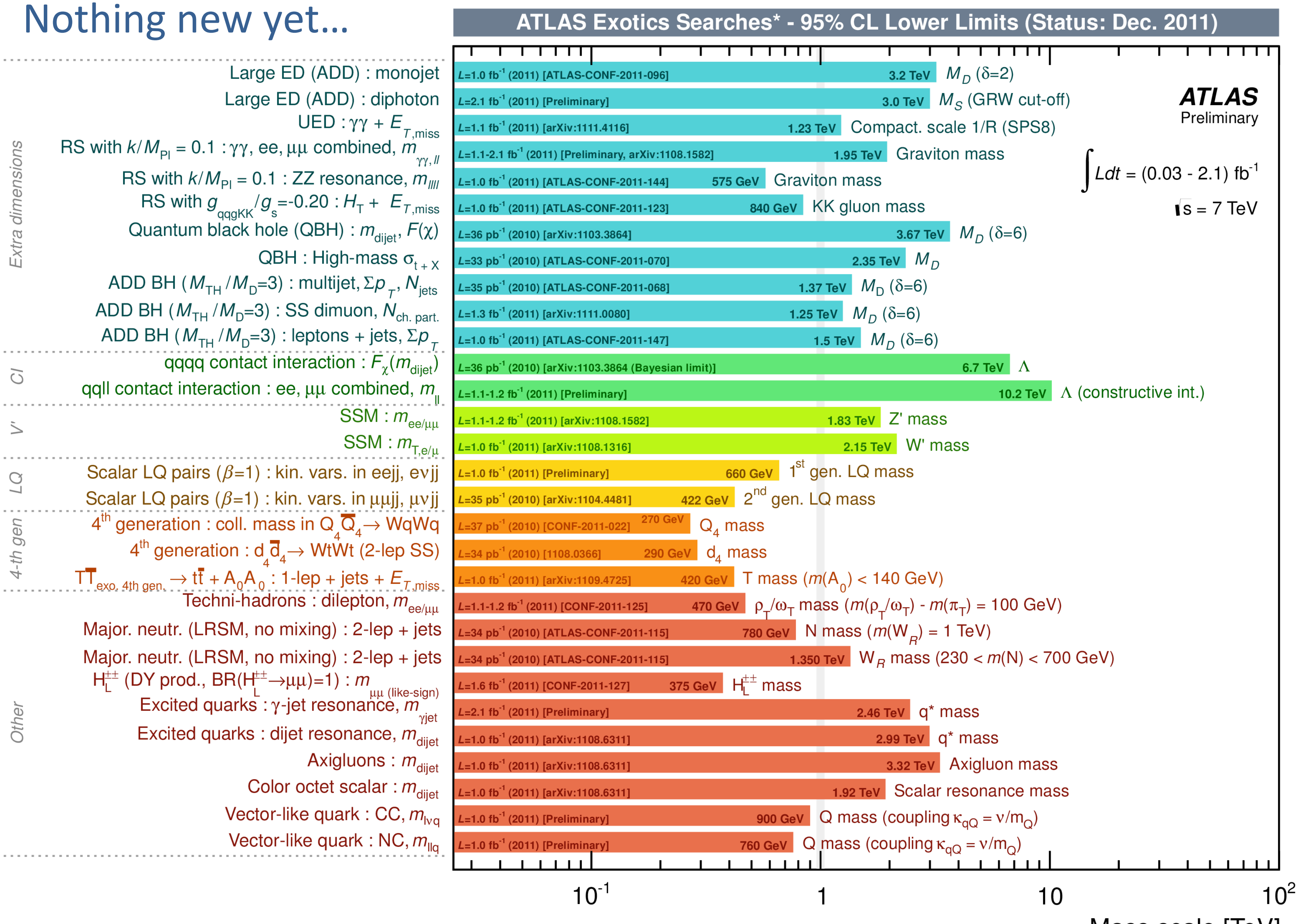


Central value $\pm 1\sigma$: $M_H = 96^{+31}_{-24}$ GeV
95% CL upper limit: 169 GeV

Nothing new yet…



Nothing new yet...



*Only a selection of the available results leading to mass limits shown

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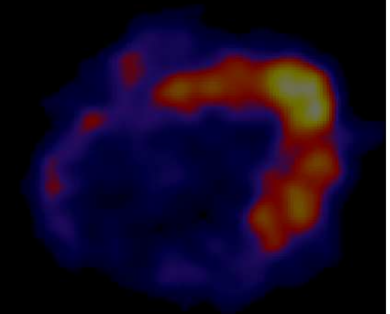

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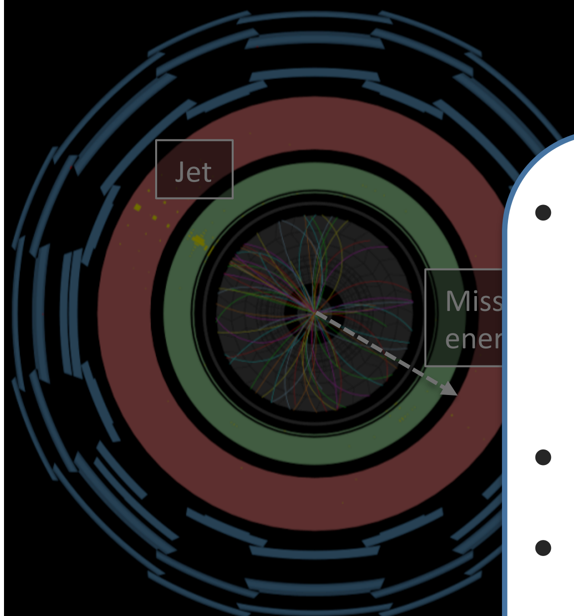

ATLAS mono-jet event display

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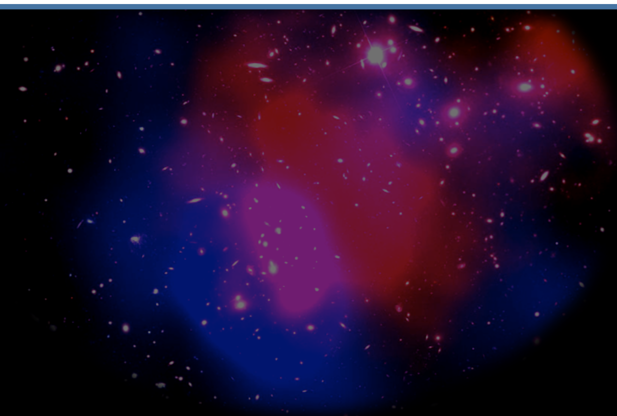
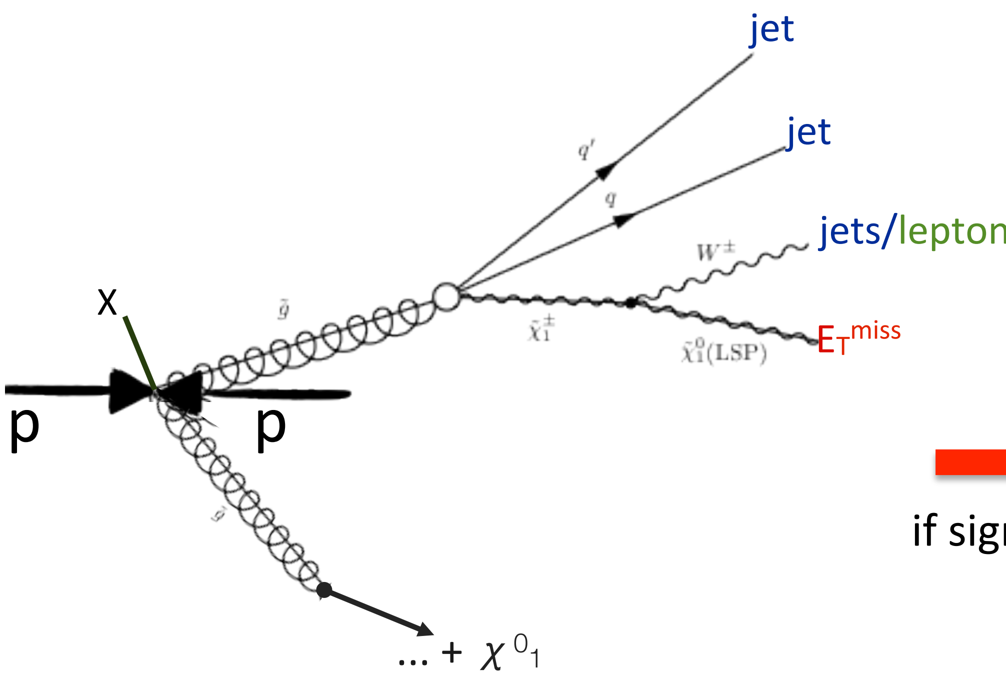
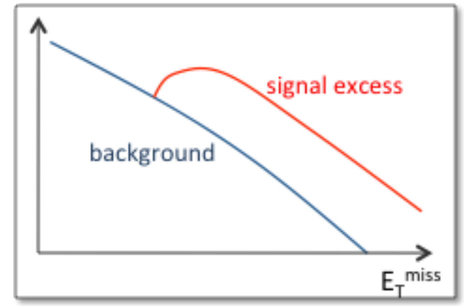


Galaxy cluster Abell 2744

1: “Standard” Dark Matter Searches at Colliders

One possibility: search for large missing ET in (supersymmetric) cascade decays





It’s all about controlling the backgrounds.

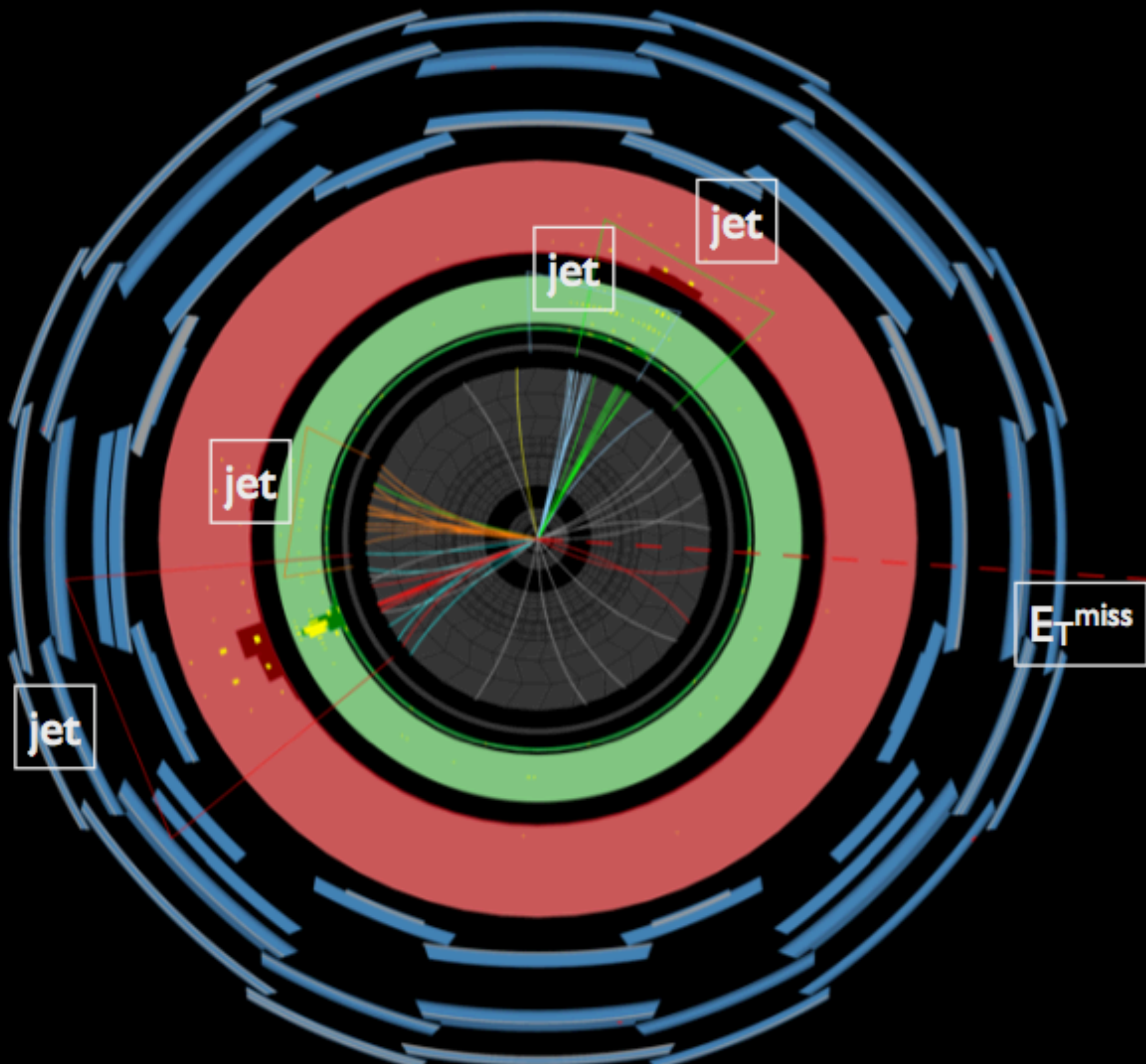
experimental signature:
jets + (leptons) + E_T^{miss}
[2 LSPs escape scape detection]

if signal → Measure spectra, kinematic endpoints, model fits, etc

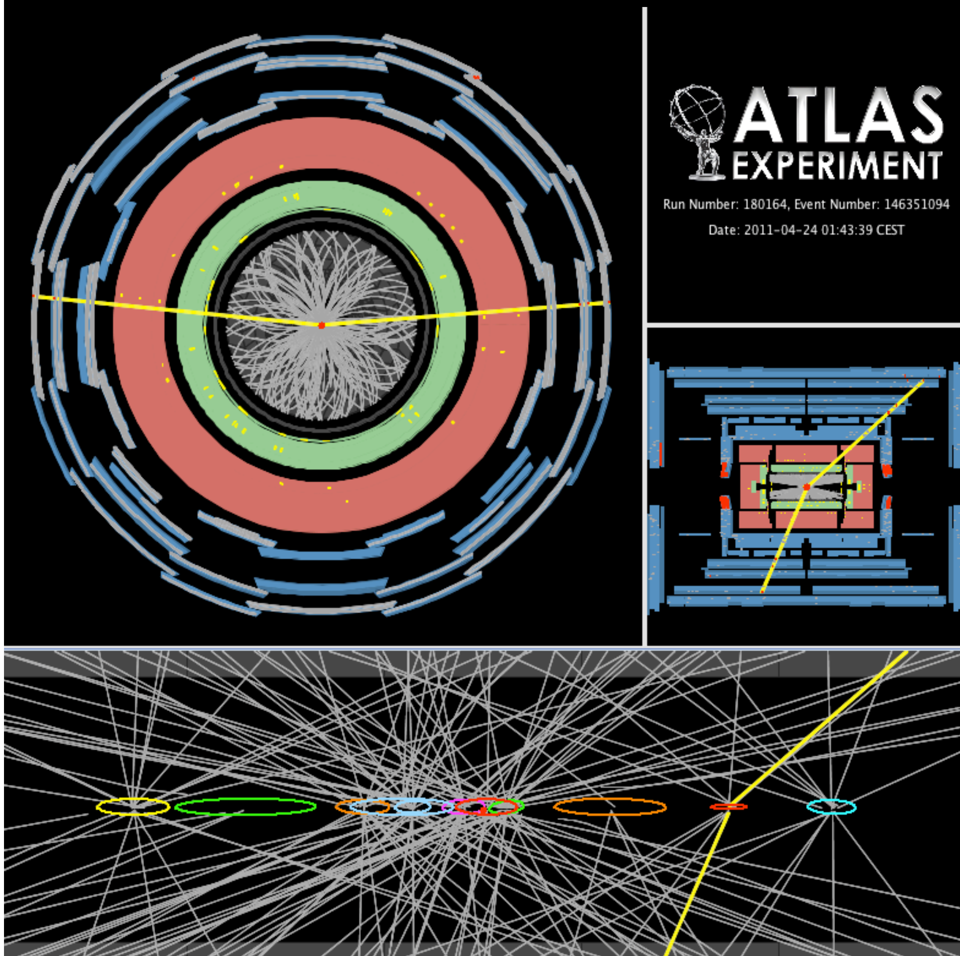
↓

Number of invisibles
Mass scale of invisibles
Spin

Task: measure transverse energy

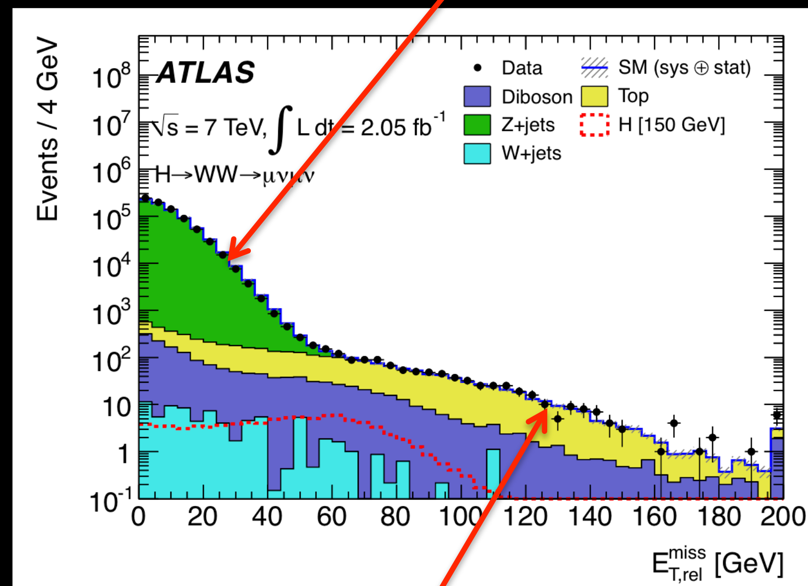


Difficulty: event pile-up



$Z \to \mu\mu$ event in ATLAS with 20 reconstructed vertices

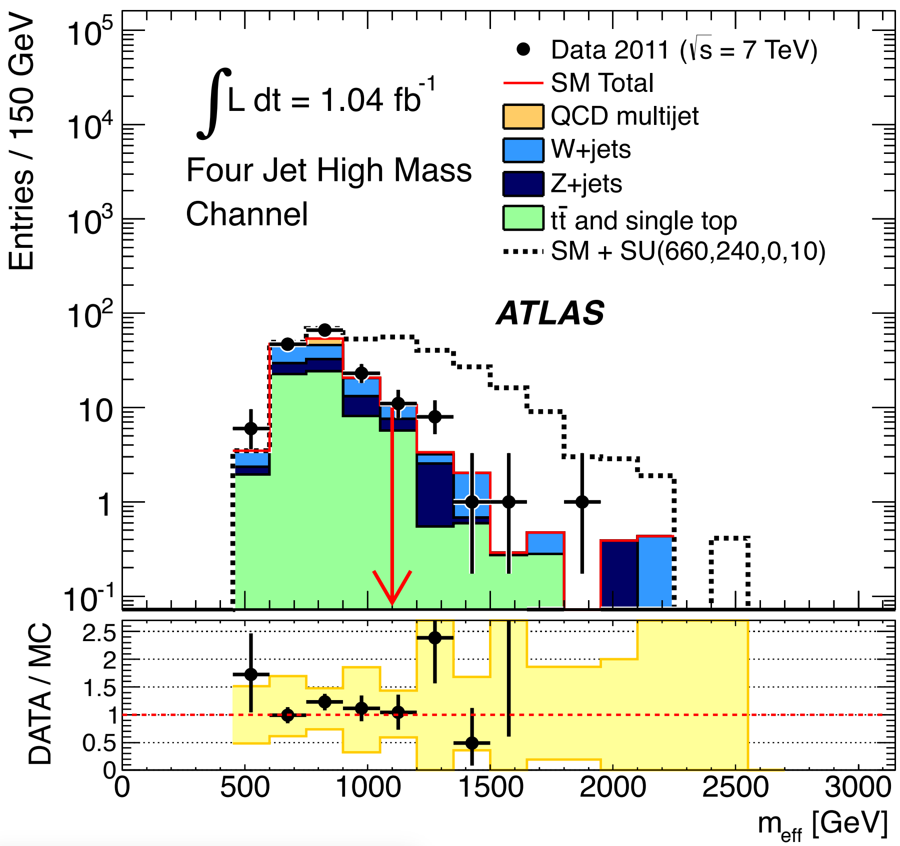
Z+jets: mix of fake and true missing ET



Top quark pairs: genuine missing ET from real ν's

Searches for strongly produced squarks and gluinos

… do not yet reveal a signal



arXiv:1109.6572

Plot shows measured sum of jet and missing transverse momenta

Heavy squarks and gluinos would lead to excess over expected SM events at high tail of distribution

No such excess seen in current data

Can translate into limit on SUSY mass scale

Searches for strongly produced squarks and gluinos

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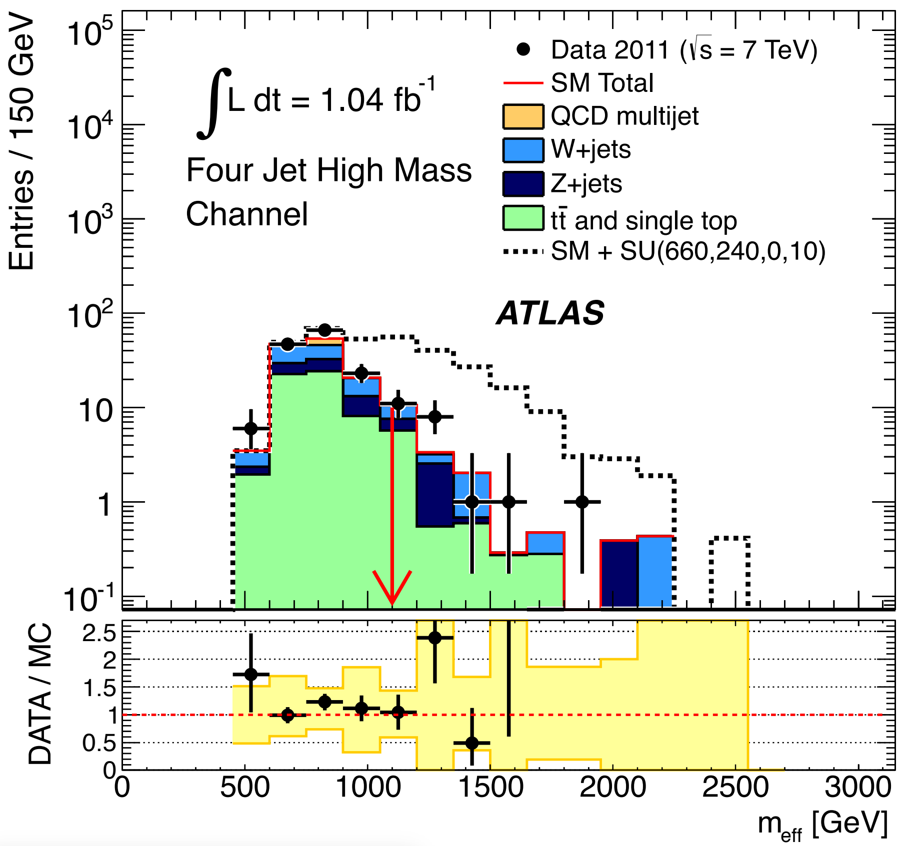
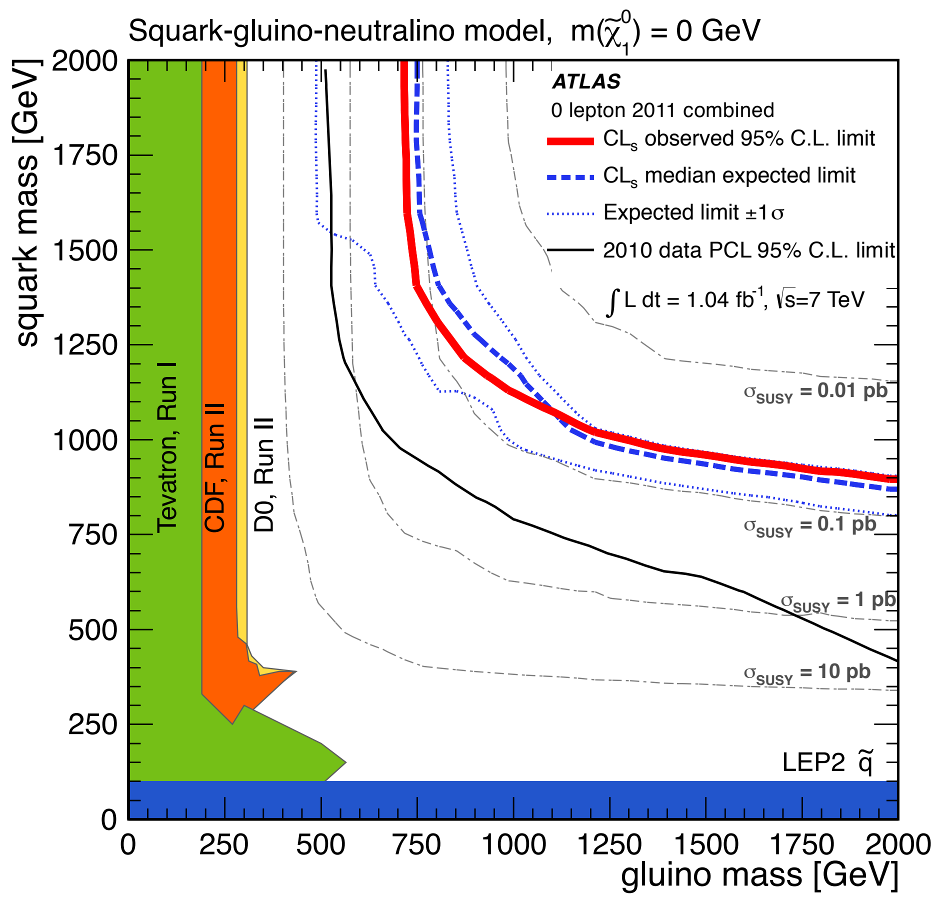




arXiv:1109.6572

Searches for strongly produced squarks and gluinos

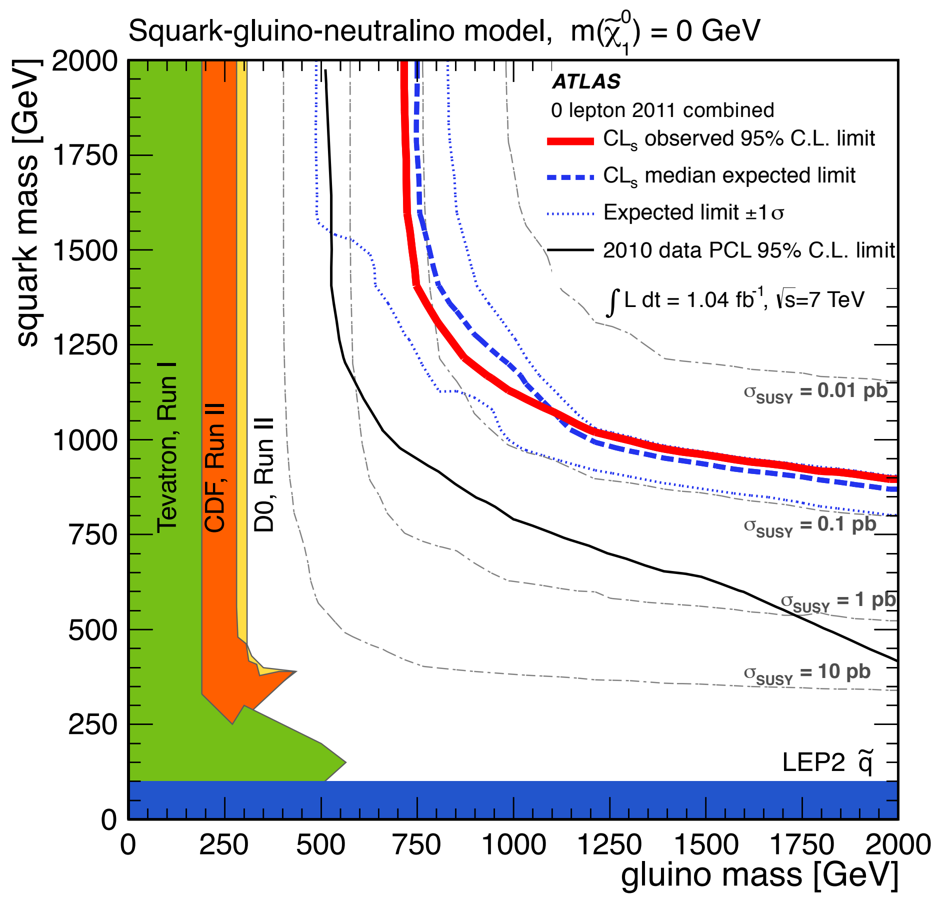
… do not yet reveal a signal

Under moderate assumptions on the SUSY mass hierarchy, ATLAS (similarly CMS) excludes:

$m(\tilde{q}) \approx m(\tilde{g}) < 1$ TeV

$m(\tilde{q}) < 875$ TeV ($\forall\ m(\tilde{g}) < 2$ TeV)

$m(\tilde{g}) < 700$ TeV ($\forall\ m(\tilde{q}) < 2$ TeV)

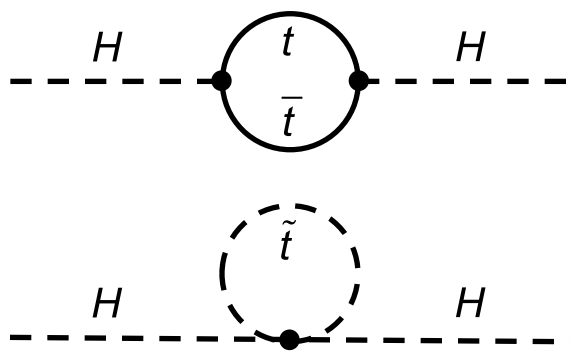


arXiv:1109.6572

Does SUSY hide from our analyses?

How could strong SUSY production exist but be hidden?

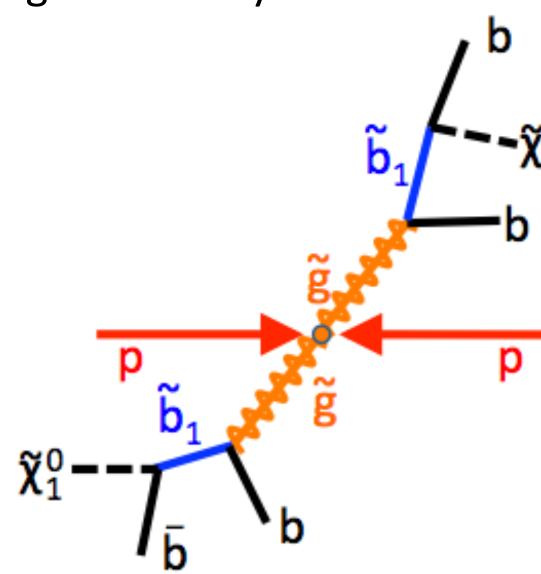
Recall: we need to cancel the Higgs virtual corrections. Most important is top loop



Contrary to the SM, 3rd generation squarks can be lighter than 1st and 2nd generations

→ Maybe all squarks except stop and sbottom are heavy?

E.g. look for sbottoms from gluino decays:



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ATLAS-CONF-2012-003

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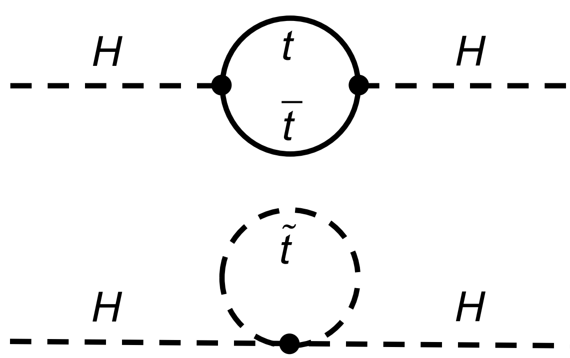

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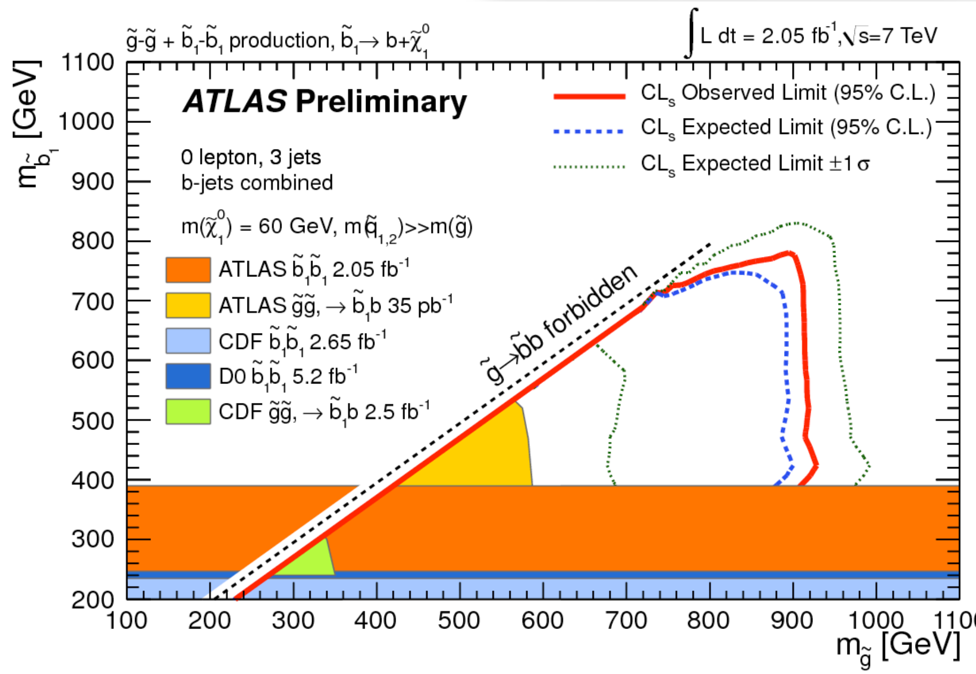


Gluinos produce sbottoms which decay to bottom and neutralino. The bottom quarks can be “tagged” in the detector

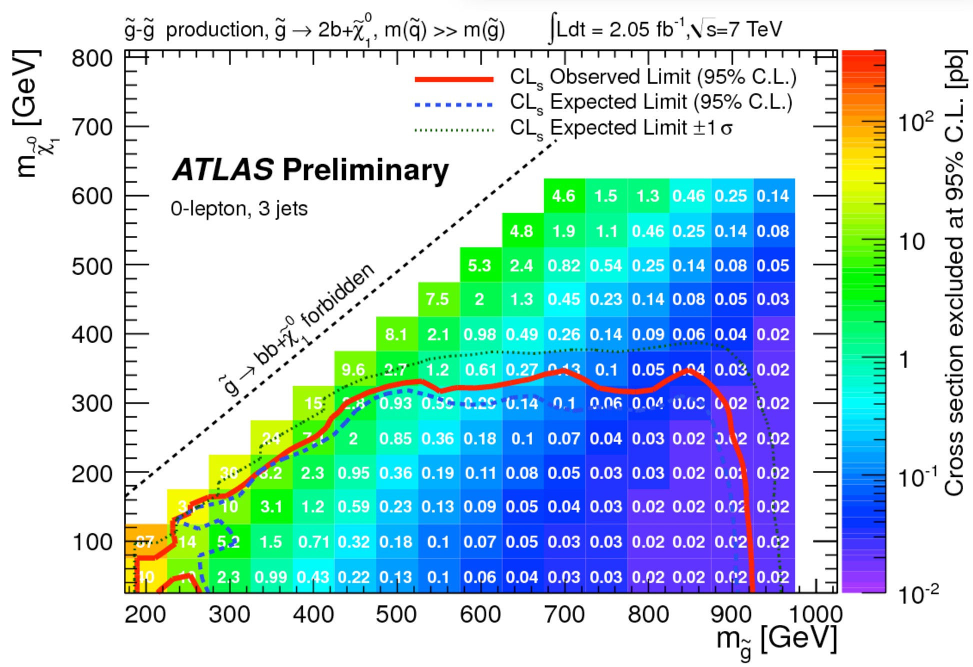
Does SUSY hide from our analyses?

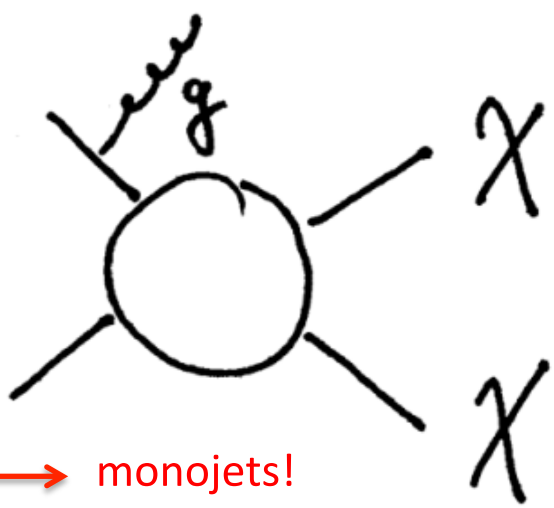
How could strong SUSY production exist but be hidden?

ATLAS-CONF-2012-003

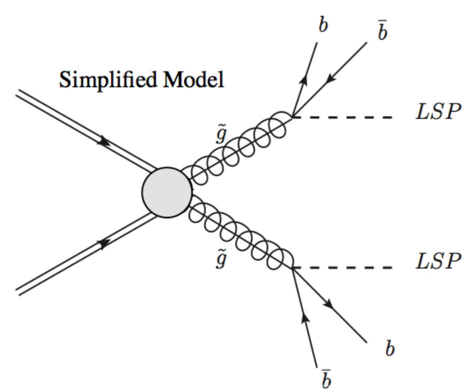
Maybe the neutralinos are almost as heavy as the squarks and gluinos so that not enough missing E_T is produced in the decays to select SUSY events?

Maybe squarks and gluinos are all too heavy and only neutralinos (WIMPs) are produced?

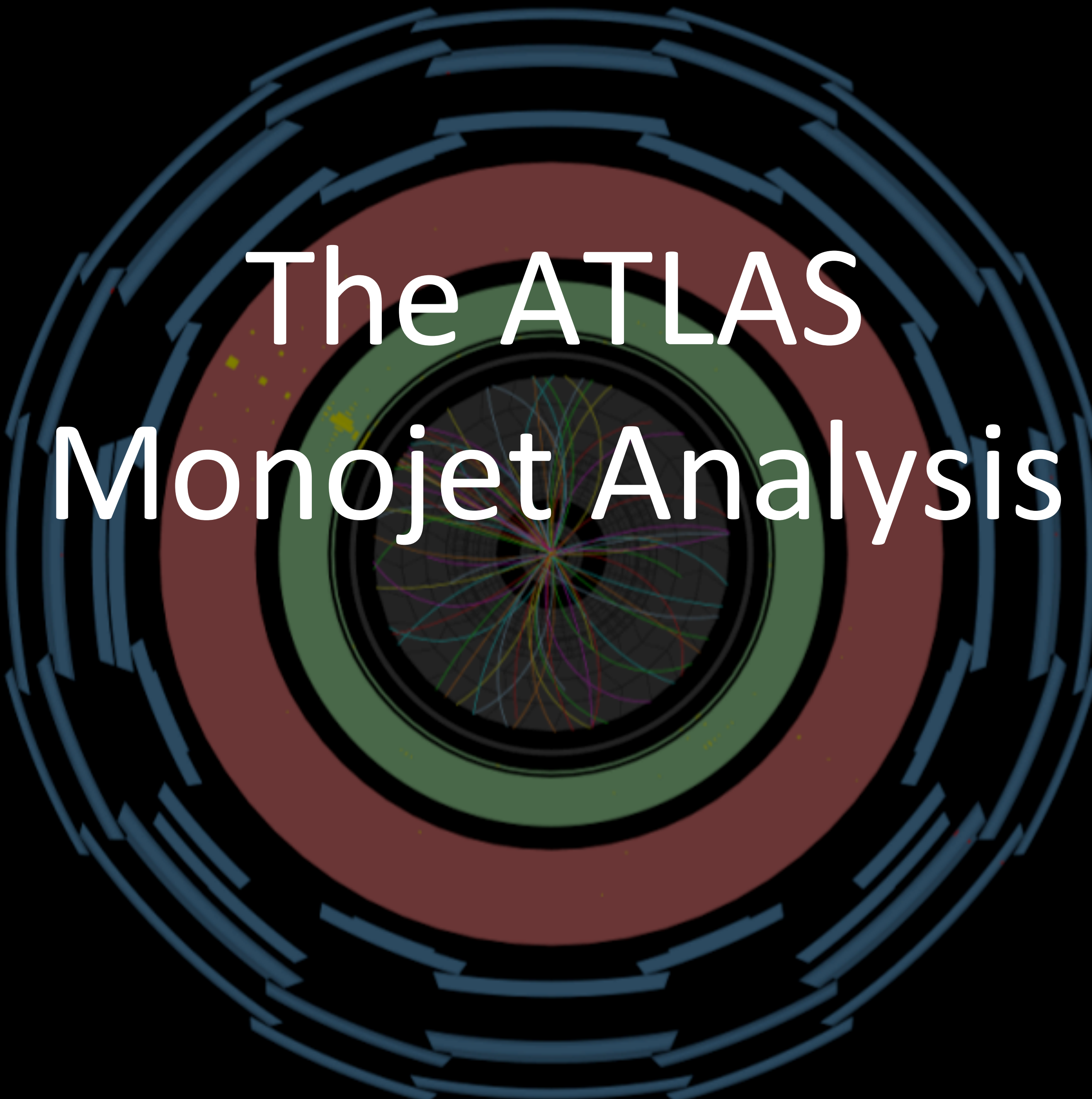


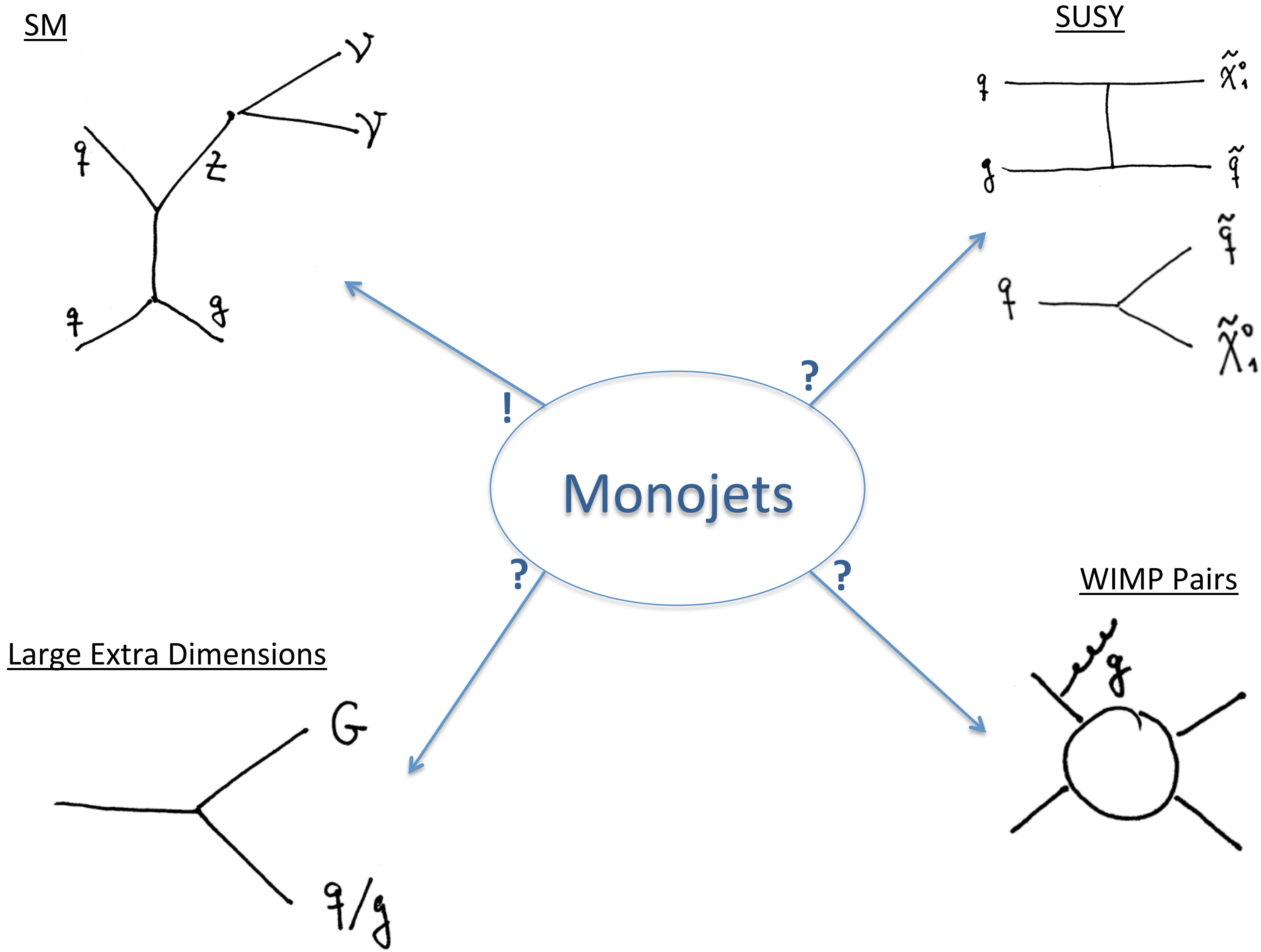


→ monojets!

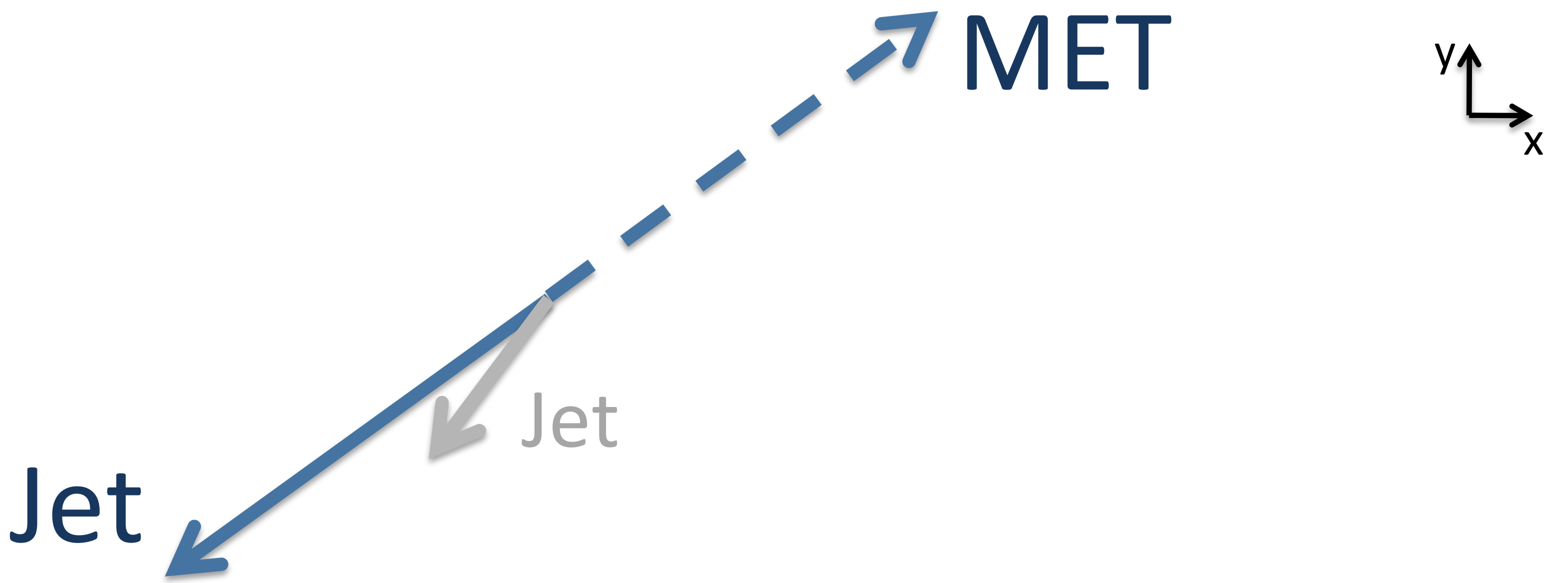


The ATLAS Monojet Analysis

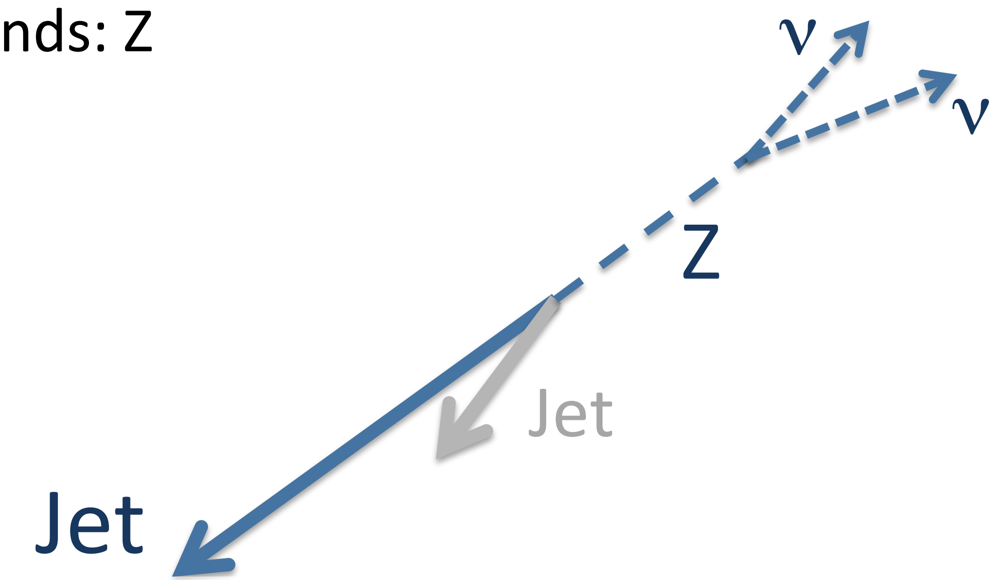



SM
SUSY
!
?
?
?
Monojets
WIMP Pairs
Large Extra Dimensions
G
q/g

Signal

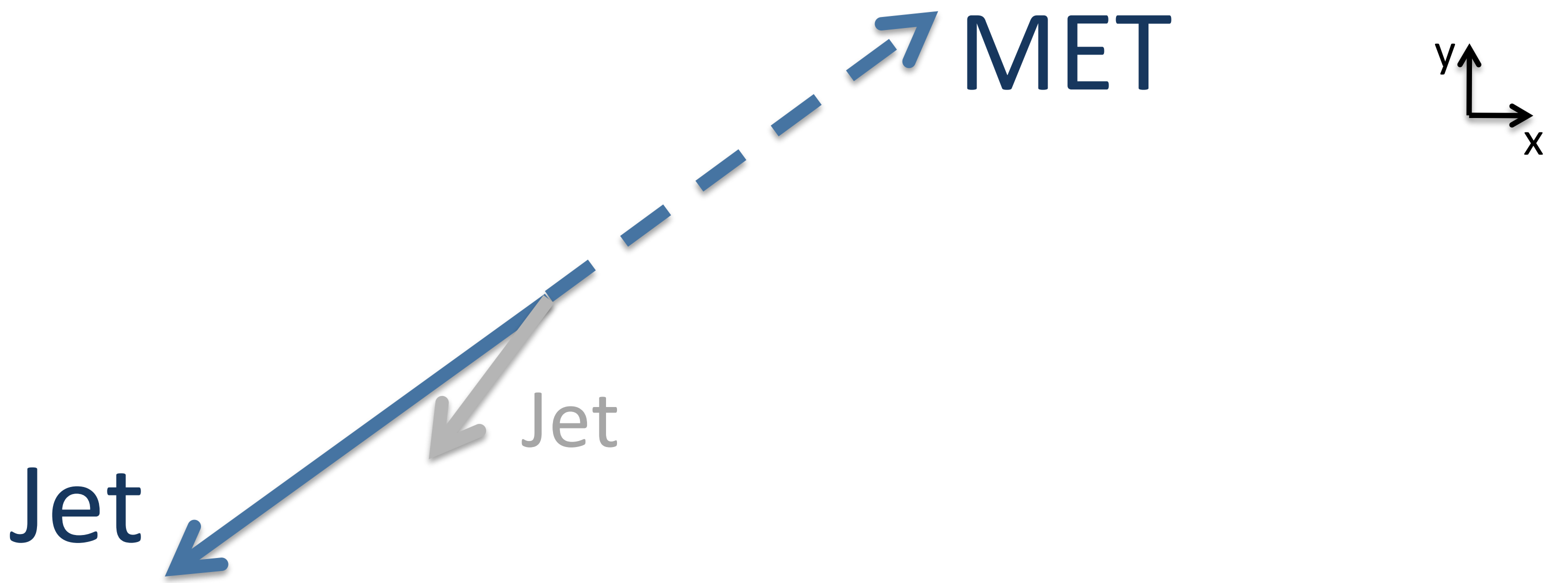


Backgrounds: Z

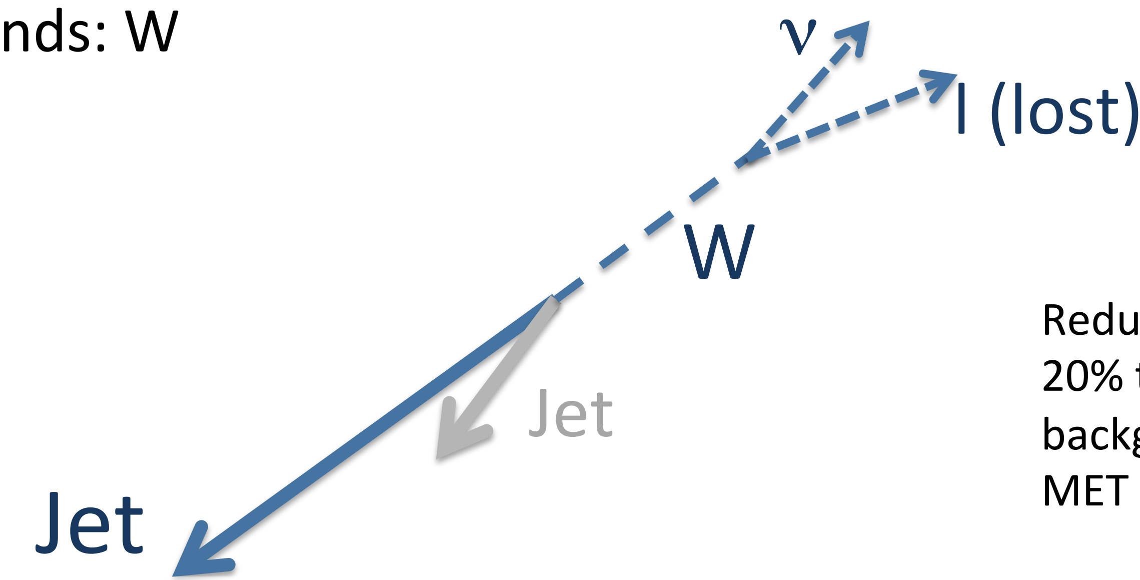


Irreducible SM background, 50% to 80% of total background depending on MET cuts.

Signal

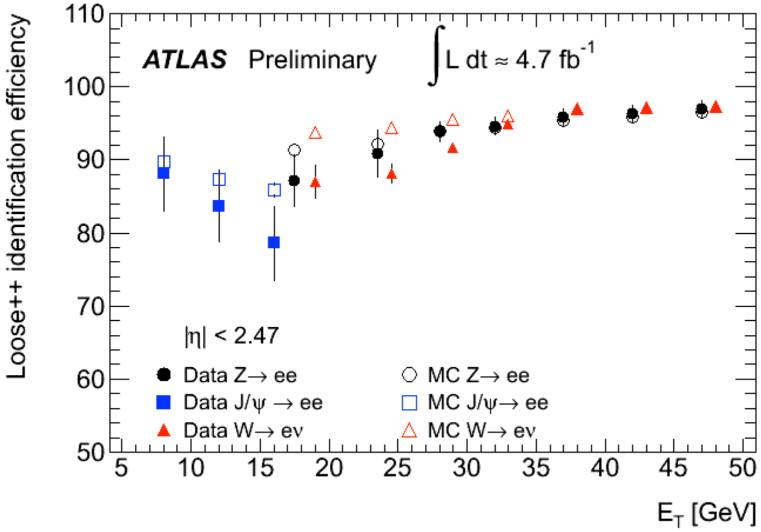


Backgrounds: W

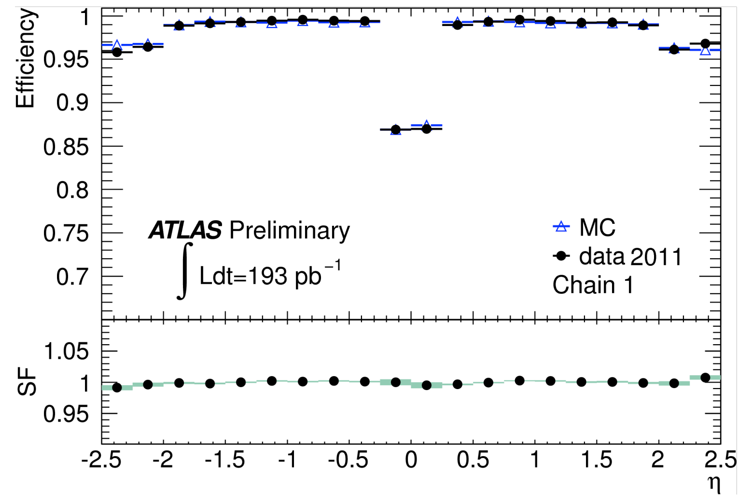


Reducible SM background, 20% to 50% of total background depending on MET cuts.

Electron reconstruction efficiency within the detector acceptance!

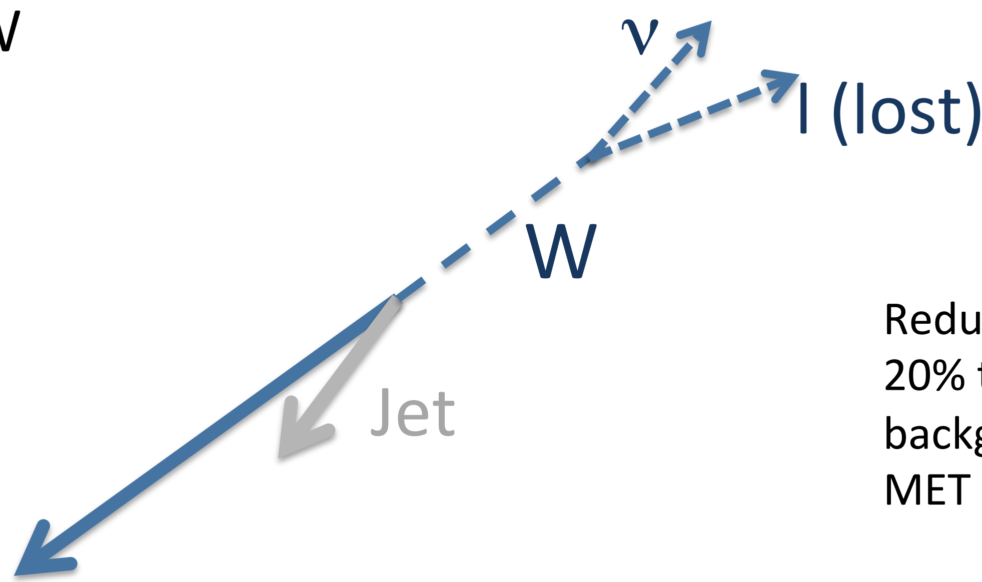


Muon reconstruction efficiency with detector acceptance



Both electrons and muons are efficiently reconstructed **within** the detector coverage!

Backgrounds: W



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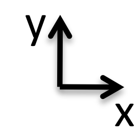
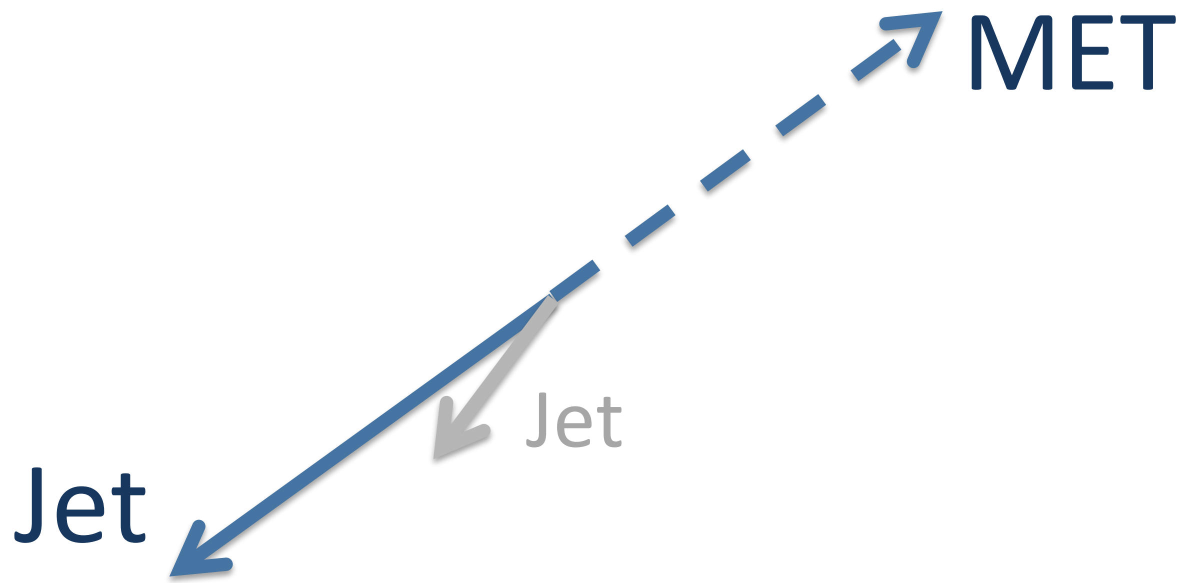
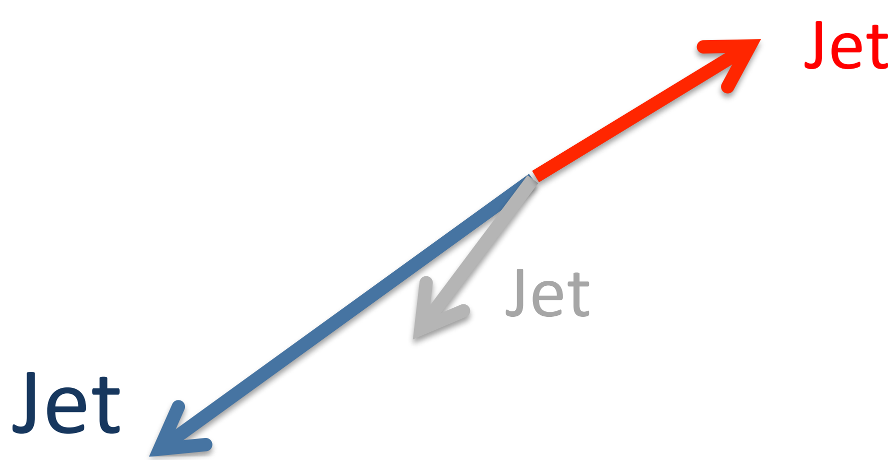


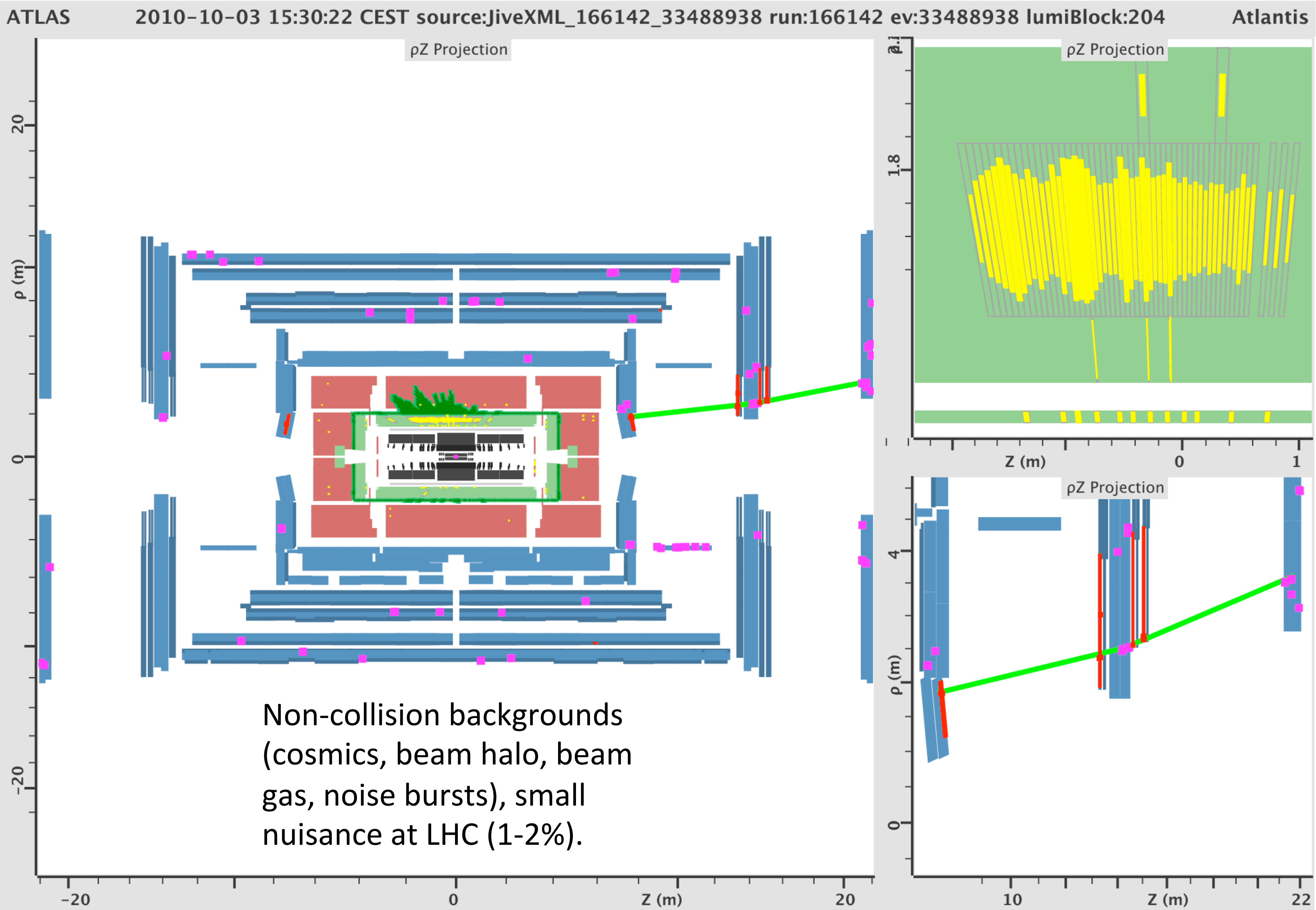
Signal



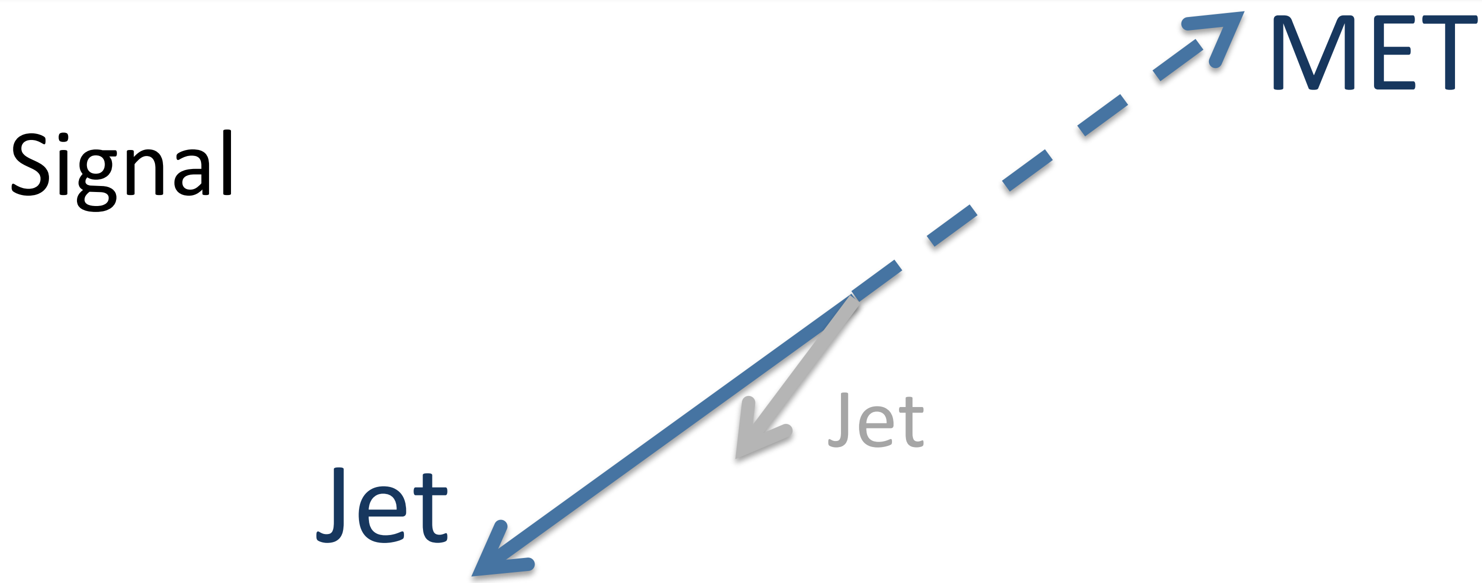
Backgrounds: multijets



QCD background from jet mismeasurement, almost negligible due to $\Delta\phi$ cuts (1-2%).



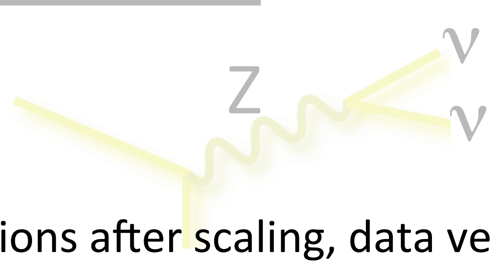
Non-collision backgrounds (cosmics, beam halo, beam gas, noise bursts), small nuisance at LHC (1-2%).

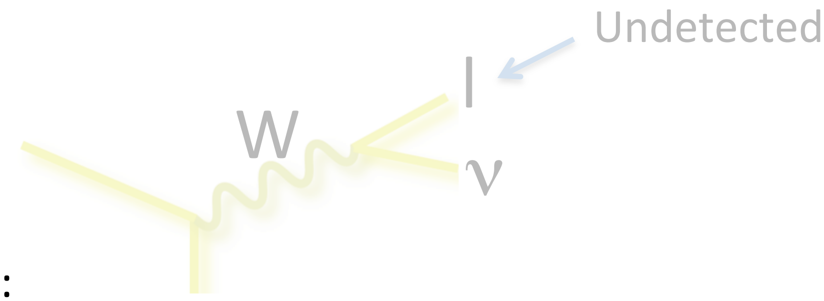


- 2010 (35pb^{-1}) and first part of 2011 (1 fb^{-1}) public
  - 5 fb^{-1} analysis released soon
- Simple selection strategy:
  - Large missing ET
  - One and only one high p_T jet
  - Check for excess beyond Standard Model backgrounds
  - Do this for a number (MET|jet) cuts (in GeV): (120|120), (220|250), (300|350)

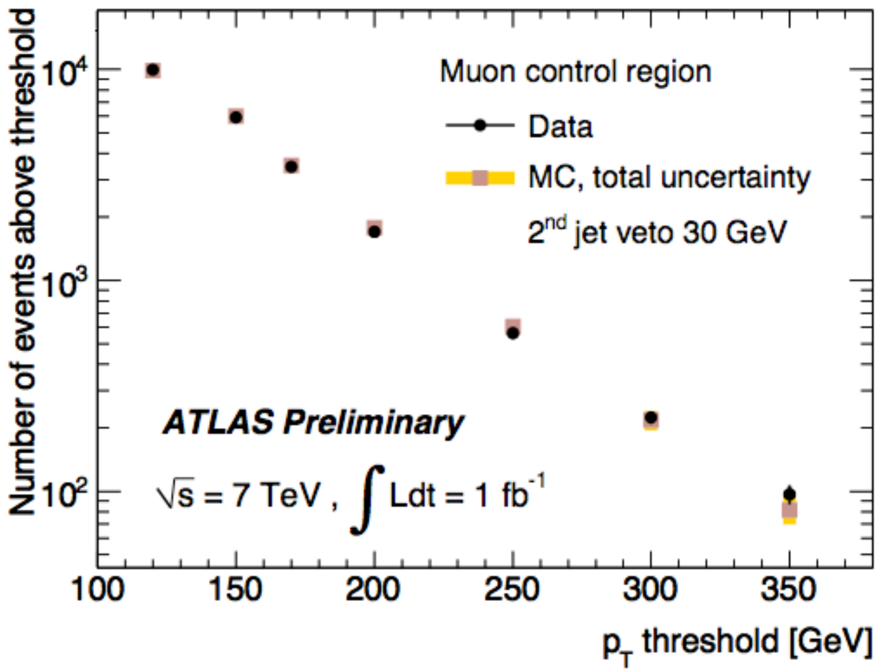
Electroweak Backgrounds

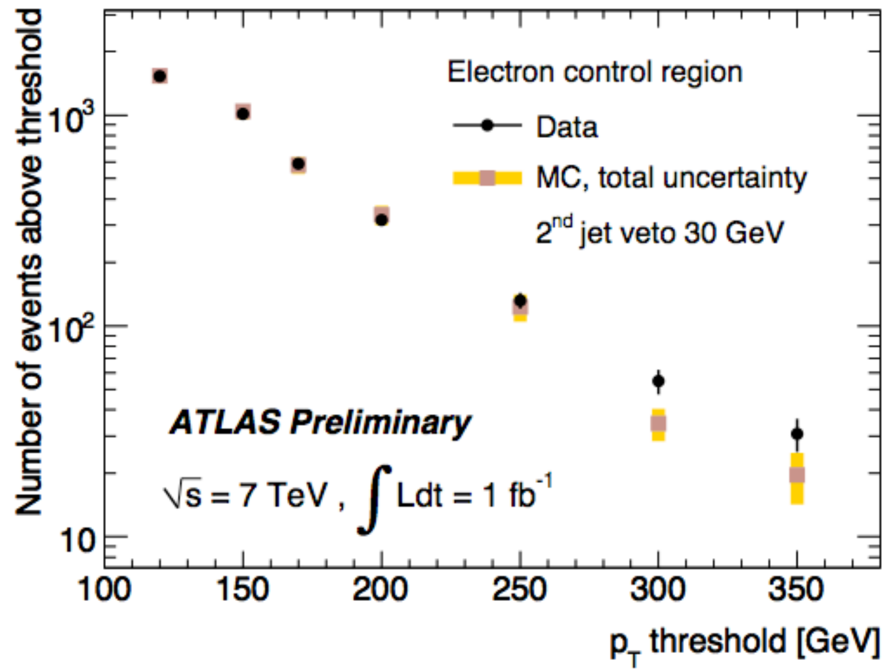
Main backgrounds:

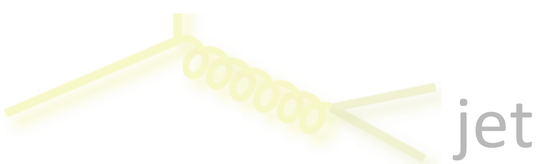


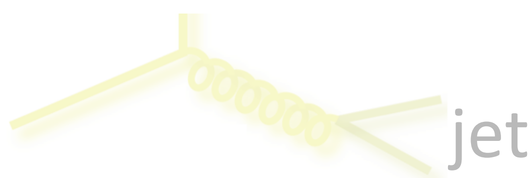


Control regions after scaling, data versus sum of MC:

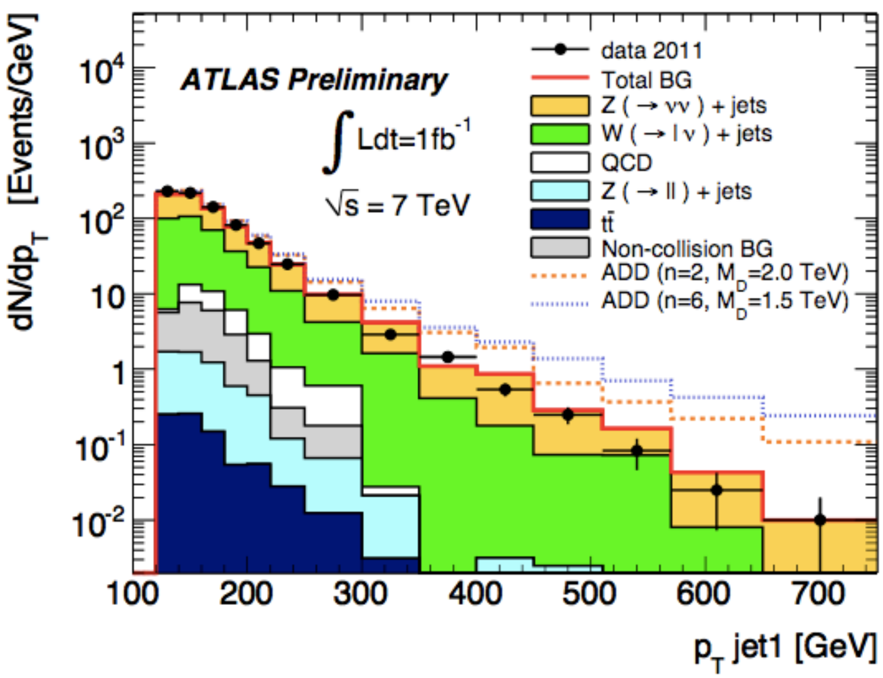


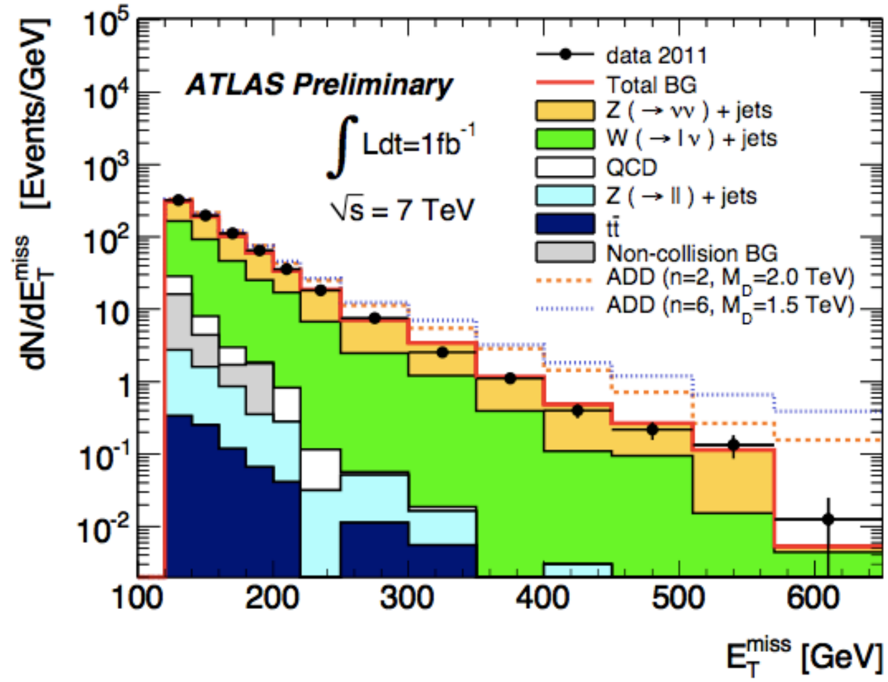






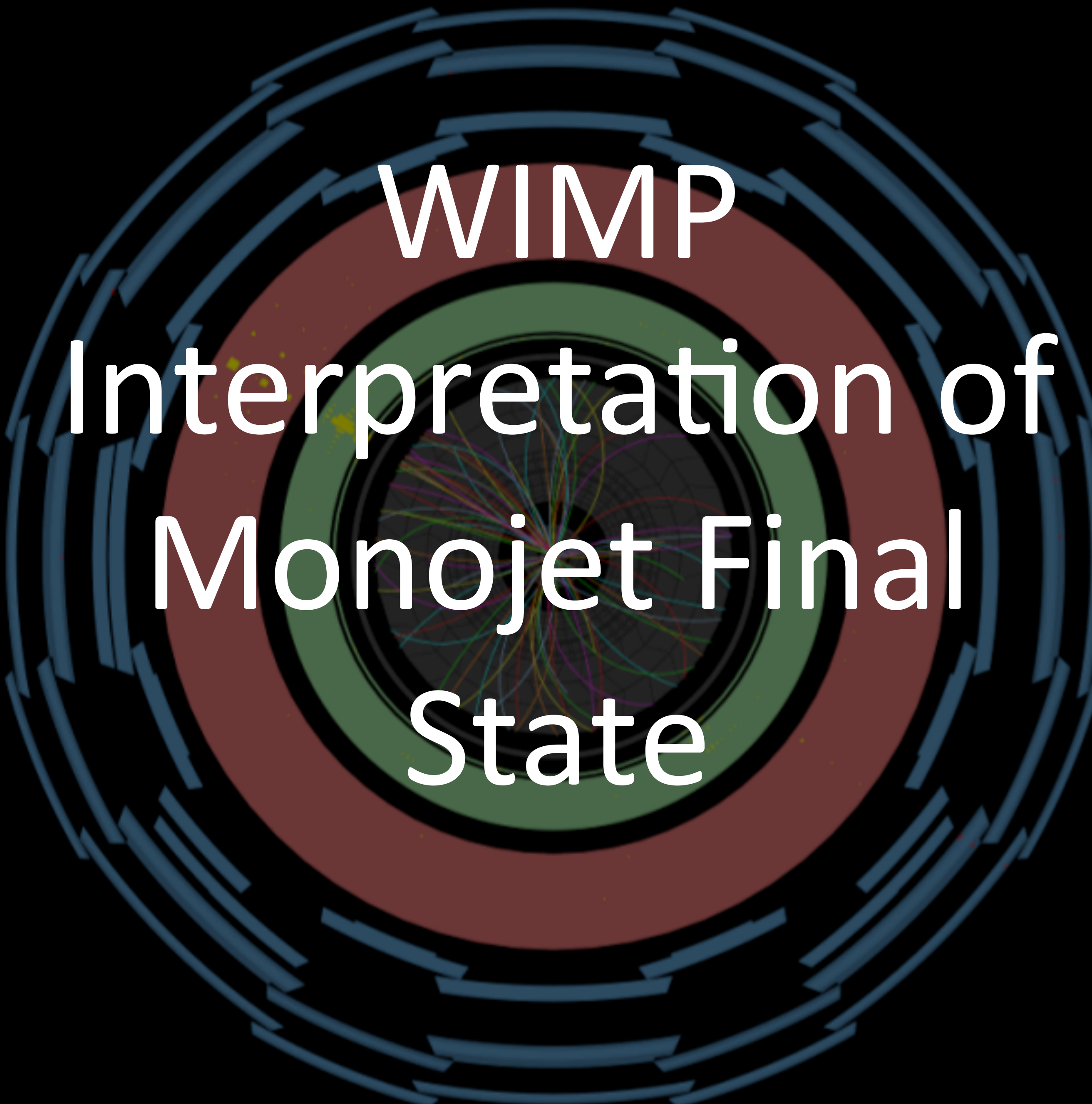
Results





The Standard Model holds tight…

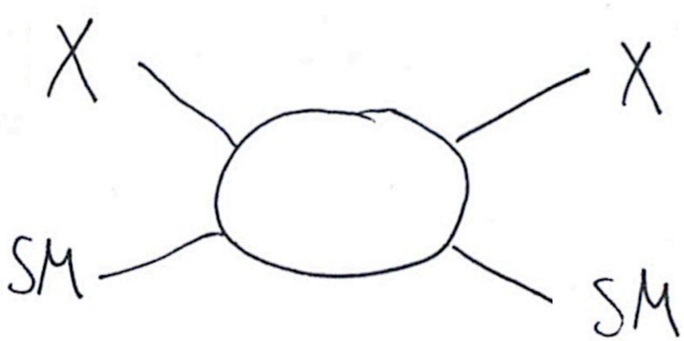
WIMP Interpretation of Monojet Final State



2: Generic WIMP Searches at Colliders

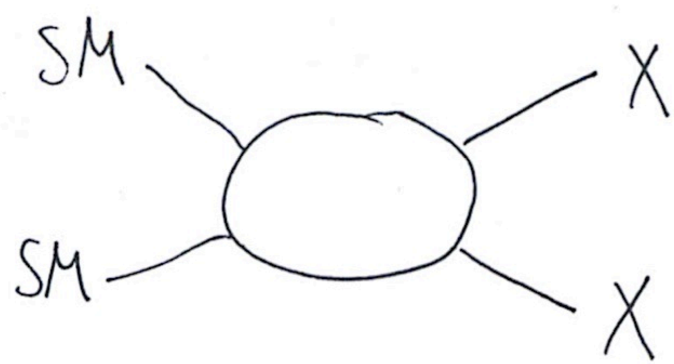
- Consider WIMP pair production at colliders, idea goes back to:
  - Birkedal et al (hep-ph/0403004)
  - Beltran et al: Maverick Dark Matter (hep-ph/1002.4137)
- Latest papers about ATLAS $1fb^{-1}$ result:
  - Fox et al, arxiv:1109.4398 (FNAL crew)
  - Rajamaran et al, arxiv:1108.1196 (UCI crew)
- All based on the idea:

Direct DM searches:



If this interaction exists…

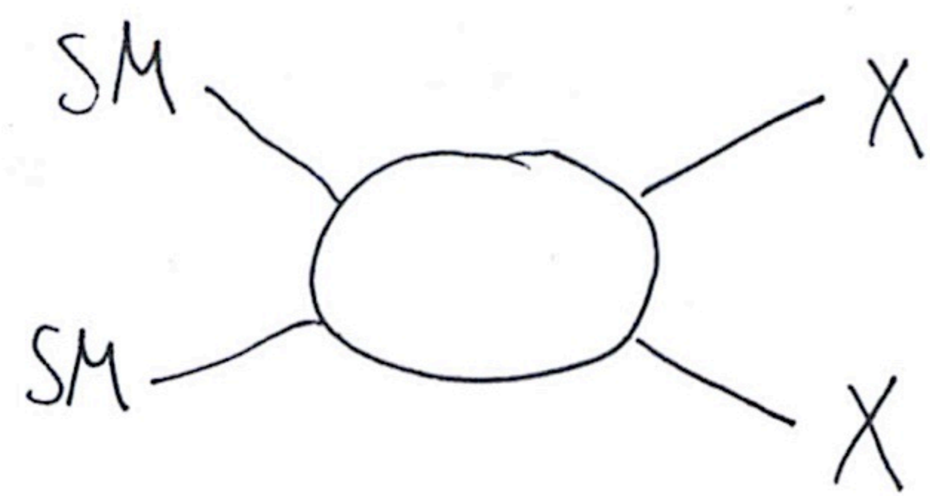
Colliders:



… this one must exist, too.
But can we see it?

Generic WIMP Searches at Colliders

Assume:
- X exists and can be pair produced
- Only X in reach at LHC



Generic WIMP Searches at Colliders

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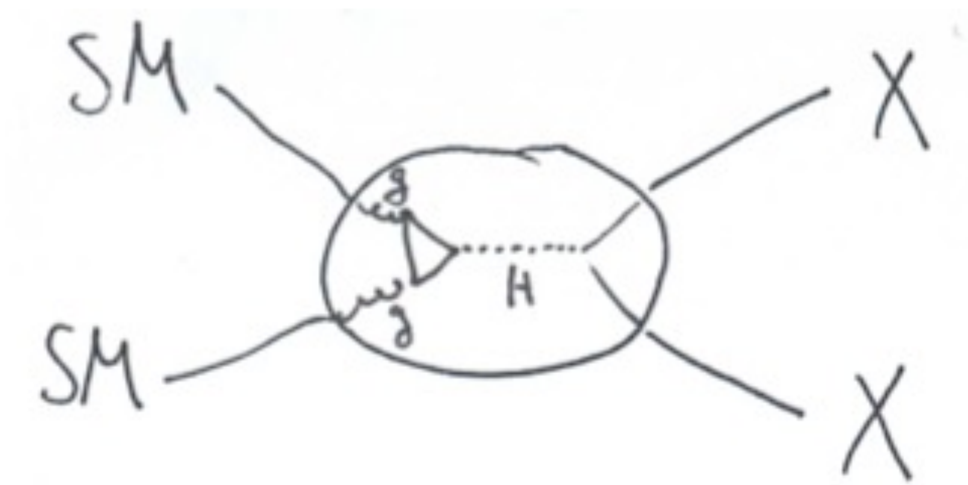

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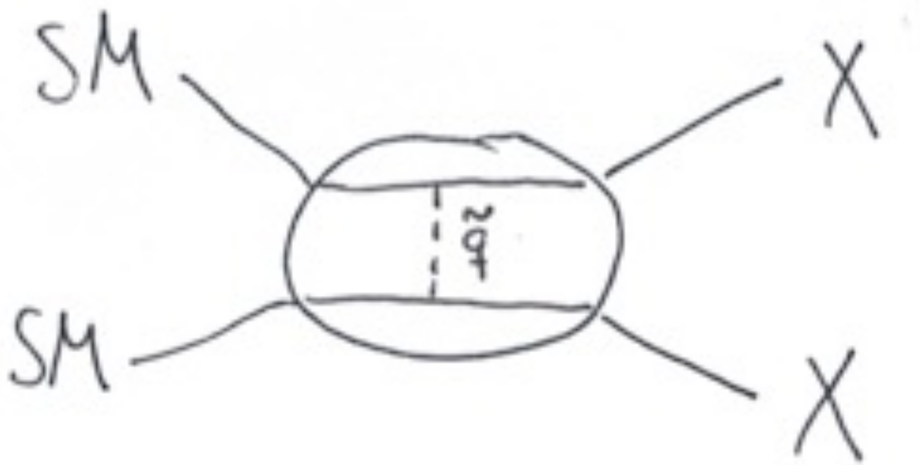

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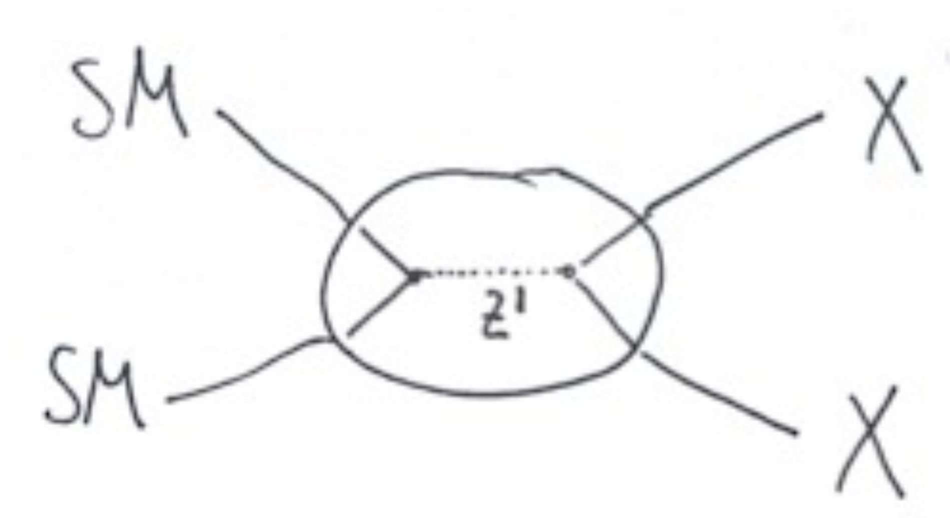
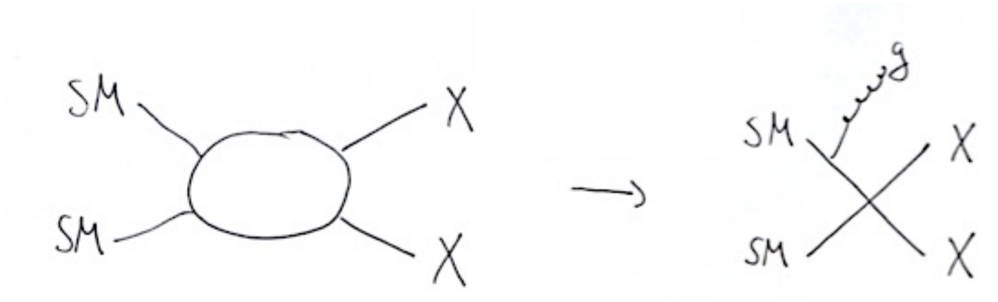


Generic WIMP Searches at Colliders



<u>Assume:</u>

- X exists and can be pair produced
- Only X in reach at LHC
- Effective field theory approach
- X—SM coupling set by m_χ and Λ

$$\mathcal{L} = \mathcal{L}_{SM} + i\bar{X}\gamma^\mu\partial_\mu X - M_X\bar{X}X + \sum_{q,i,j}\frac{G_{qij}}{\sqrt{2}}\,\bar{X}\Gamma_i^X X\;\bar{q}\Gamma_q^j q$$

$$G_{qij} \sim \frac{1}{\Lambda^n} \qquad\qquad \Lambda = \frac{M_{Z'}}{g_{q,X}}$$

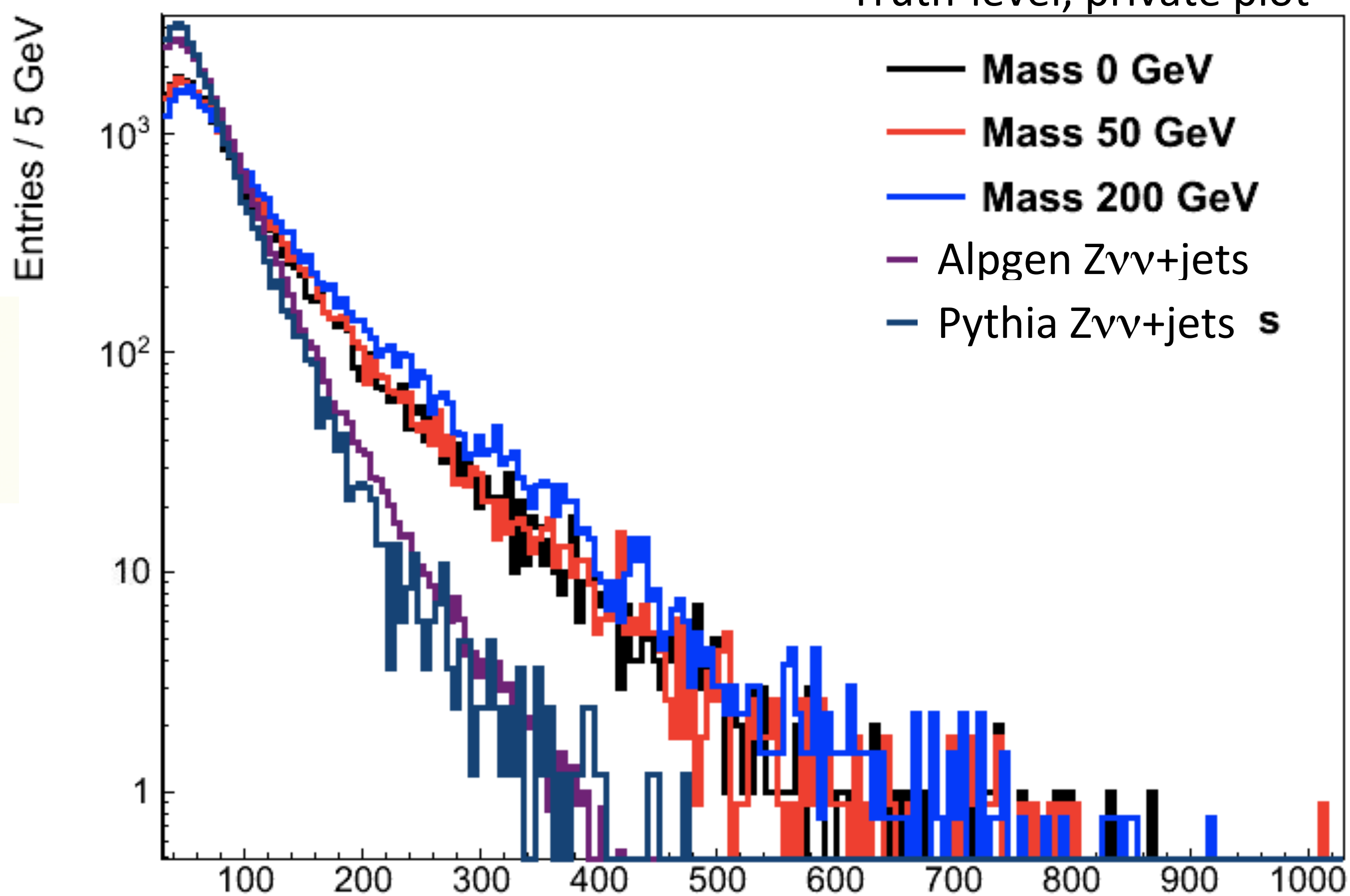
Cutoff scale

Expected signal missing ET distributions

- Take vector operator as example

$$\frac{(\bar{\chi}\gamma^{\mu}\chi)(\bar{u}\gamma_{\mu}u)}{\Lambda^2}$$

Truth-level, private plot



Missing transverse energy (GeV)

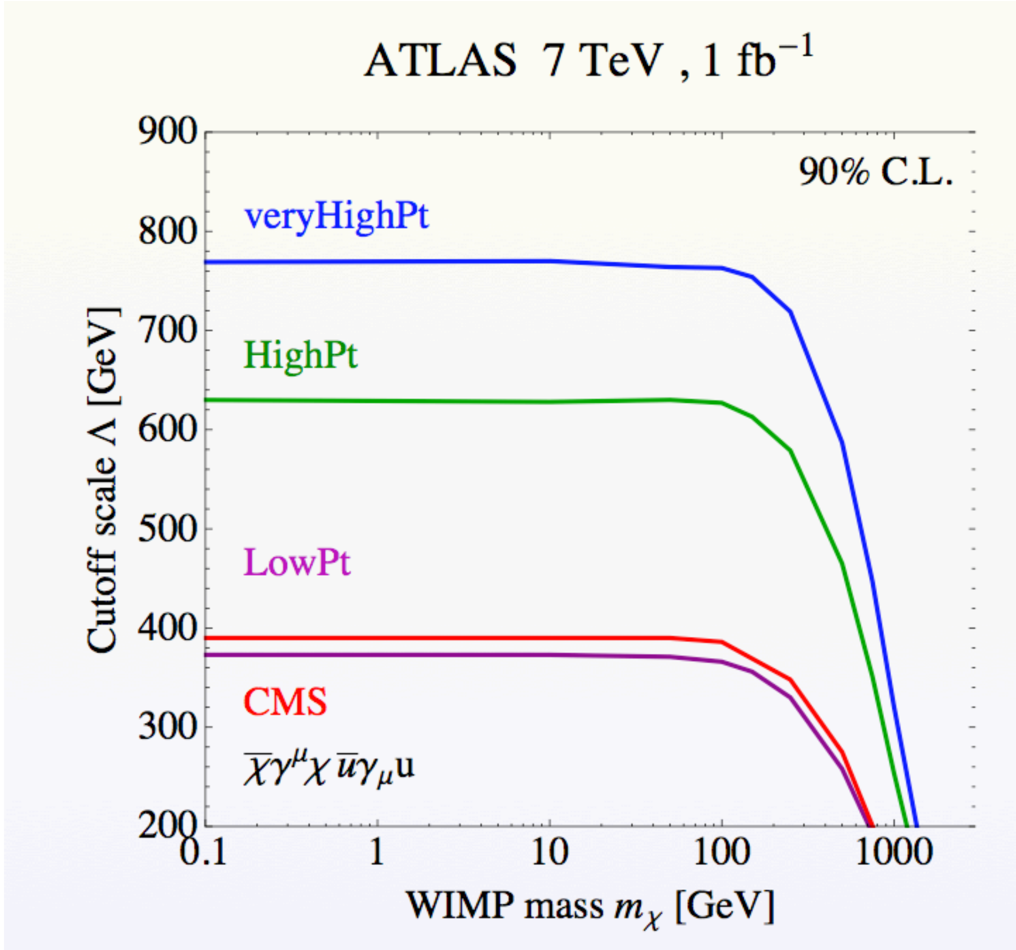
Expect harder MET spectrum even for m_{χ}= 0 GeV!

Limits on suppression scale Λ

- Take vector operator as example

$$\frac{(\bar{\chi}\gamma^{\mu}\chi)(\bar{u}\gamma_{\mu}u)}{\Lambda^2}$$

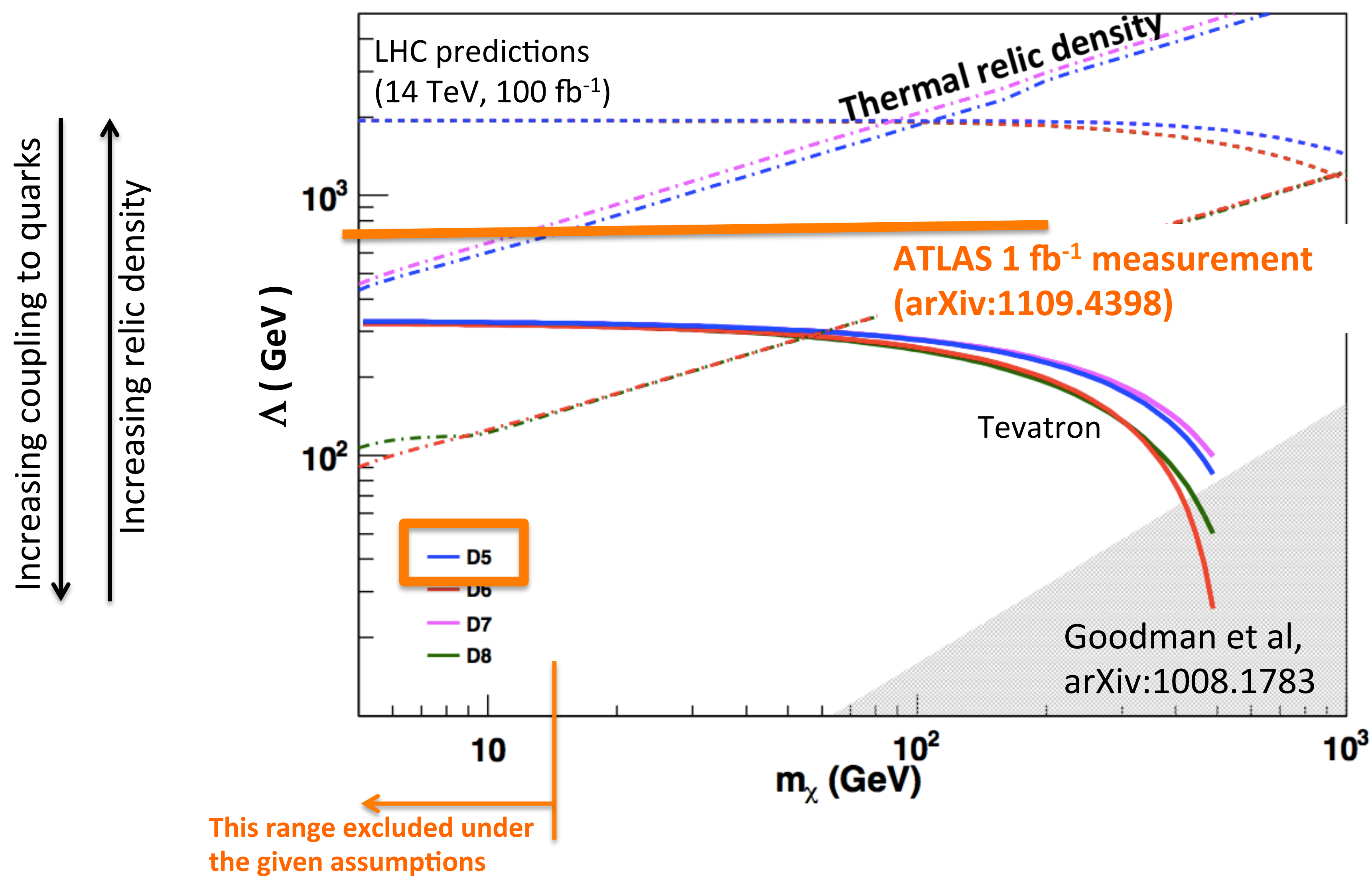
- Convert cross section limits into limit on Λ for particular m_χ



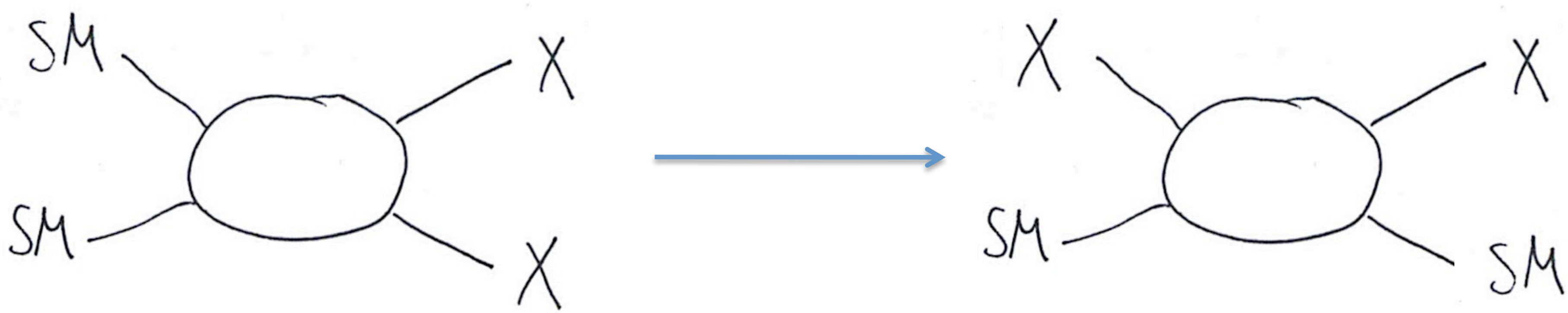
arXiv:1109.4398

Limits on suppression scale Λ

Compare to values of Λ consistent with thermal relic density



Limits in “direct-detection plane”



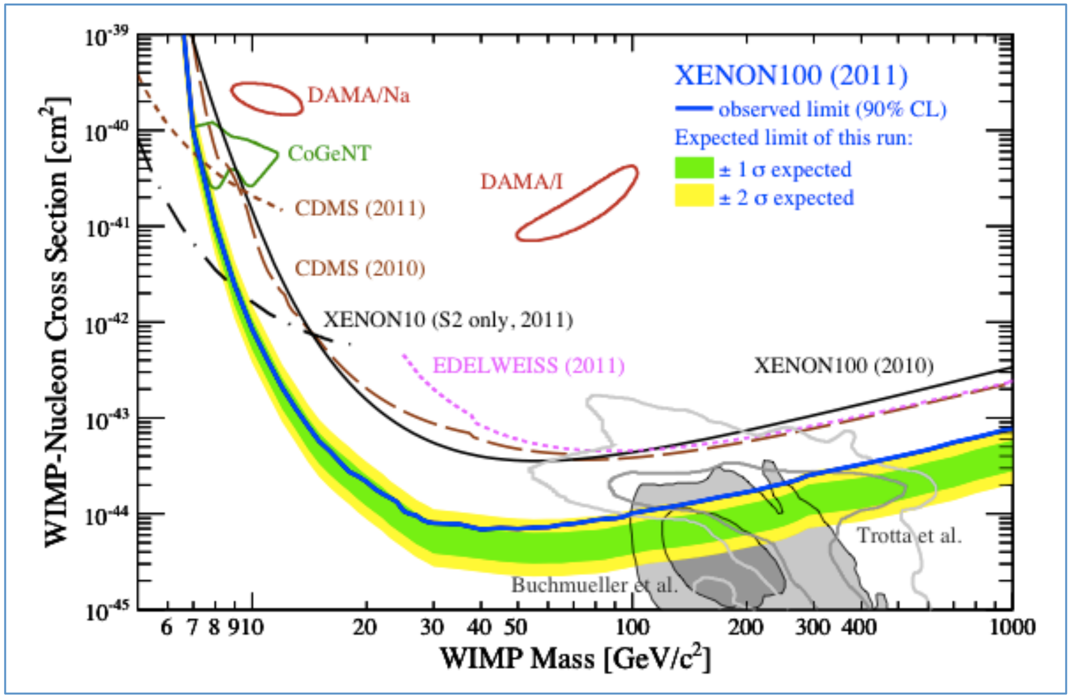
Now convert the high-energy limit on Λ into limits on $\sigma_{\chi\text{-Nucleon}}$

Caveats:

- Uncertainty of hadronic matrix elements
- Spin-independent vs spin-dependent interactions depending on operator
- Simple transfer of LHC limits potentially problematic if
  - mediators are light
  - interactions are non-flavour-universal

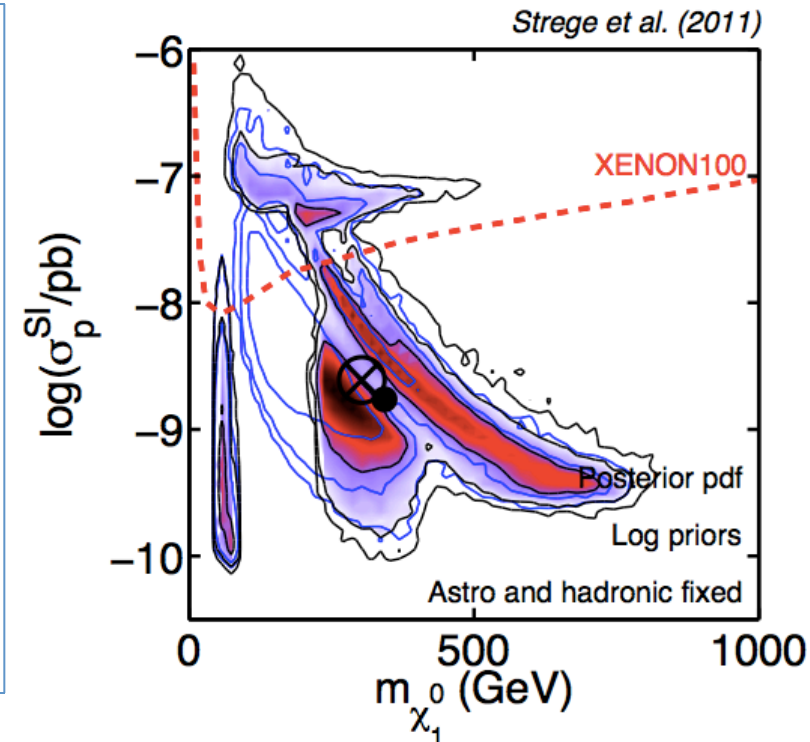
CMSSM fits in "direct-detection plane"

Fit including LHC**2010**, WMAP, g-2, excluding XENON100



arXiv:1104.2549

Fit including LHC**2011**, WMAP, g-2, excluding XENON100

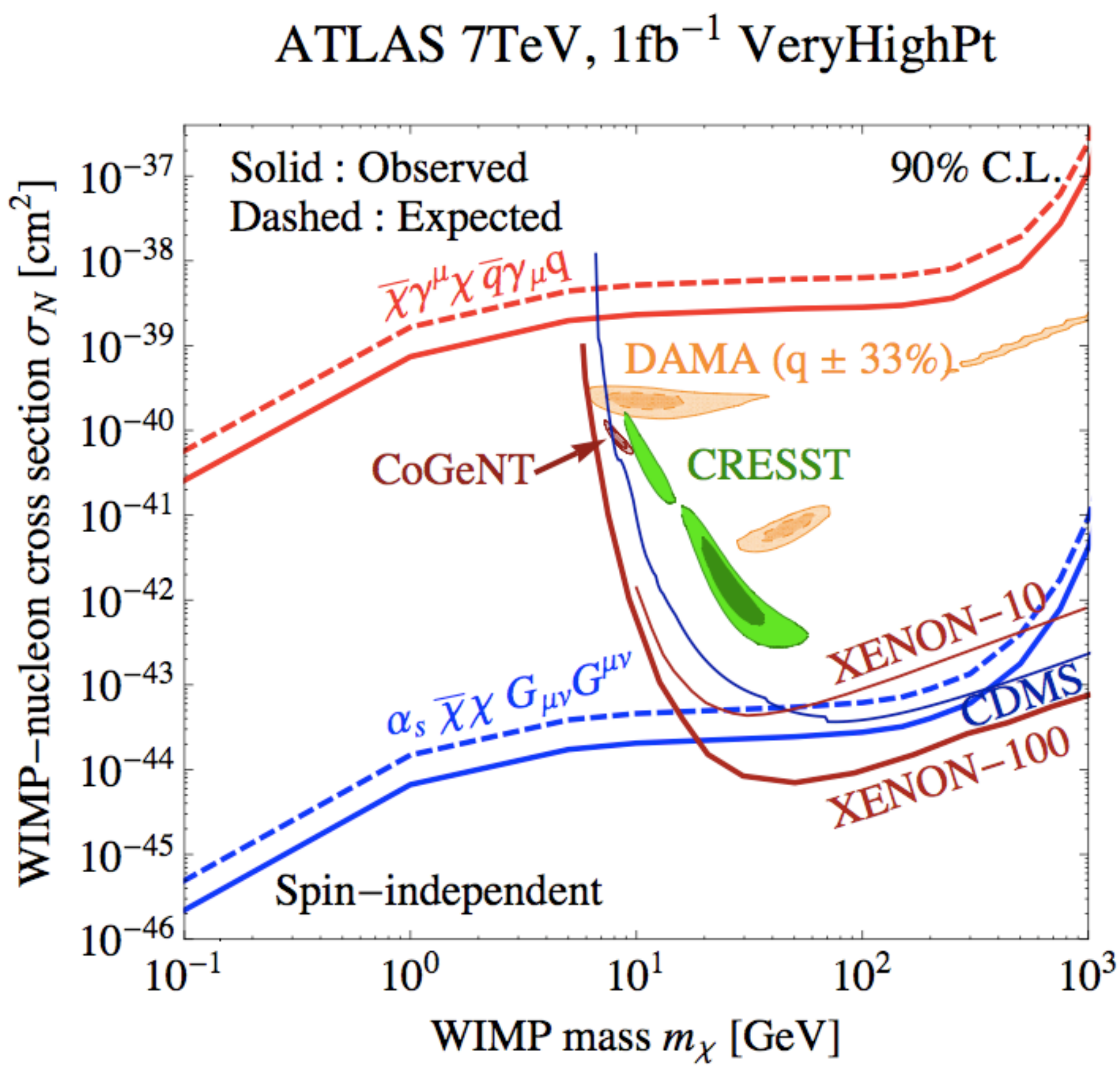


arXiv:1112.4192

One way of transferring LHC data!

Spin independent Nucleon-WIMP scattering cross section

- LHC measurement translates into one line per operator
- Low-mass LHC reach complementary to direct-detection experiments
- LHC limits don't suffer from astrophysical uncertainties
- $5fb^{-1}$ ATLAS analysis to be released in April



arXiv:1109.4398

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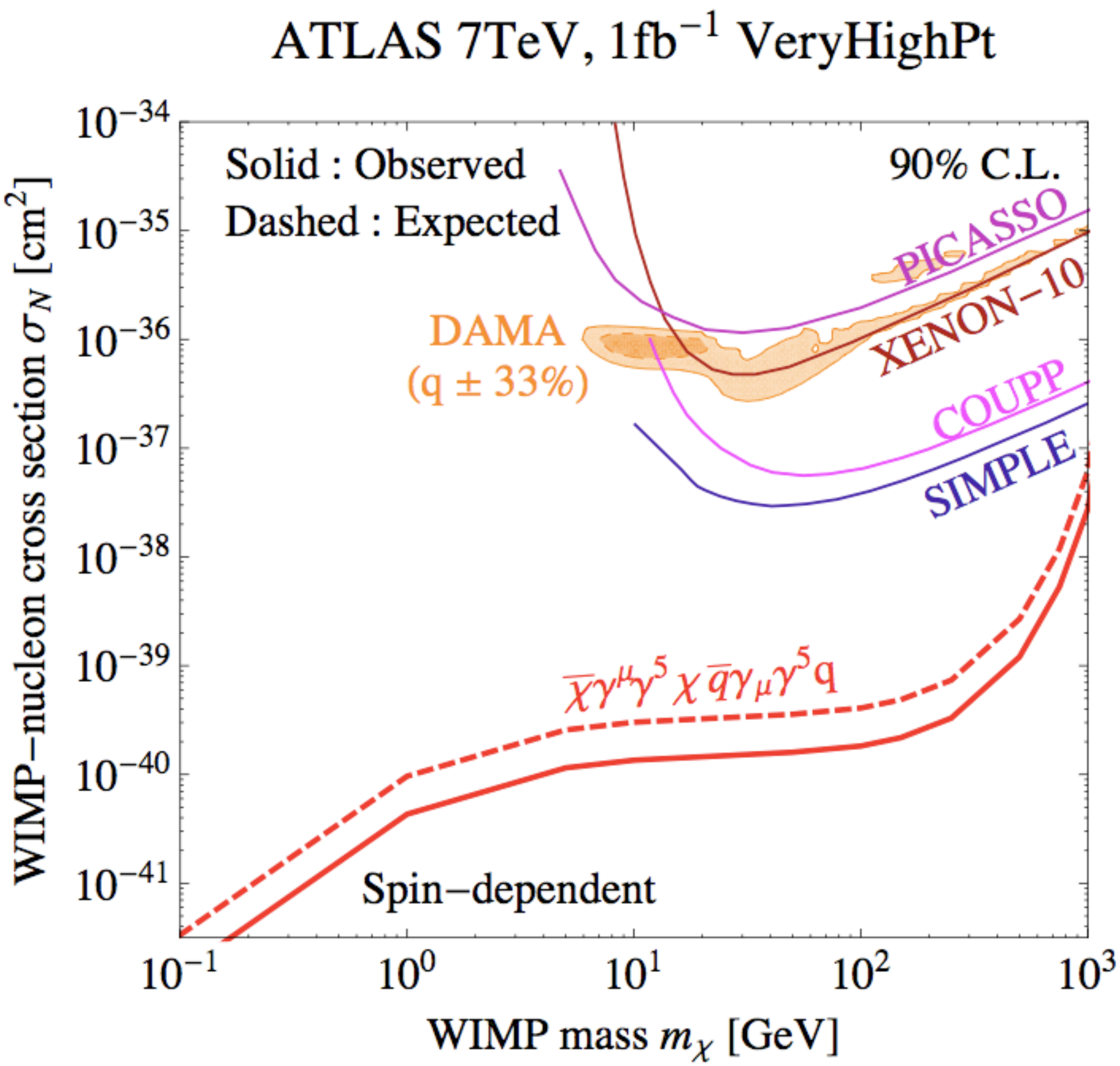
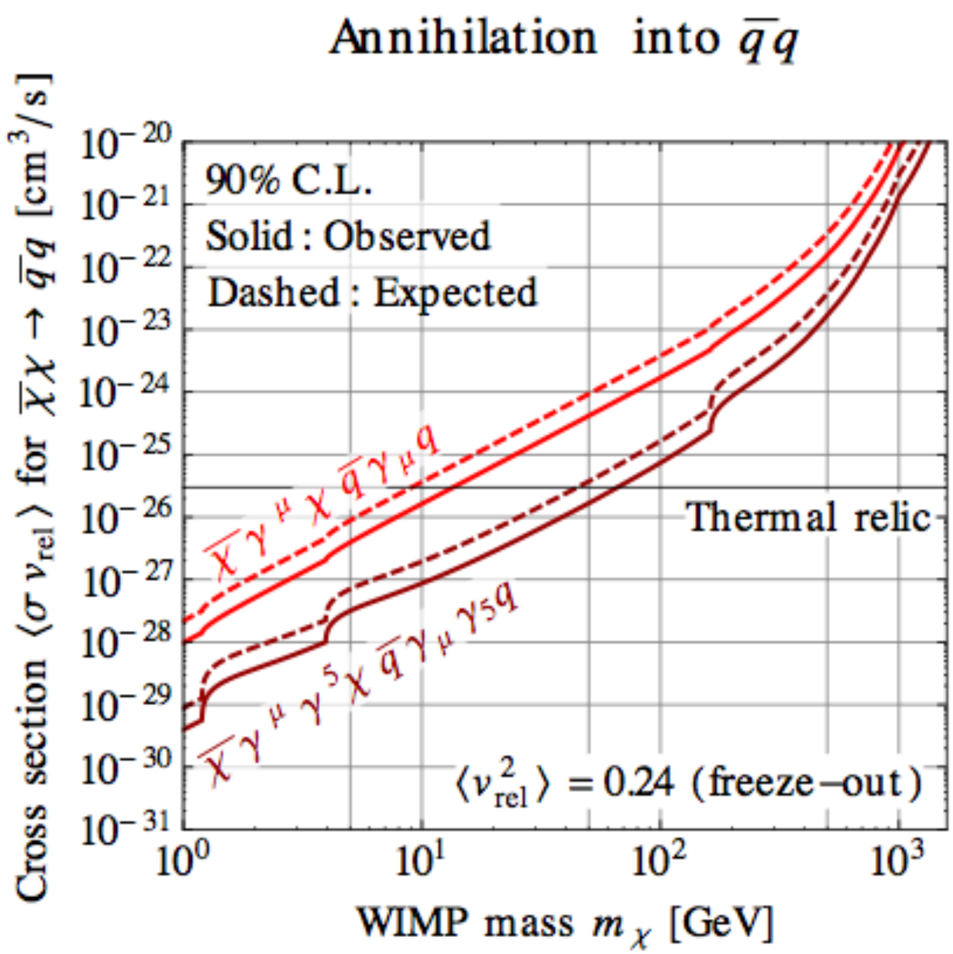


arXiv:1109.4398

LHC limits on annihilation cross section

- DM annihilation at freeze-out temperatures
- Assume DM couples to quarks only
- Assume effective field theory approach is correct for LHC and early universe
- Relic cross sections ruled out for masses < 15 and 70 GeV for vector and axial-vector operators



arXiv:1109.4398

Fermi / HESS limits

Fermi stacked Galactic satellites,
PRL 107, 241302 (2011)

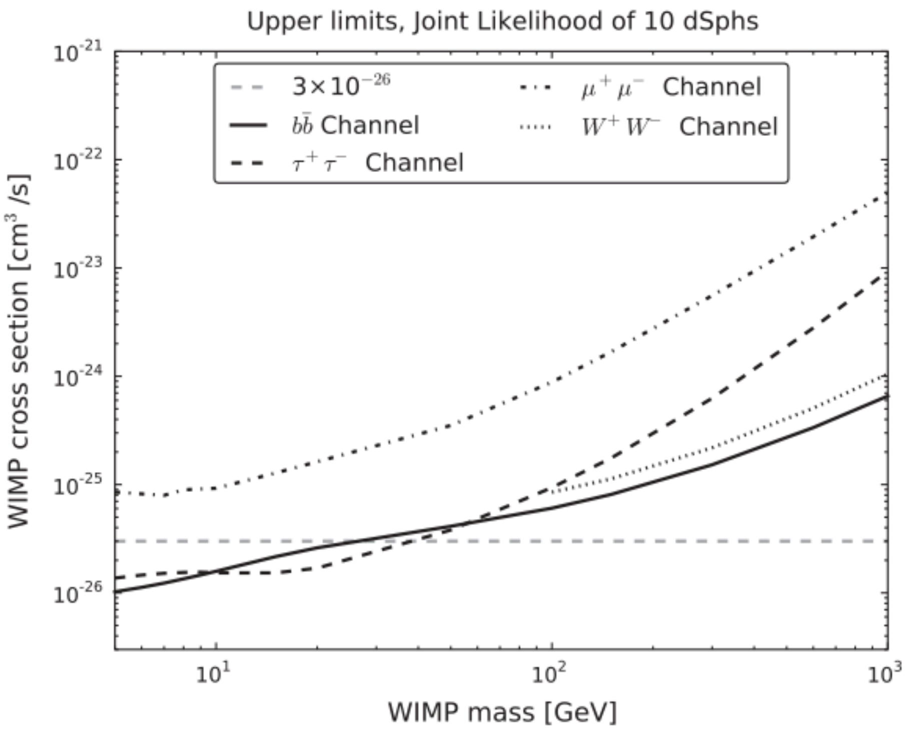
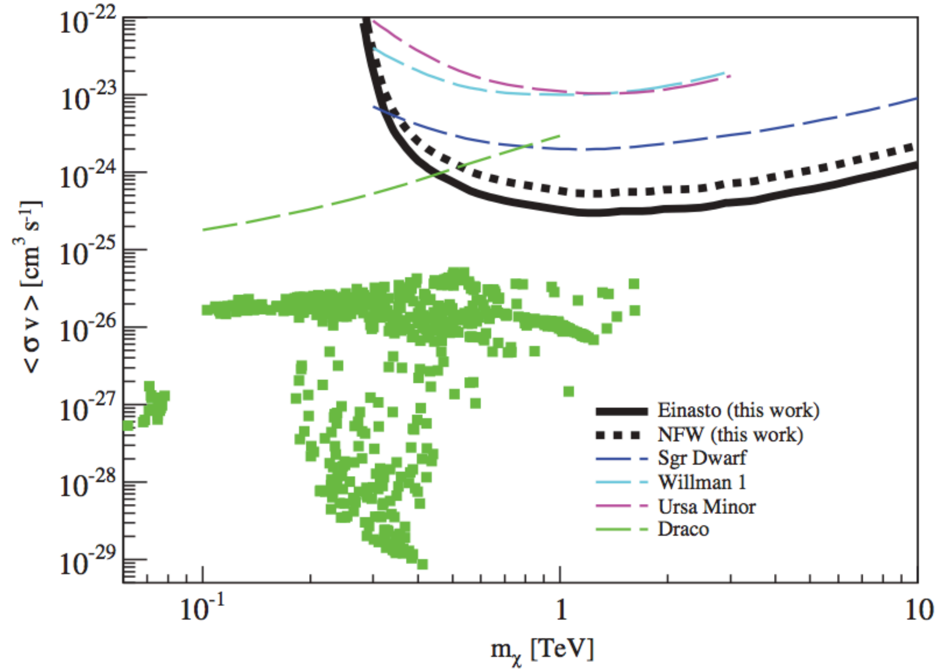


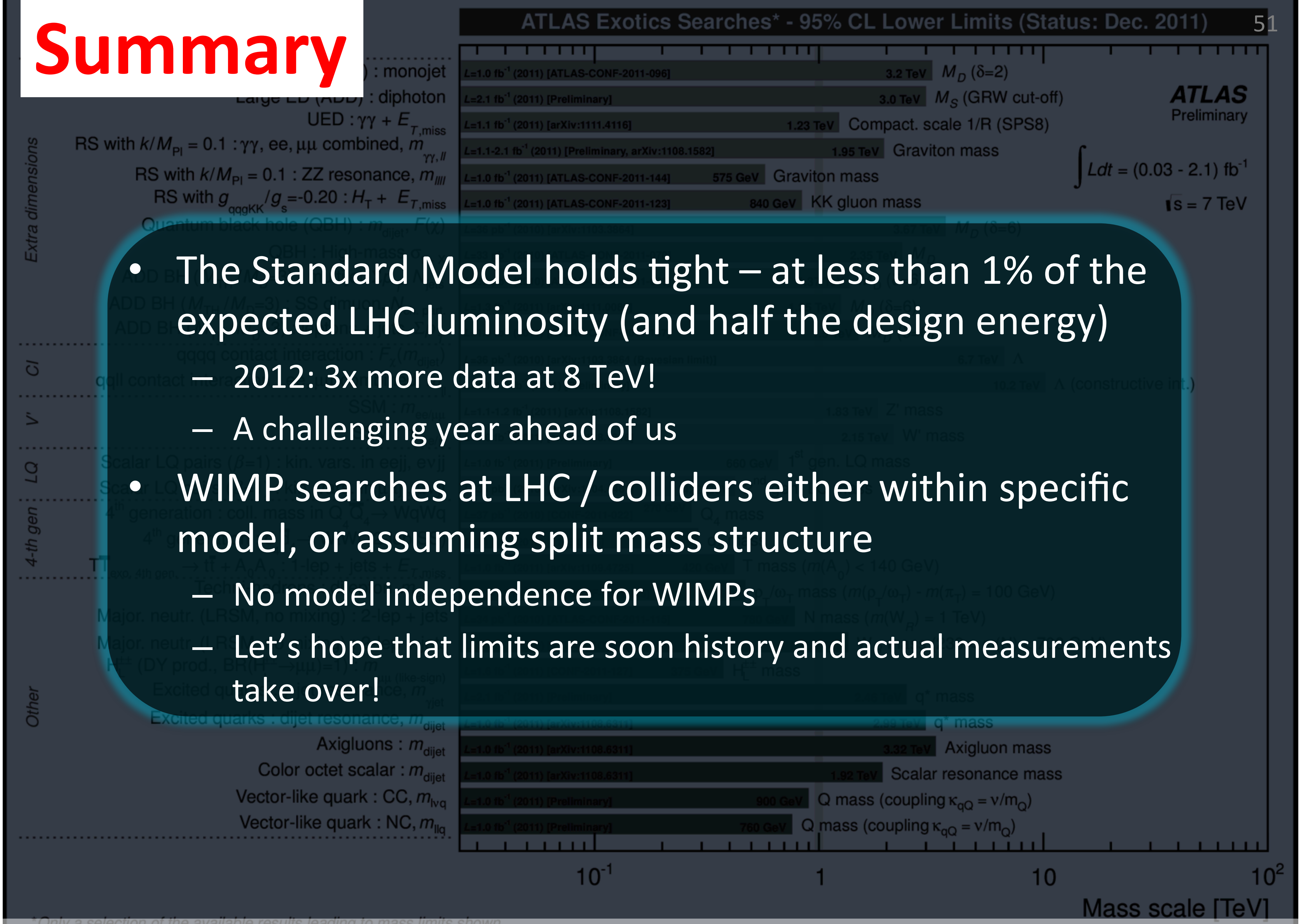
FIG. 2. Derived 95% C.L. upper limits on a WIMP annihilation cross section for the $b\bar{b}$ channel, the $\tau^+\tau^-$ channel, the $\mu^+\mu^-$ channel, and the W^+W^- channel. The most generic cross section ($\sim 3 \times 10^{-26}$ cm^3 s^{-1} for a purely s-wave cross section) is plotted as a reference. Uncertainties in the J factor are included.

HESS Galactic Center Analysis,
PRL 106, 161301 (2011)



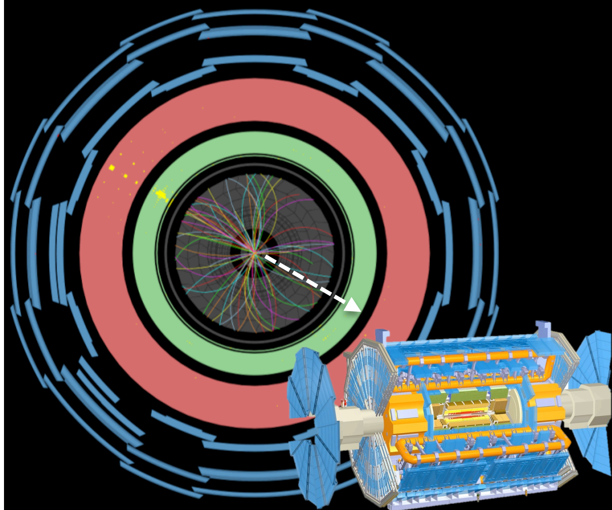
WIMP annihilation into quark-antiquark pairs

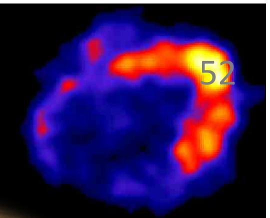
Summary

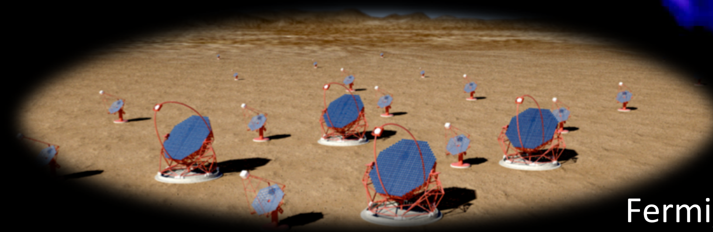


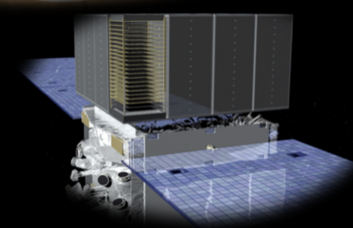
- The Standard Model holds tight – at less than 1% of the expected LHC luminosity (and half the design energy)
  - 2012: 3x more data at 8 TeV!
  - A challenging year ahead of us
- WIMP searches at LHC / colliders either within specific model, or assuming split mass structure
  - No model independence for WIMPs
  - Let's hope that limits are soon history and actual measurements take over!

Future









Fermi, CTA

LHC physics
- Searches with ATLAS
- Interpret new physics
- Presentation of data
- Dark Matter to LHC
- LHC to Dark Matter

The Dark Matter connection
- Combine data
- Exploit complementarities

VHE γ-rays
- Indirect Dark Matter searches