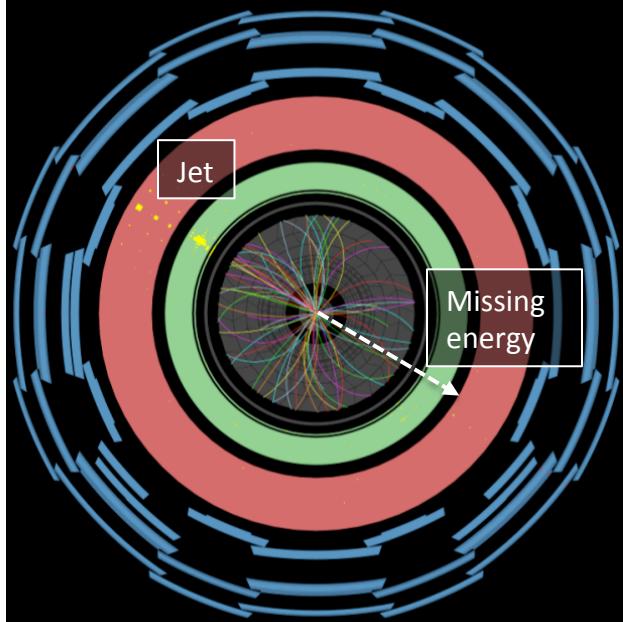


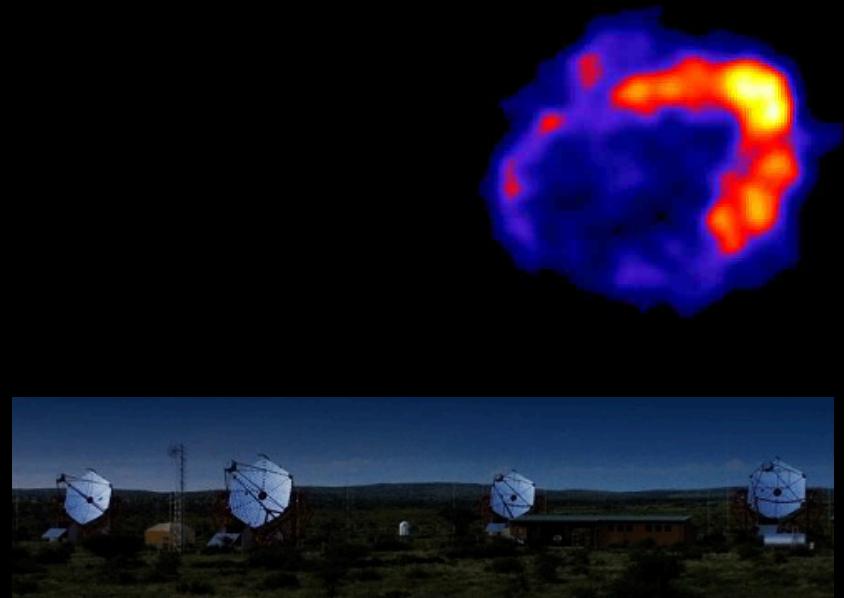
Going after the Dark at the LHC

David Berge (CERN)

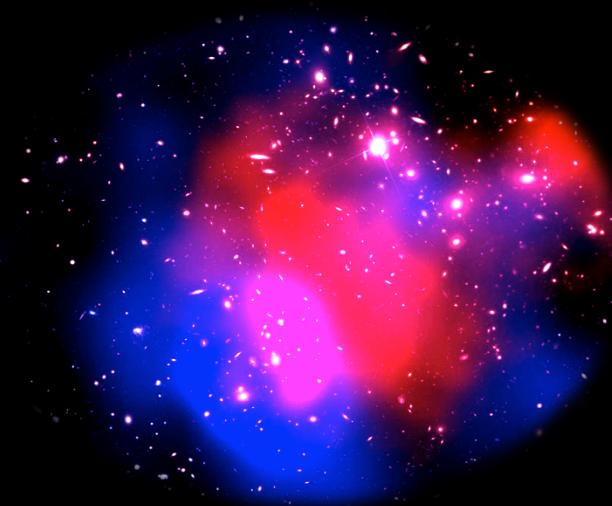


ATLAS mono-jet event display

Supernova remnant RX J1713



H.E.S.S. experiment

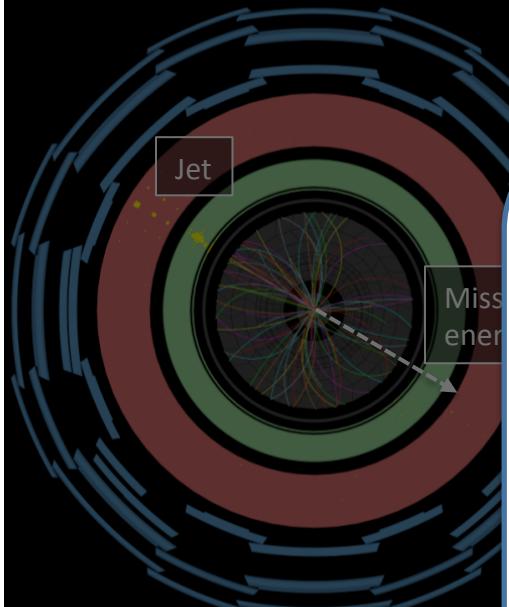


Galaxy cluster Abell 2744

Going after the Dark at the LHC

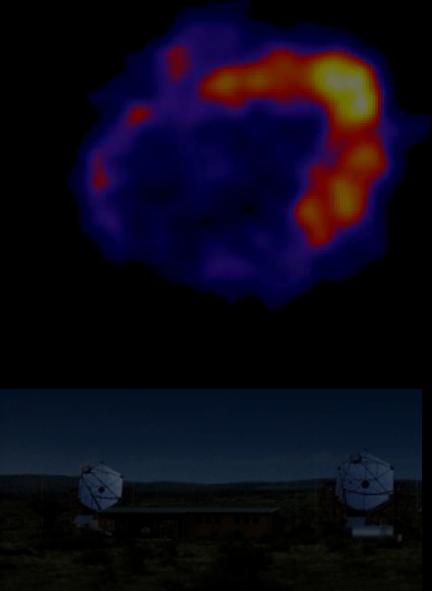
David Berge (CERN)

Supernova remnant RX J1713



ATLAS mono-jet event display

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



H.E.S.S. experiment



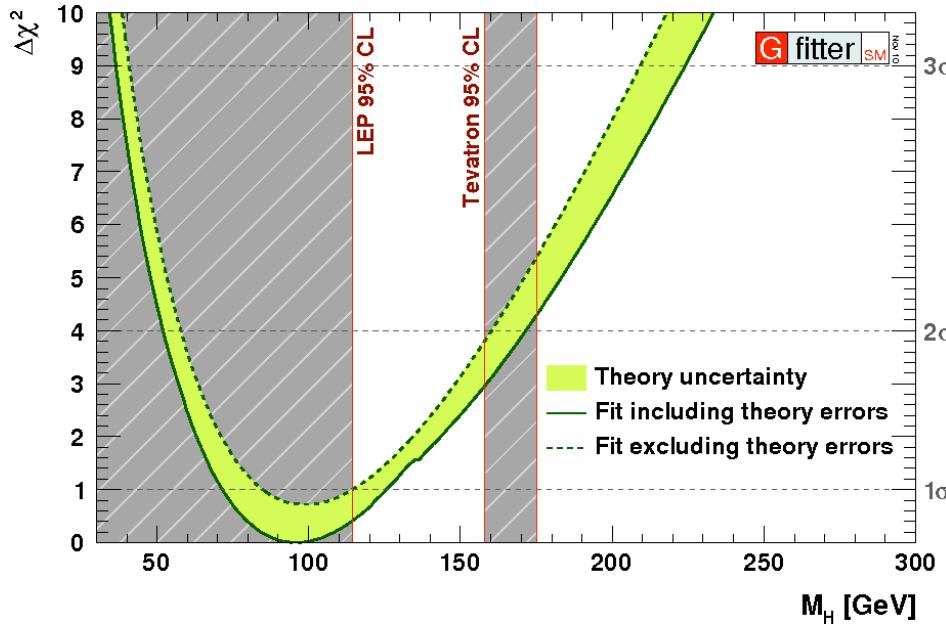
Galaxy cluster Abell 2744

Arguments for new physics (at the TeV scale)

3

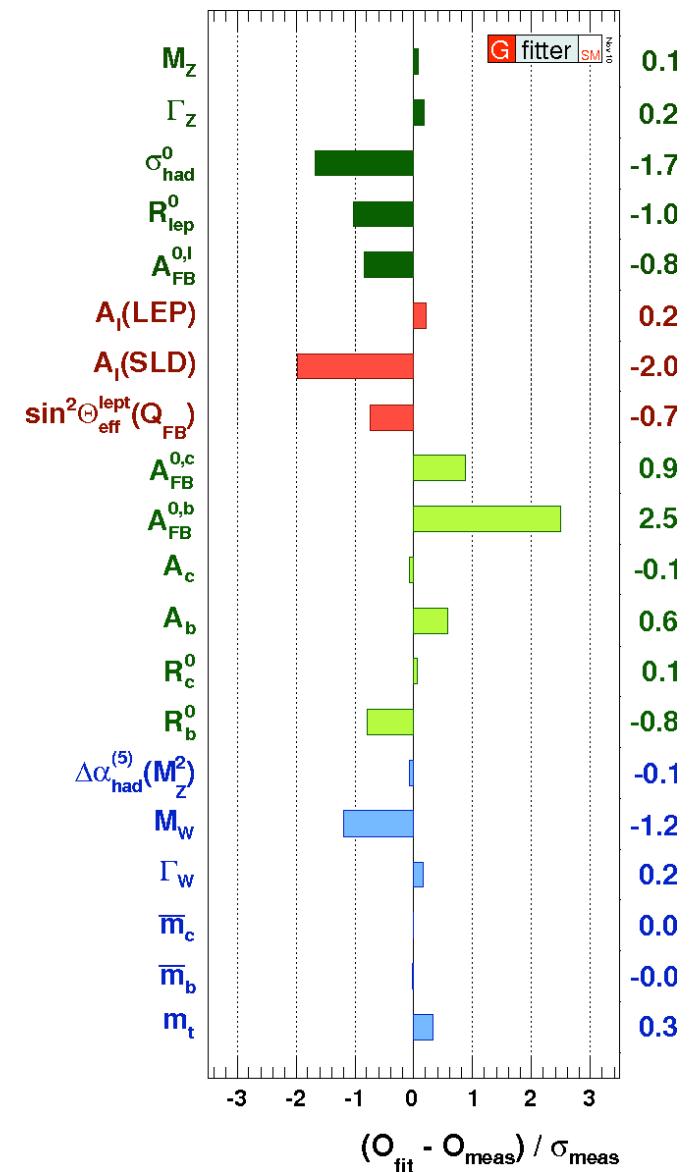
No unambiguous experimental result requires new physics at the TeV scale

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



Central value $\pm 1\sigma$: $M_H = 96^{+31}_{-24}$ GeV

95% CL upper limit: 169 GeV

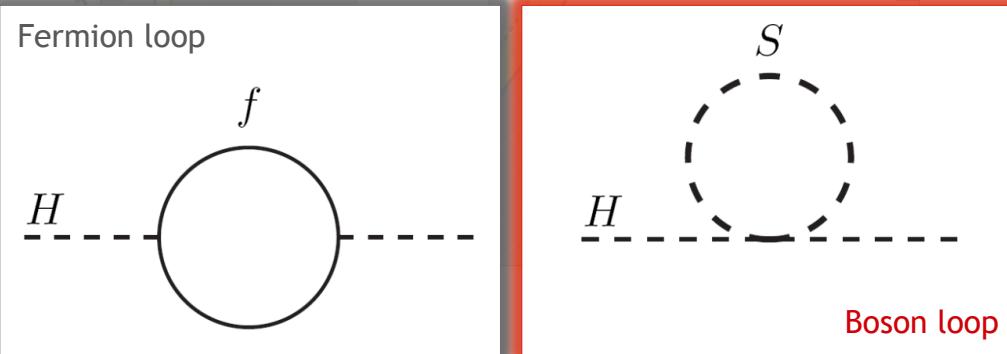
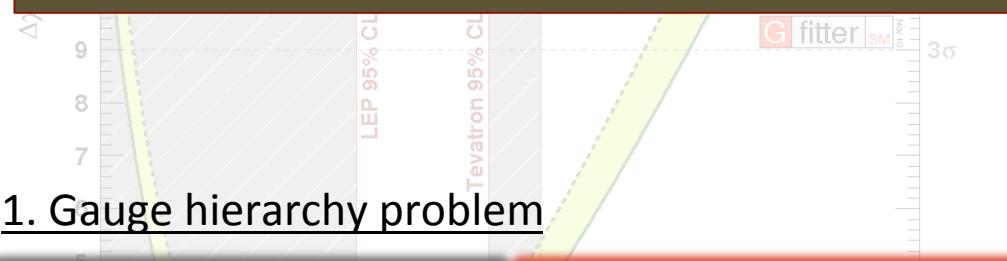


Arguments for new physics (at the TeV scale)

4

No unambiguous experimental result requires new physics at the TeV scale

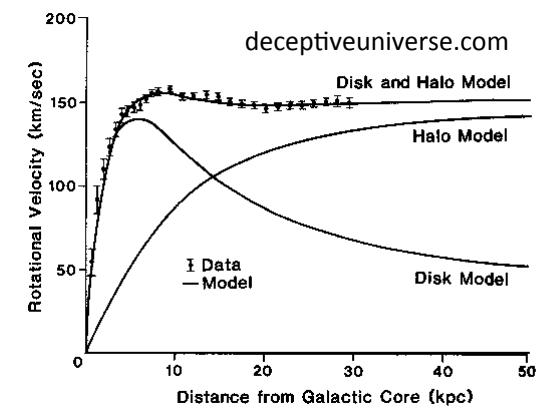
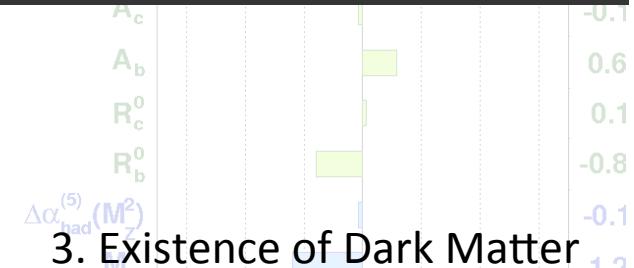
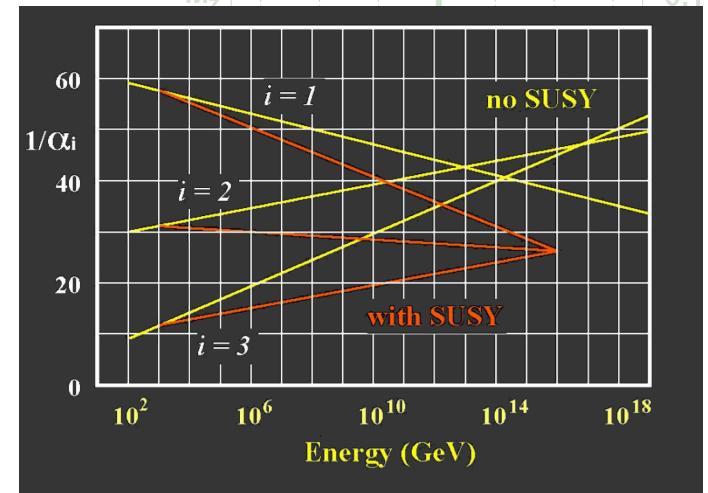
Theoretical considerations suggestive of new (TeV) physics:



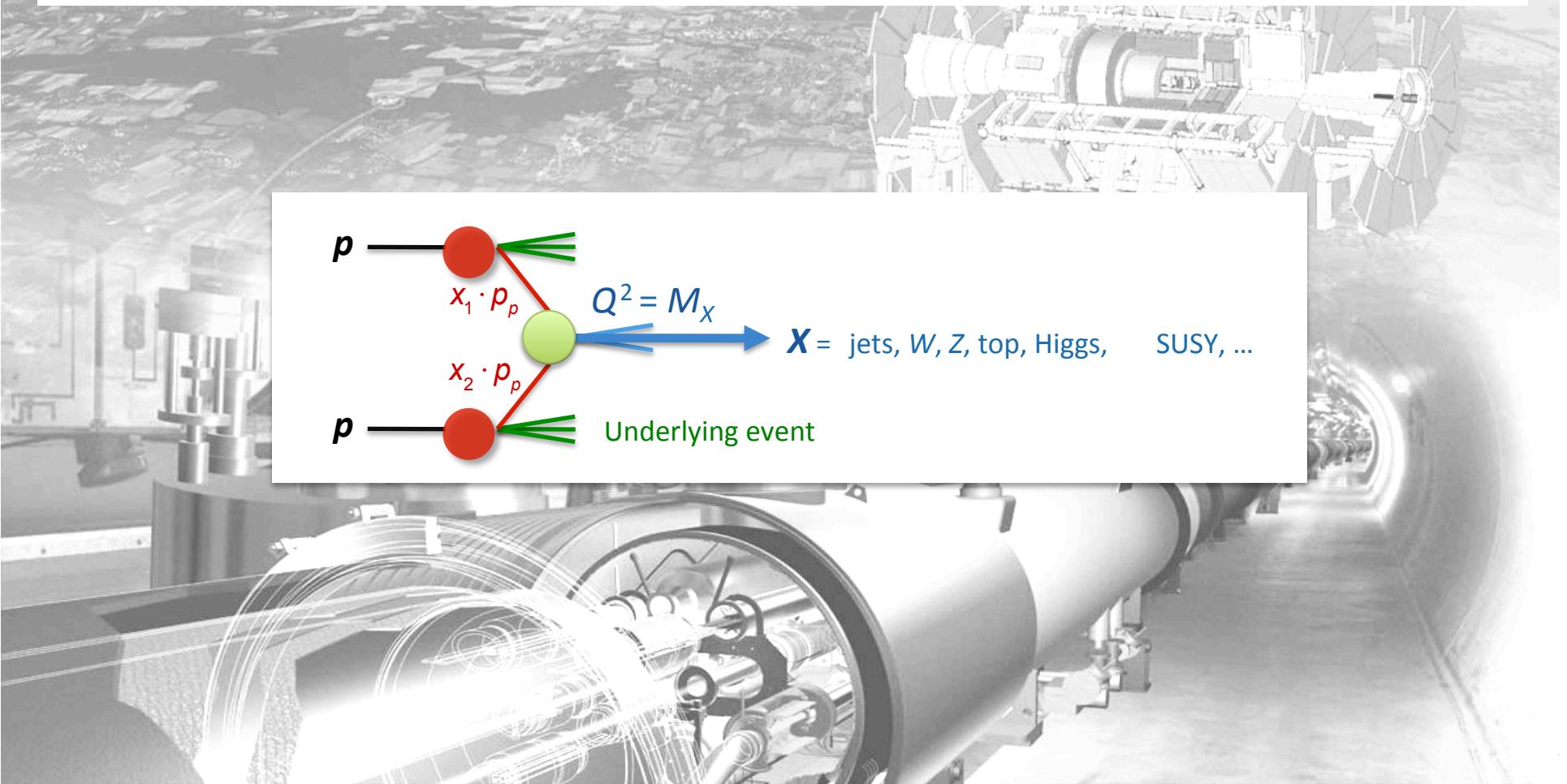
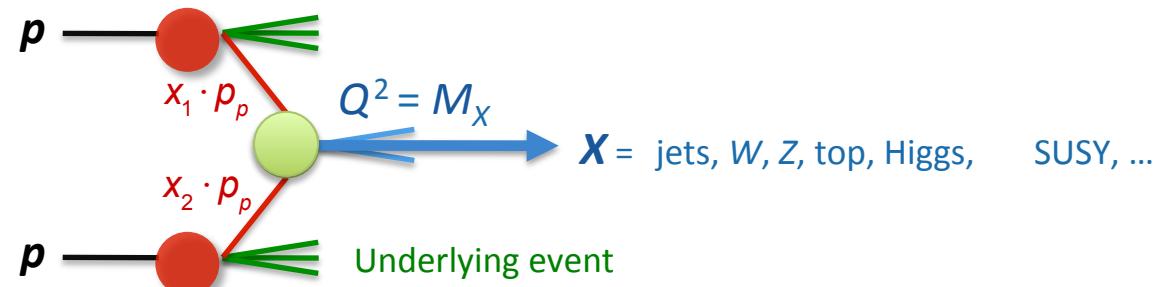
Higgs radiative corrections
95% CL upper limit: 169 GeV

David Berge (CERN) / 1 Mar 2012

2. Unification of gauge couplings

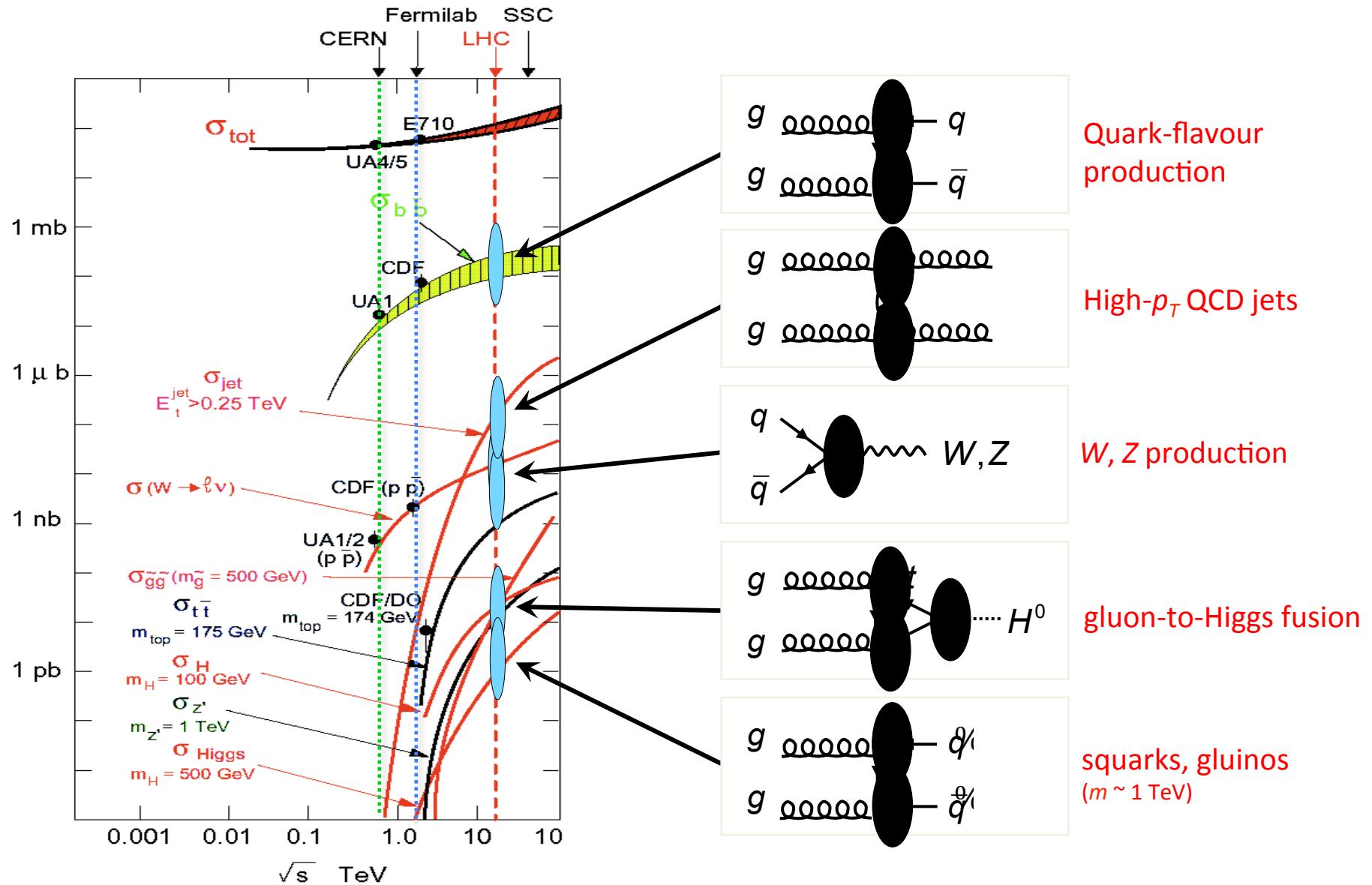


Wanted: new particles
Needed: multi-TeV proton collider



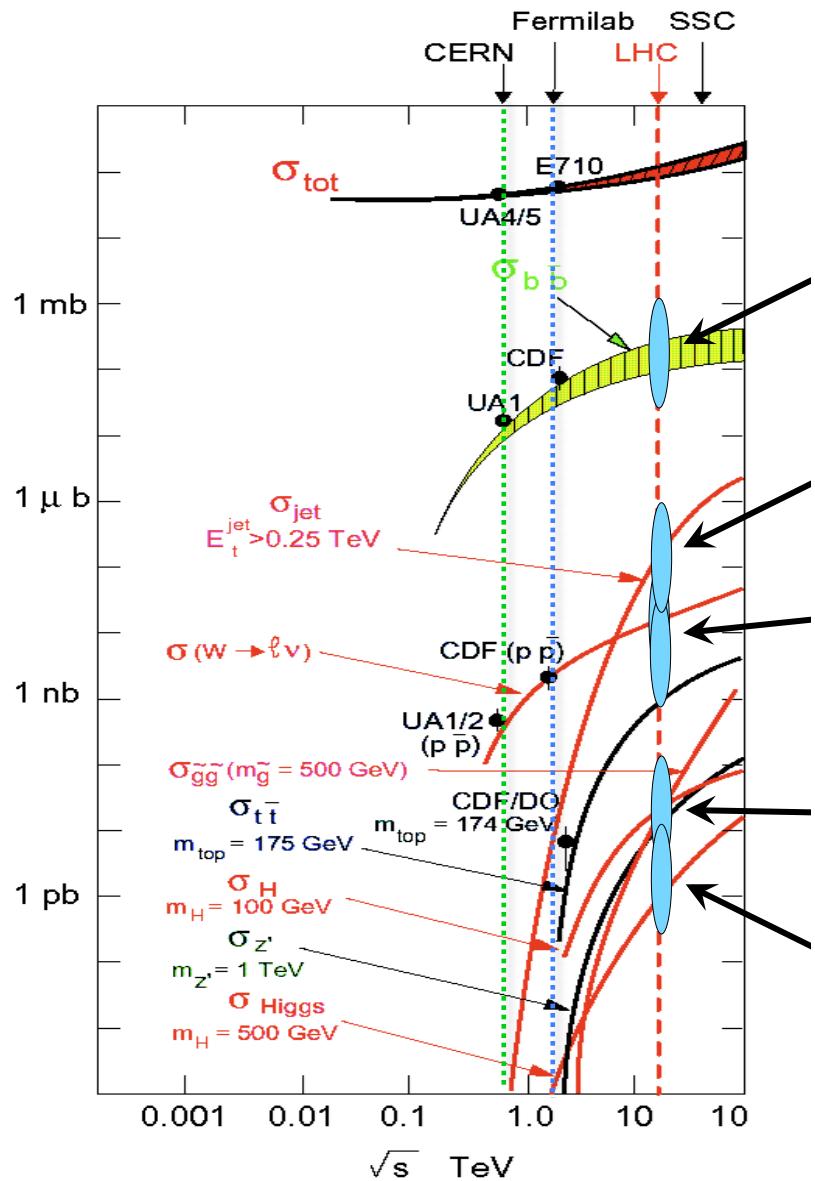
Typical production cross sections at a hadron collider

6



Typical production cross sections at a hadron collider

7



Need for discovery of new TeV scale physics:

- A multi-TeV accelerator
- Very large luminosities

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

“Cross section” given by Nature

“Efficiency” of detection
optimised by experimentalist

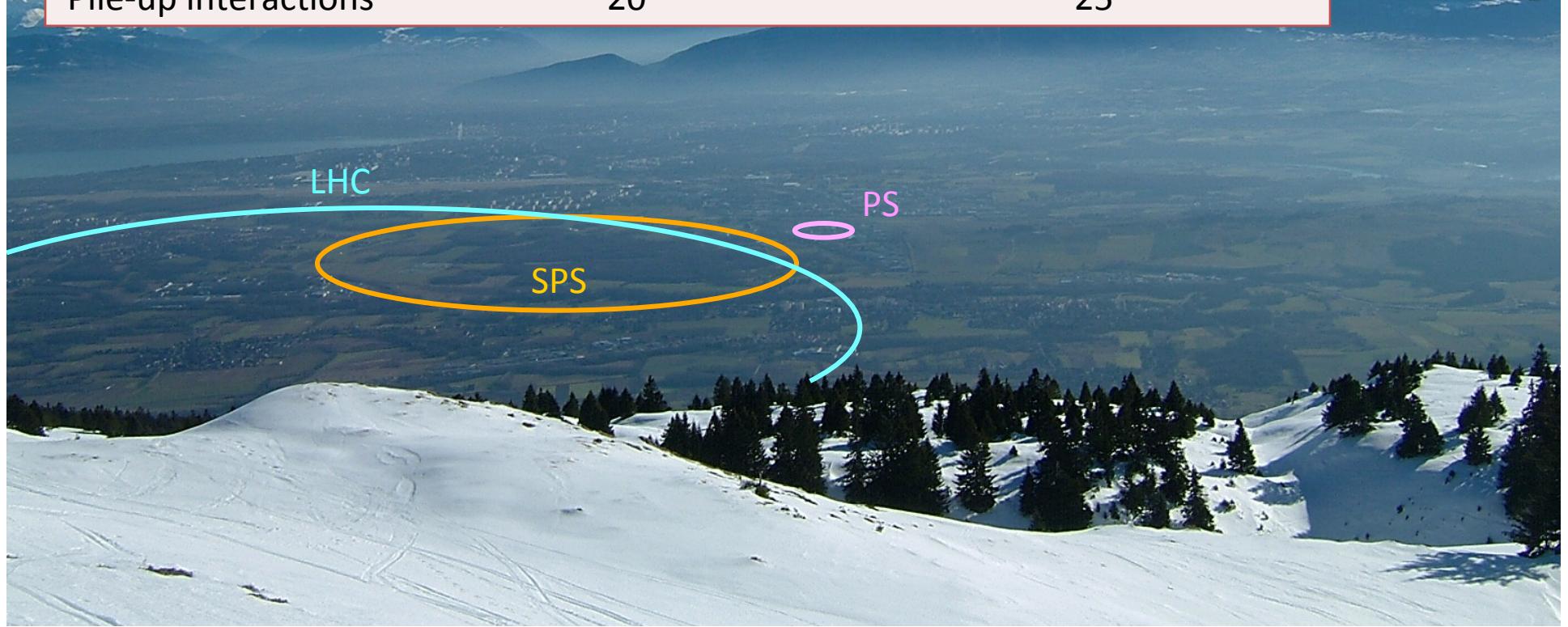
“Luminosity” – how bright are we?

- An experiment to measure high-pt physics

The Large Hadron Collider



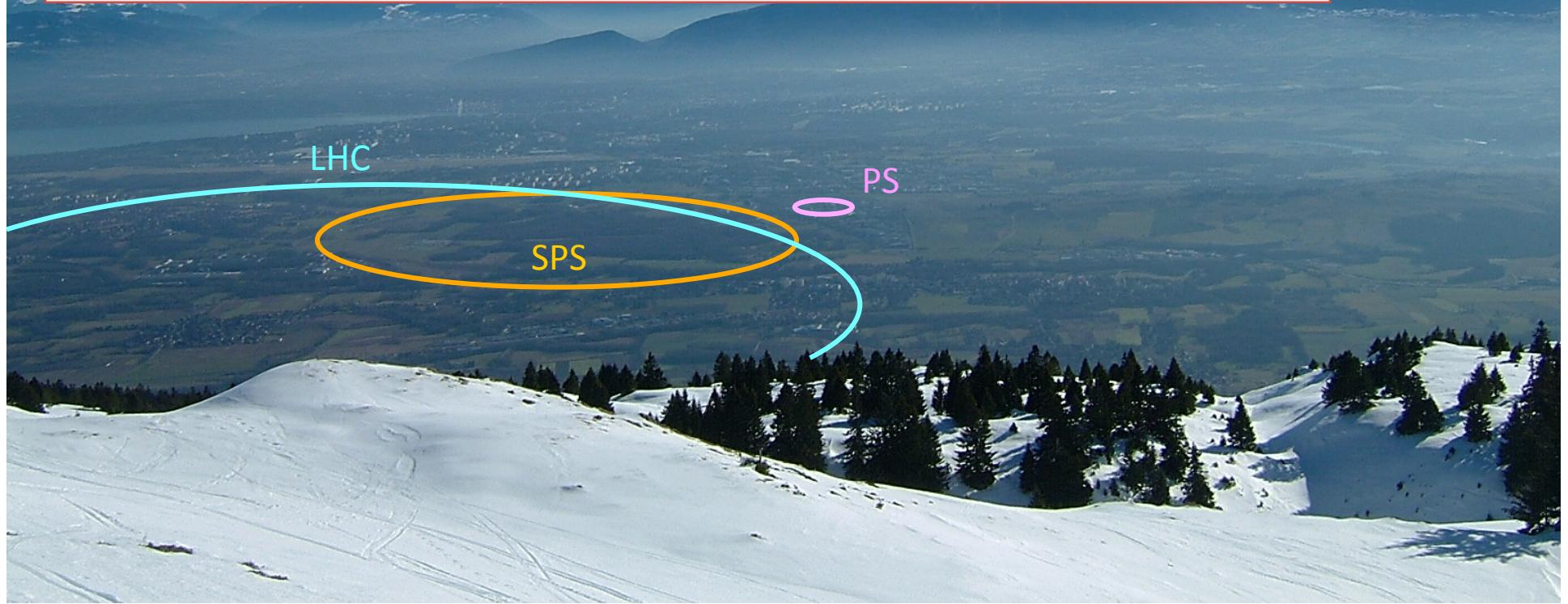
	2011 performance	Design performance
Colliding bunches	1331	2808
Energy	3.5 TeV x 3.5 TeV	7 TeV x 7 TeV
Bunch spacing	50 ns	25 ns
Luminosity	$3.6 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$	$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
Pile-up interactions	~20	~25



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	$6.8 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$	$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
Pile-up interactions	~35	~25



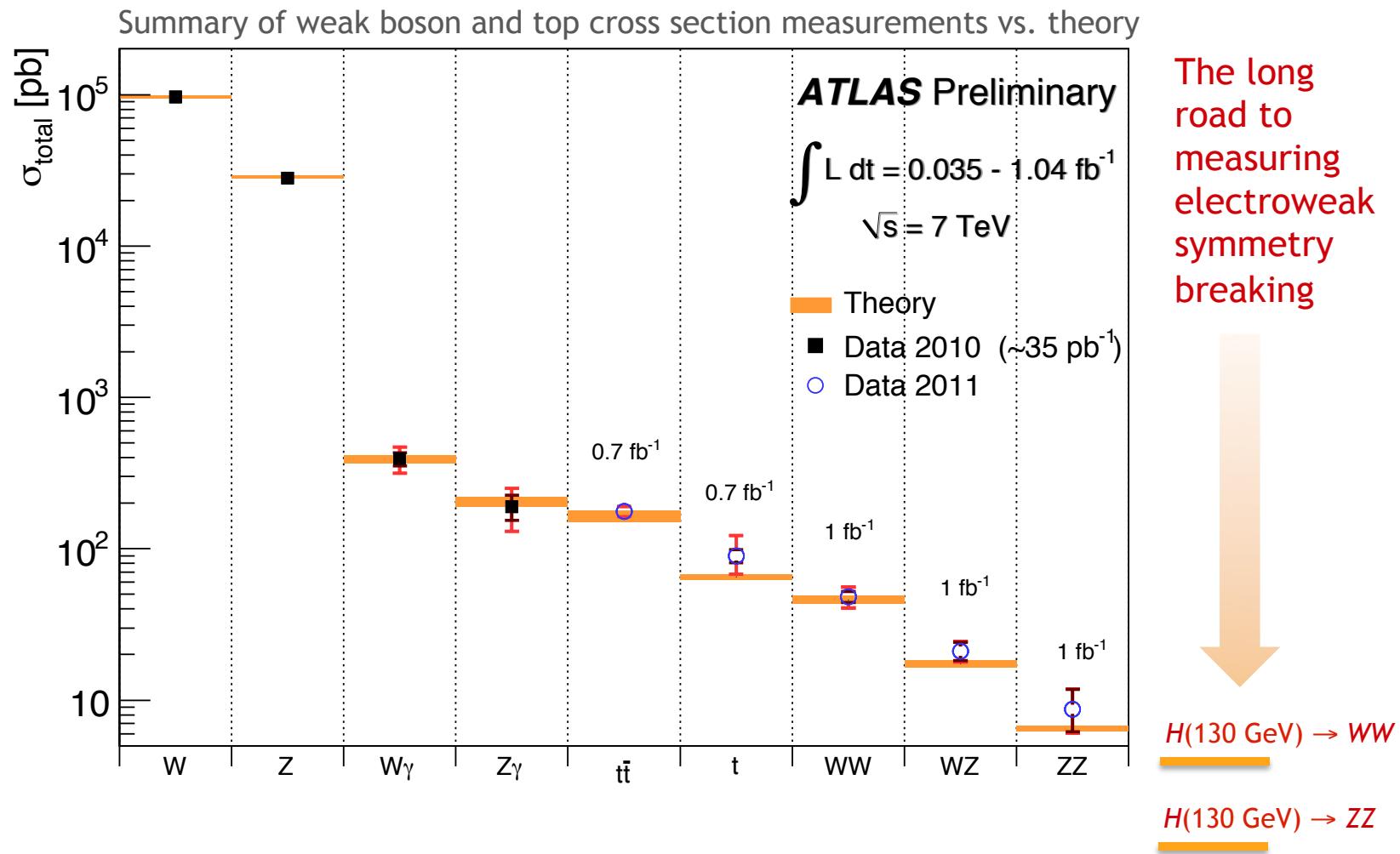
Two general-purpose experiments: ATLAS & CMS

10



Searches for the Standard Model at 7 TeV

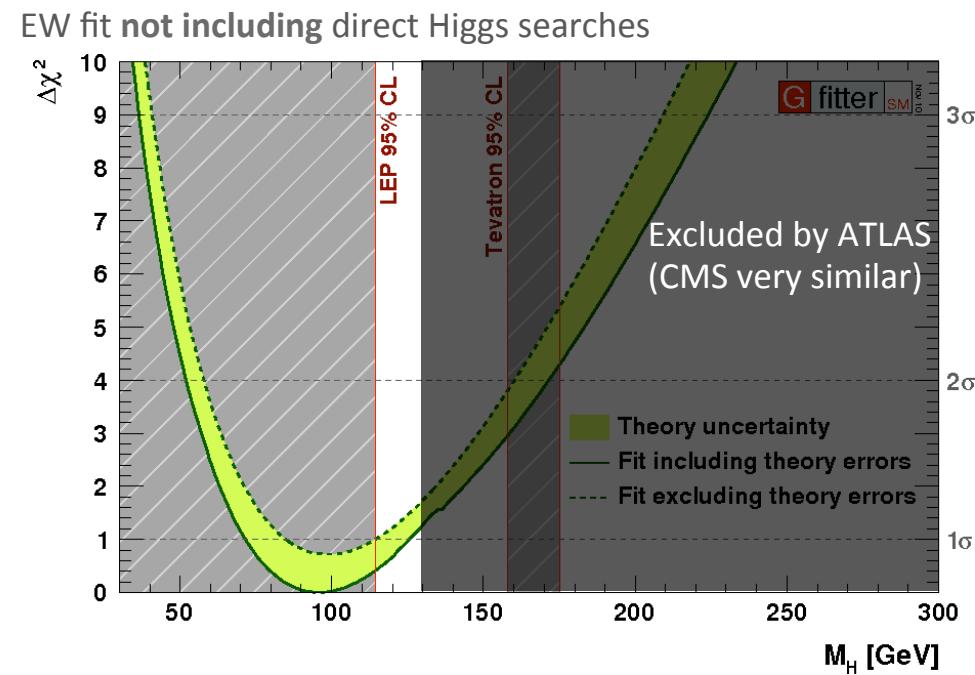
11



Pursue Standard Model measurements as important benchmarks!

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

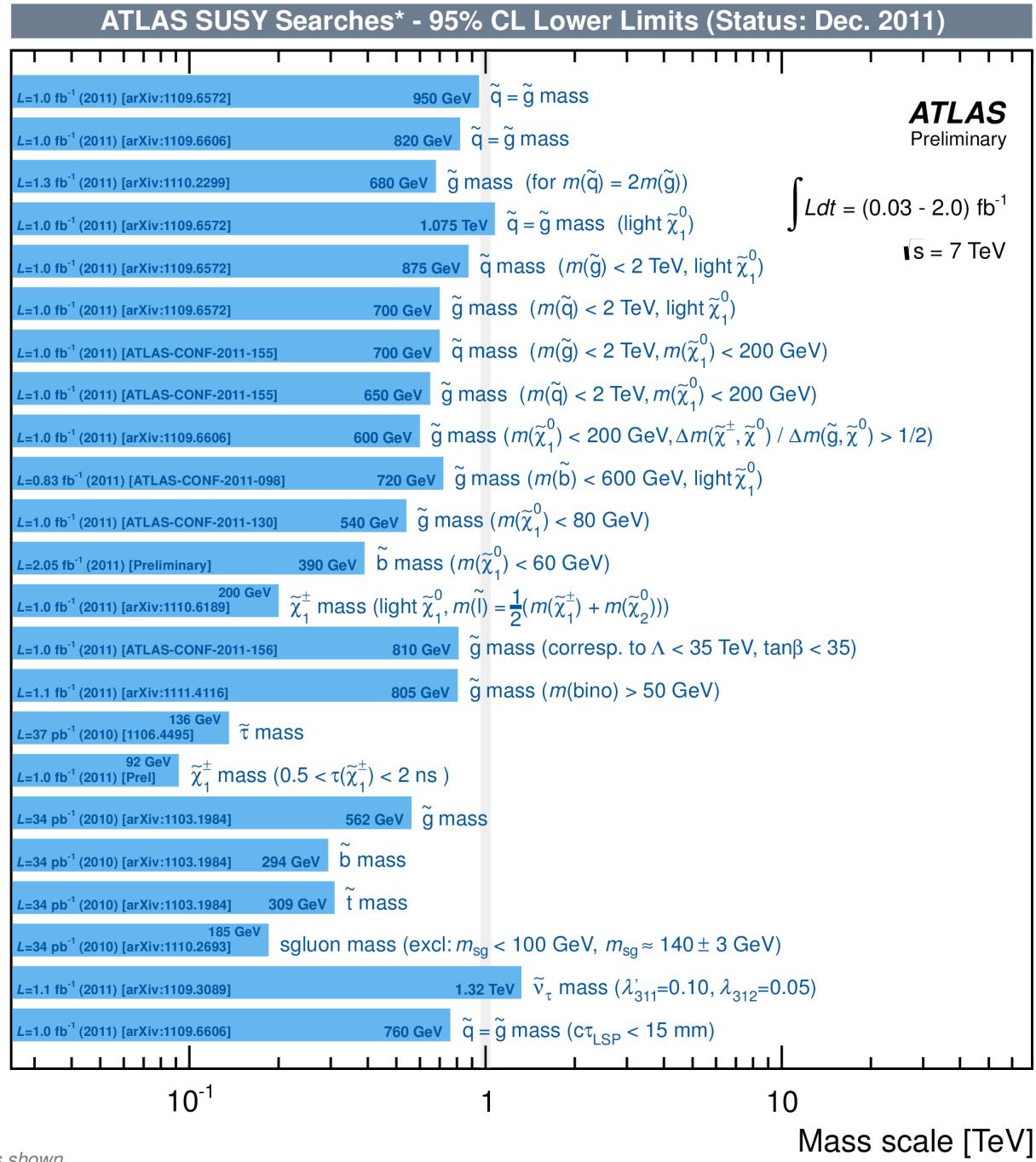
Higgs mass range narrowed down to 115.5–131 GeV
 Perhaps first indications of a signal around 125 GeV



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

Nothing new yet...

SUSY



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

Nothing new yet...

Extra dimensions

- Large ED (ADD) : monojet
- Large ED (ADD) : diphoton
- UED : $\gamma\gamma + E_{T,\text{miss}}$
- RS with $k/M_{\text{Pl}} = 0.1$: $\gamma\gamma, \text{ee}, \mu\mu$ combined, $m_{\gamma\gamma, \text{II}}$
- RS with $k/M_{\text{Pl}} = 0.1$: ZZ resonance, m_{III}
- RS with $g_{\text{qqgKK}}/g_s = -0.20$: $H_T + E_{T,\text{miss}}$
- Quantum black hole (QBH) : $m_{\text{dijet}}, F(\chi)$

QBH : High-mass $\sigma_{t+\bar{t}}$

ADD BH ($M_{\text{TH}}/M_D = 3$) : multijet, $\Sigma p_T, N_{\text{jets}}$

ADD BH ($M_{\text{TH}}/M_D = 3$) : SS dimuon, $N_{\text{ch. part.}}$

ADD BH ($M_{\text{TH}}/M_D = 3$) : leptons + jets, Σp_T

qqqq contact interaction : $F_\chi(m_{\text{dijet}})$

qlll contact interaction : ee, $\mu\mu$ combined, m_{II}

SSM : $m_{\text{ee}/\mu\mu}$

SSM : $m_{T,\text{e}/\mu}$

Scalar LQ pairs ($\beta=1$) : kin. vars. in eejj, evjj

Scalar LQ pairs ($\beta=1$) : kin. vars. in $\mu\mu jj, \mu\nu jj$

4th generation : coll. mass in Q $\overline{Q}_4 \rightarrow WqWq$

4th generation : d $\overline{d}_4 \rightarrow WtWt$ (2-lep SS)

$T\bar{T}_{\text{exo, 4th gen.}} \rightarrow t\bar{t} + A_0 A_0$: 1-lep + jets + $E_{T,\text{miss}}$

Techni-hadrons : dilepton, $m_{\text{ee}/\mu\mu}$

Major. neutr. (LRSM, no mixing) : 2-lep + jets

Major. neutr. (LRSM, no mixing) : 2-lep + jets

$H_L^{\pm\pm}$ (DY prod., BR($H_L^{\pm\pm} \rightarrow \mu\mu$)=1) : $m_{\mu\mu}$ (like-sign)

Excited quarks : γ -jet resonance, $m_{\gamma\text{jet}}$

Excited quarks : dijet resonance, m_{dijet}

Axigluons : m_{dijet}

Color octet scalar : m_{dijet}

Vector-like quark : CC, m_{lq}

Vector-like quark : NC, m_{lq}

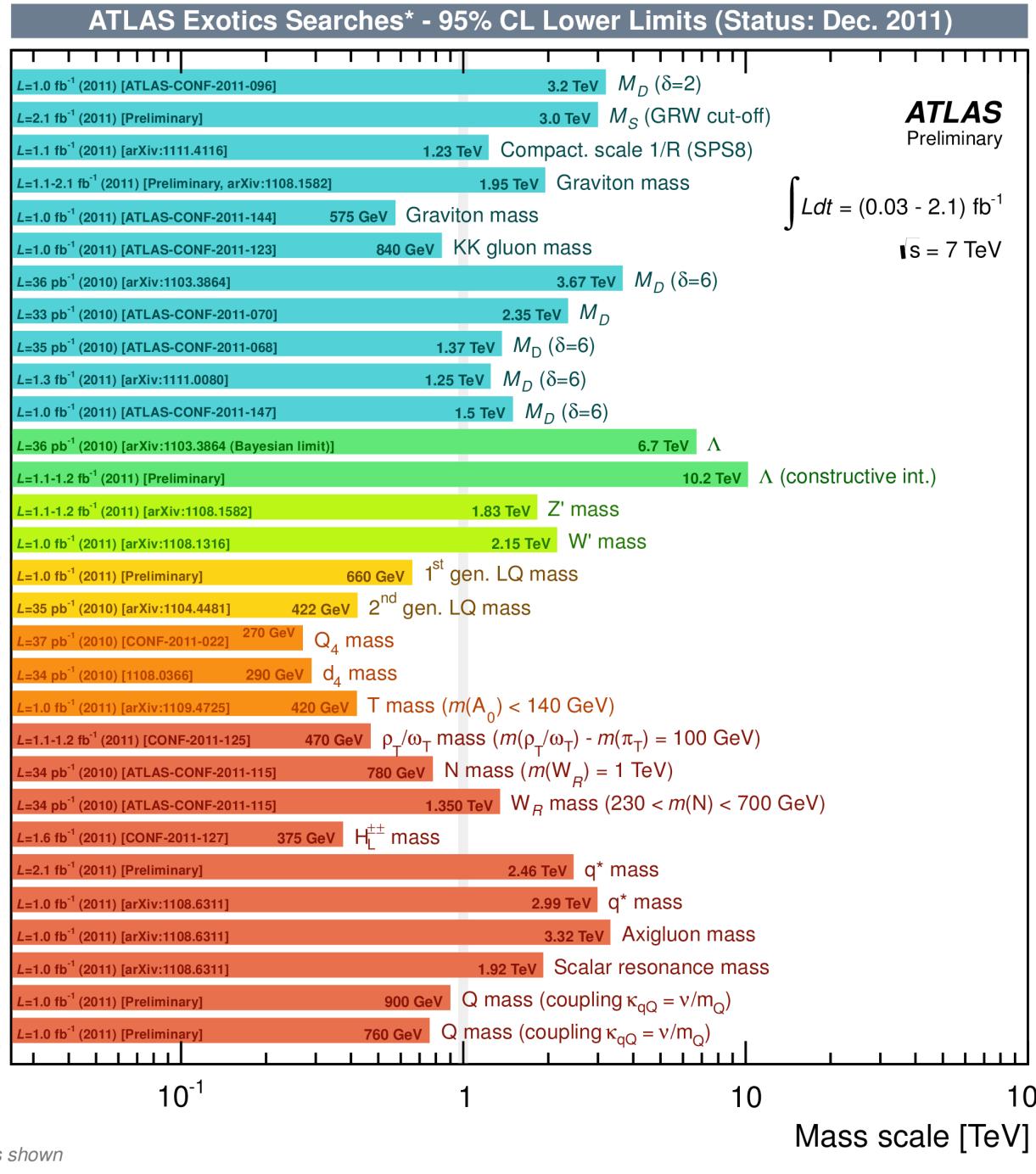
C/

V

LQ

4-th gen

Other

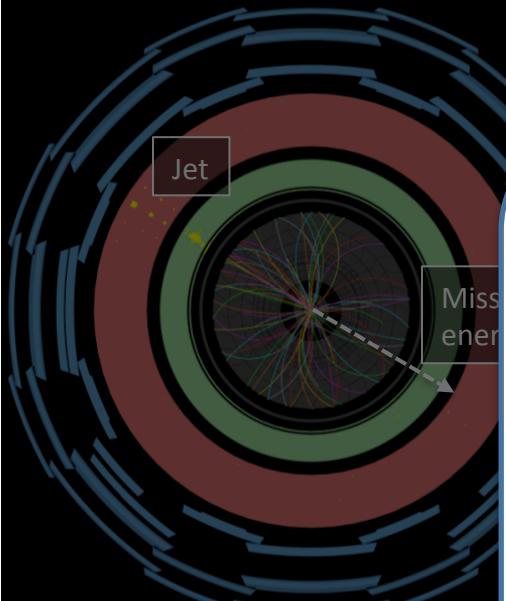


*Only a selection of the available results leading to mass limits shown

Going after the Dark at the LHC

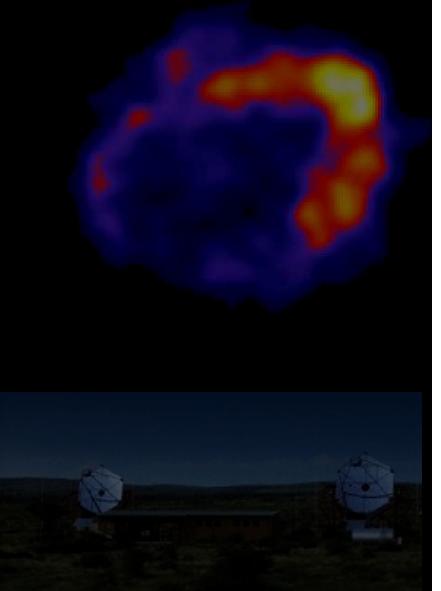
David Berge (CERN)

Supernova remnant RX J1713



ATLAS mono-jet event display

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



H.E.S.S. experiment

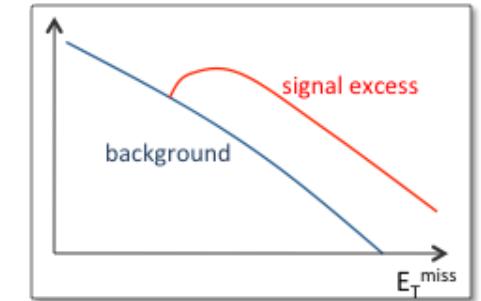
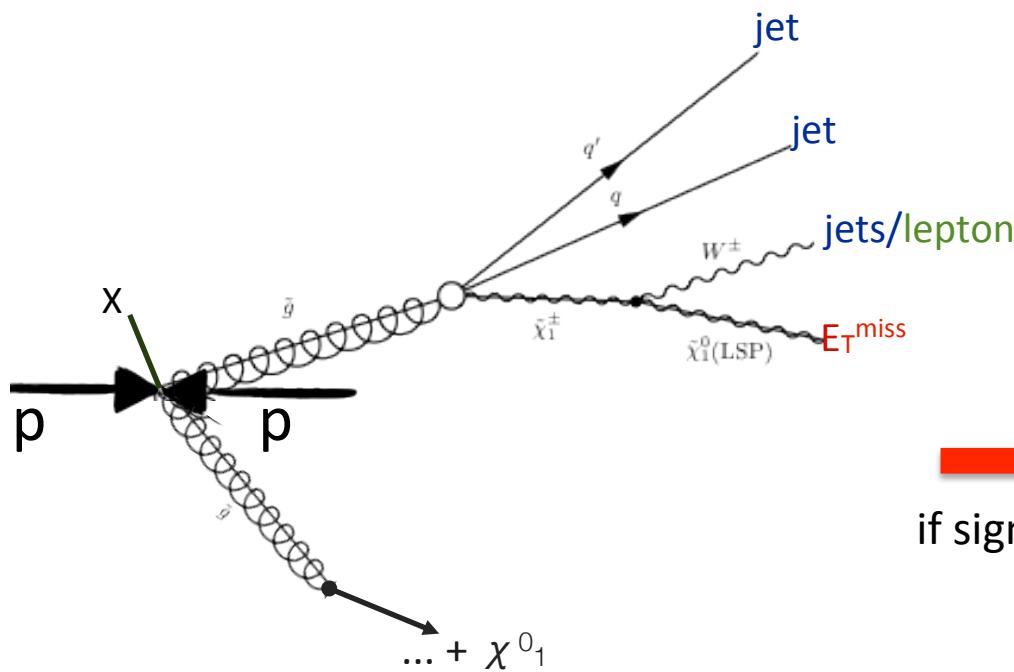


Galaxy cluster Abell 2744

1: “Standard” Dark Matter Searches at Colliders

16

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 detection]

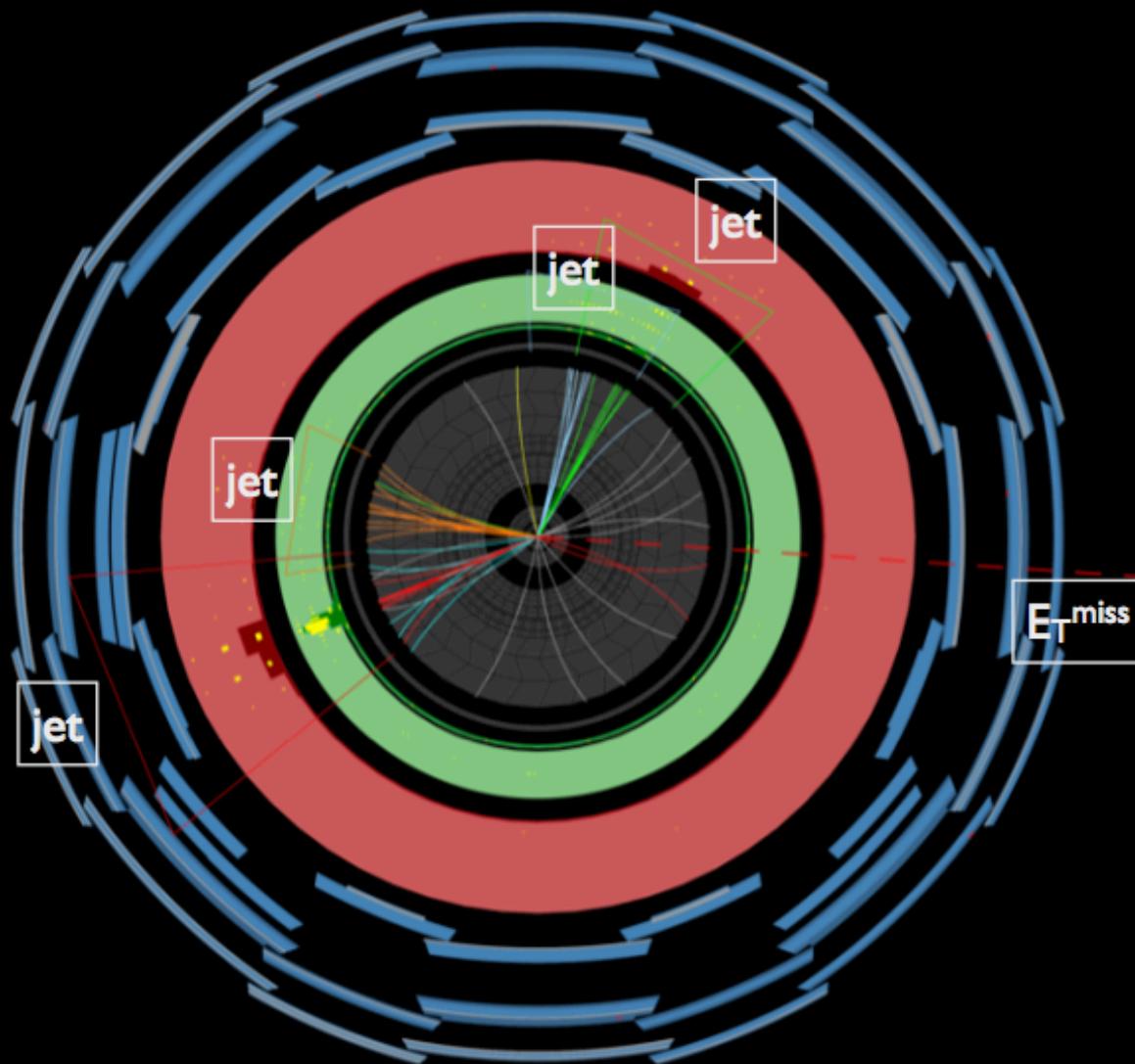
if signal

Measure spectra,
kinematic endpoints,
model fits, etc

Number of invisibles
Mass scale of invisibles
Spin

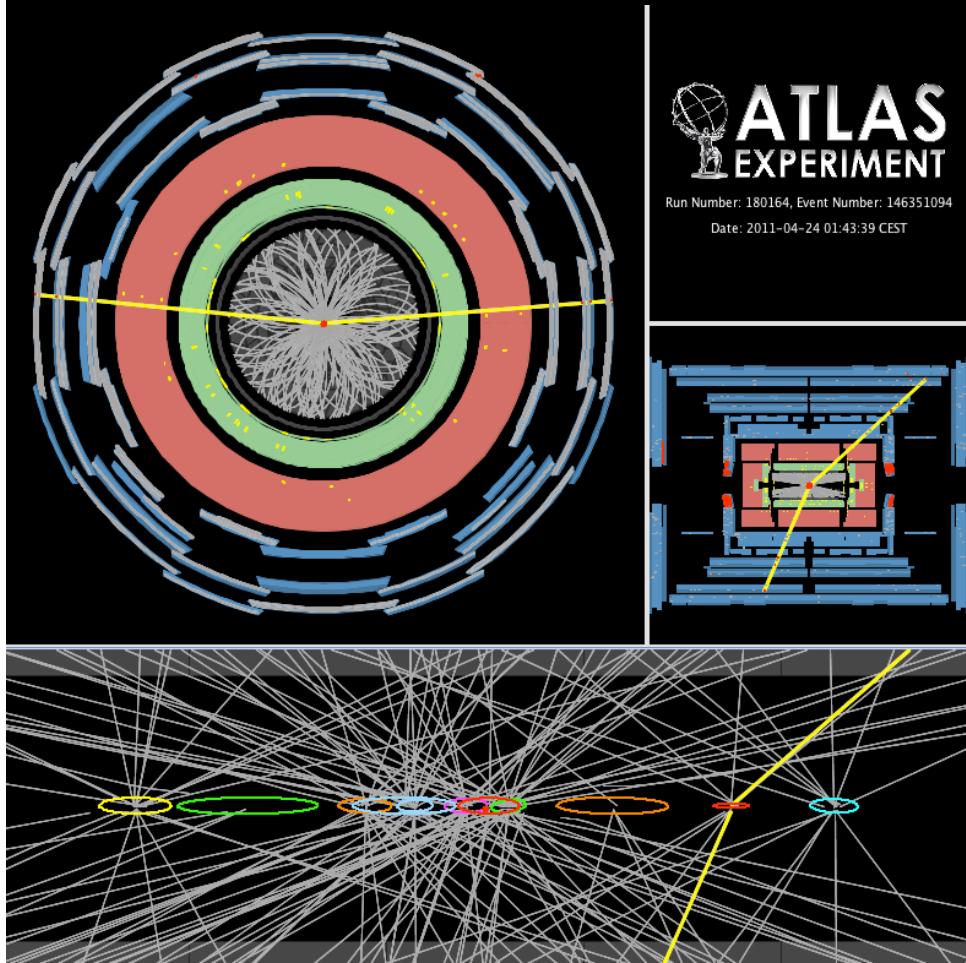
Task: measure transverse energy

17

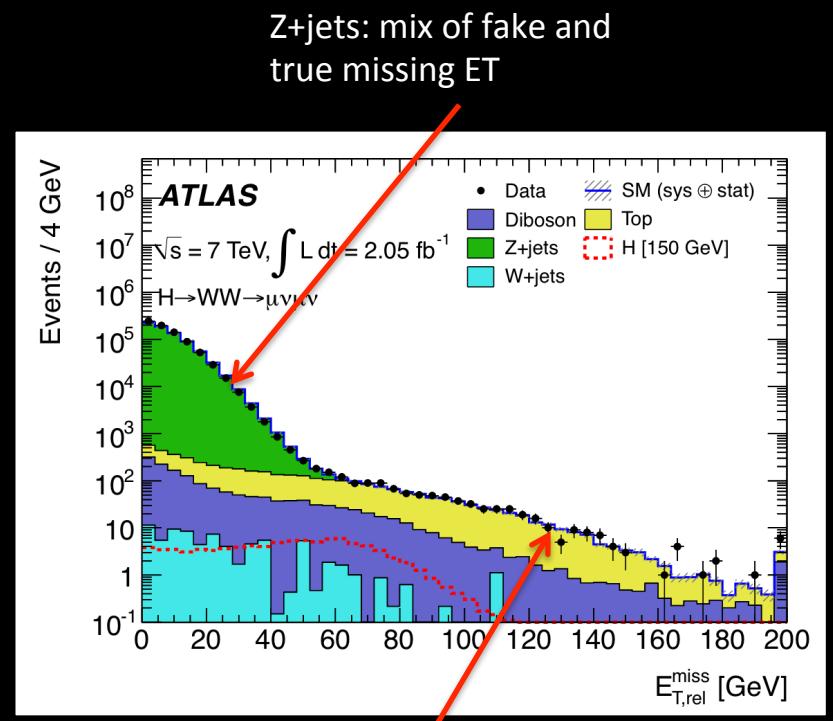


Difficulty: event pile-up

18



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

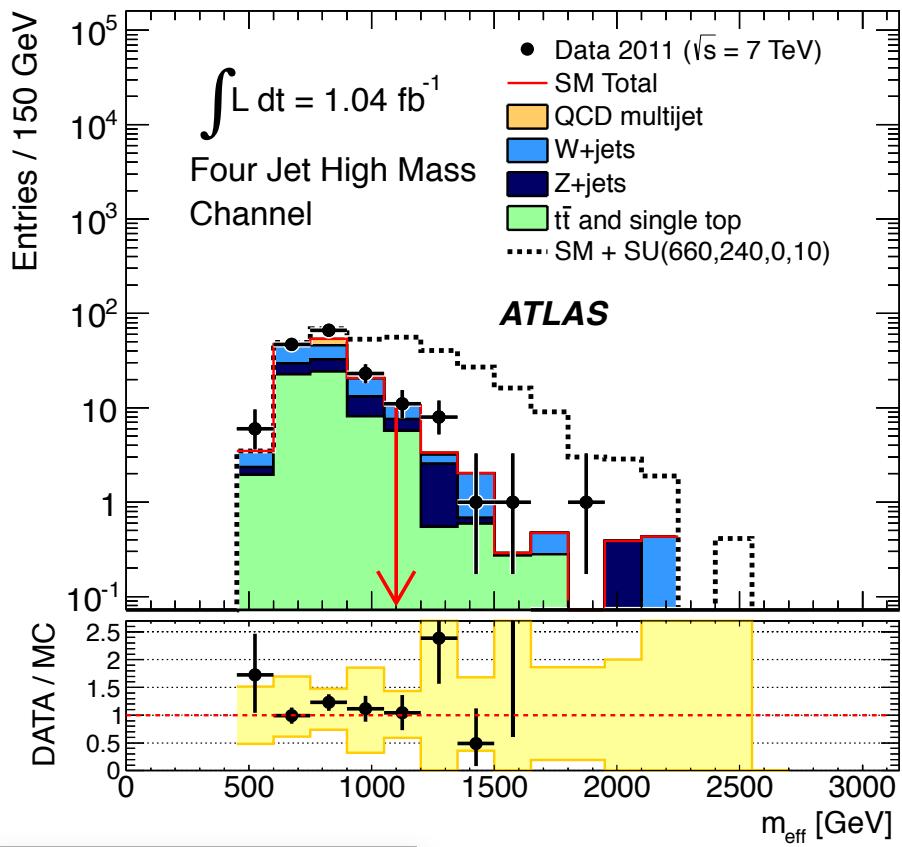


Top quark pairs: genuine missing ET from real ν's

Searches for strongly produced squarks and gluinos

... do not yet reveal a signal

19



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

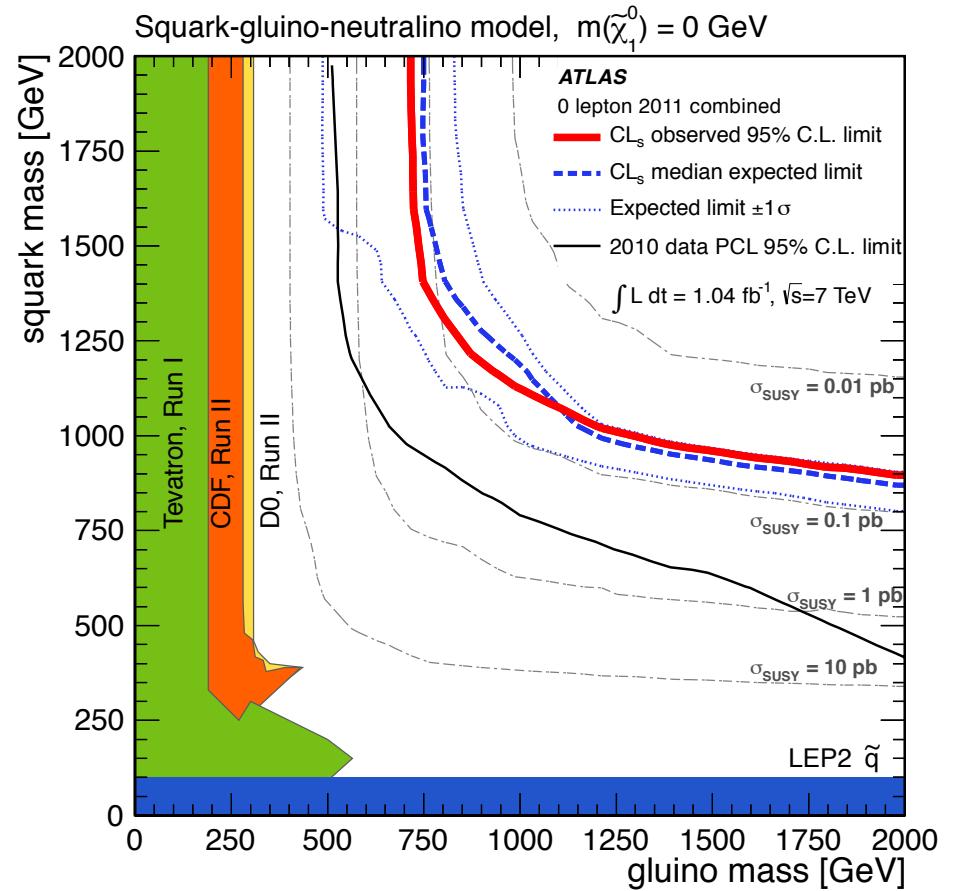
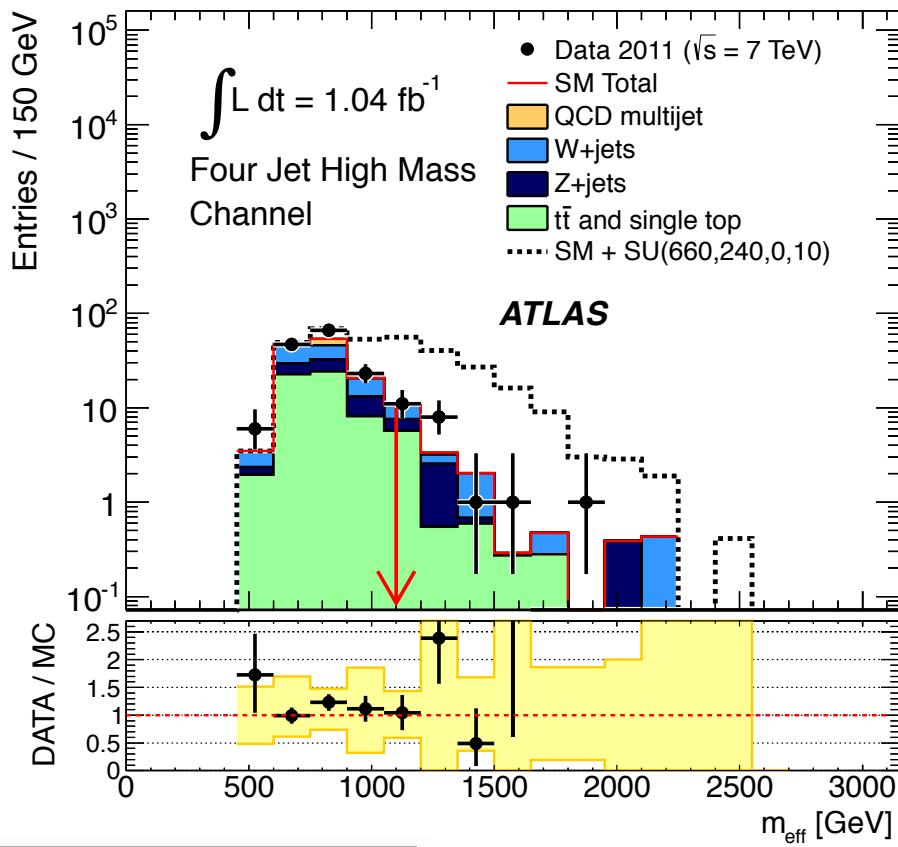
Can translate into limit on SUSY mass scale

arXiv:1109.6572

Searches for strongly produced squarks and gluinos

... do not yet reveal a signal

20



arXiv:1109.6572

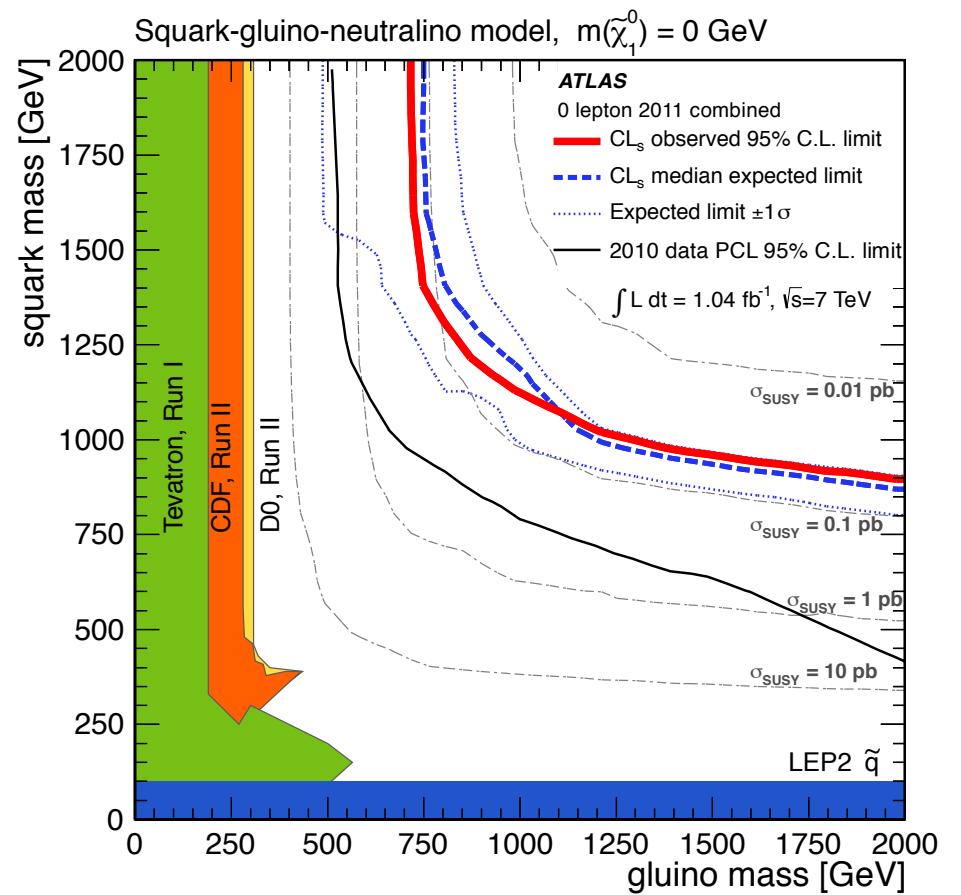
Searches for strongly produced squarks and gluinos

... do not yet reveal a signal

21

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

- $m(\tilde{q}) \approx m(\tilde{g}) < 1 \text{ TeV}$
- $m(\tilde{q}) < 875 \text{ TeV} (\forall m(\tilde{g}) < 2 \text{ TeV})$
- $m(\tilde{g}) < 700 \text{ TeV} (\forall m(\tilde{q}) < 2 \text{ TeV})$



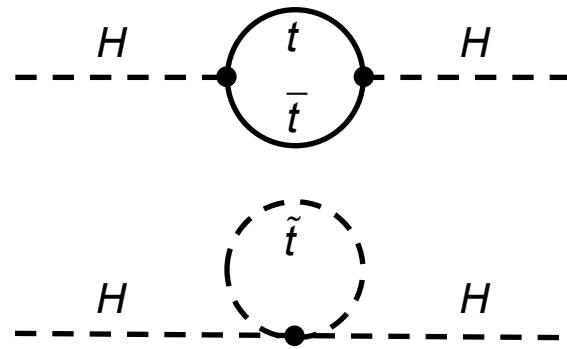
arXiv:1109.6572

Does SUSY hide from our analyses?

22

How could strong SUSY production exist but be hidden?

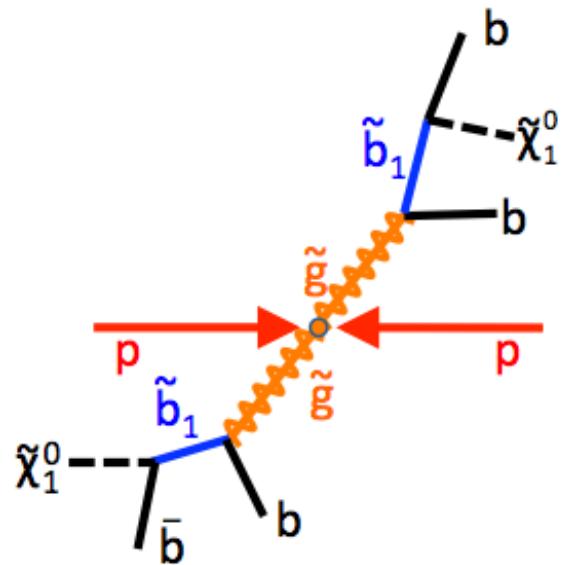
Recall: we need to cancel the Higgs virtual corrections. Most important is top loop



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:

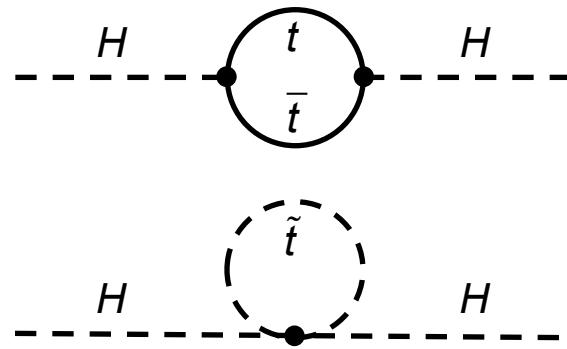


Does SUSY hide from our analyses?

23

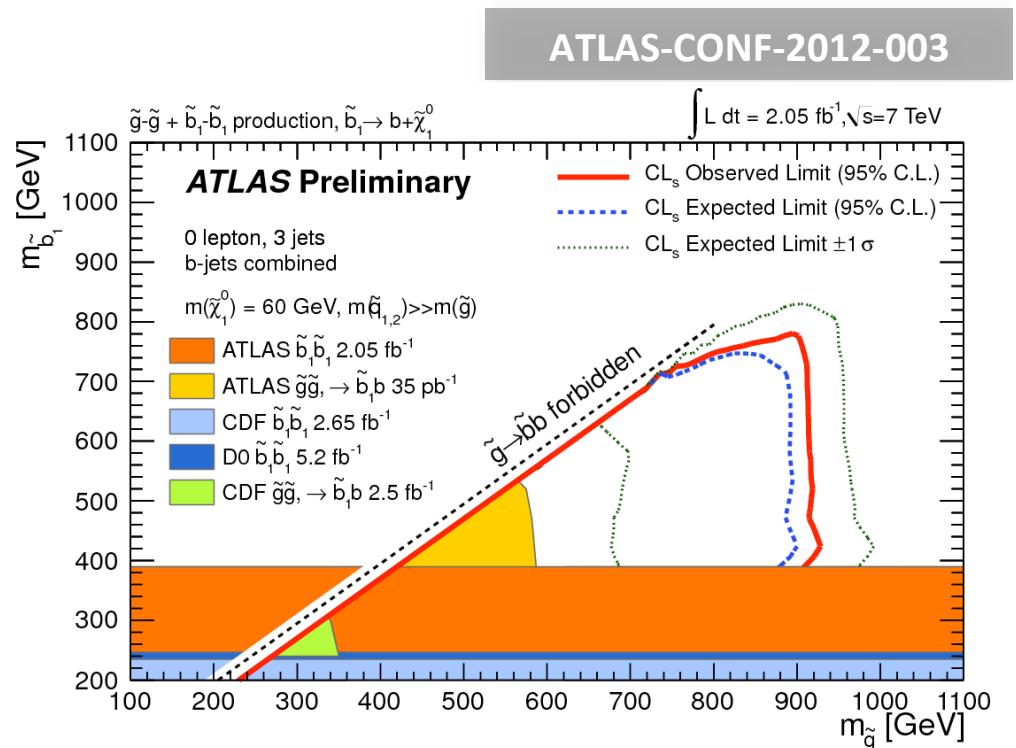
How could strong SUSY production exist but be hidden?

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?



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

Does SUSY hide from our analyses?

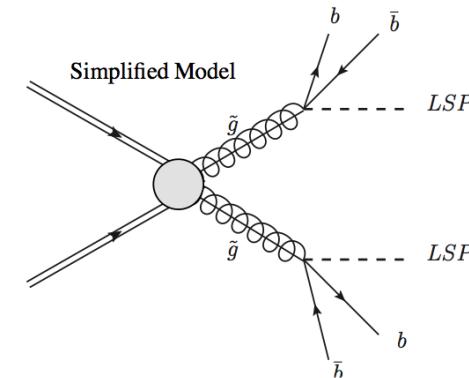
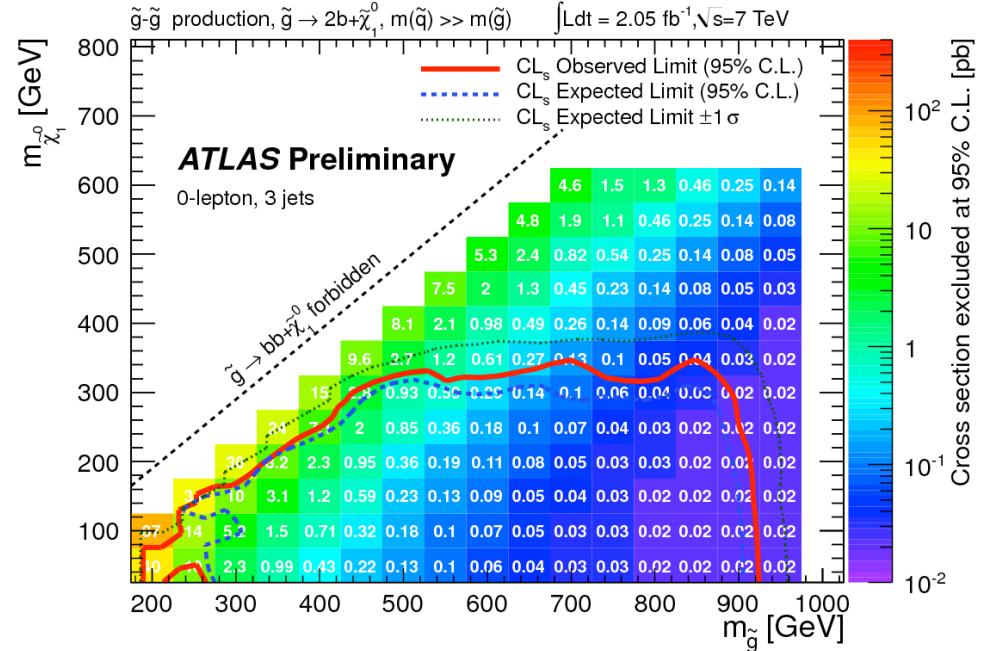
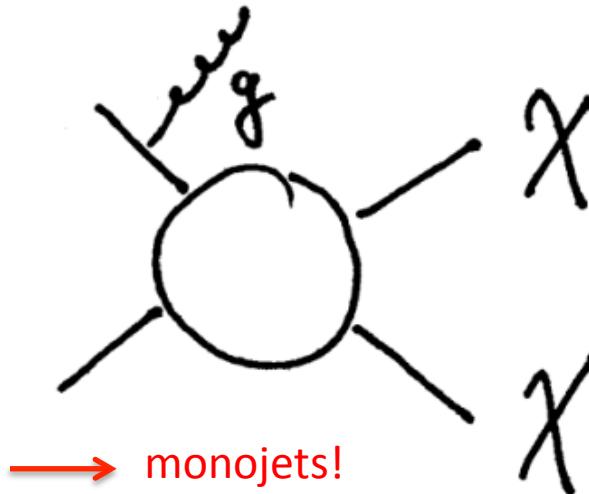
24

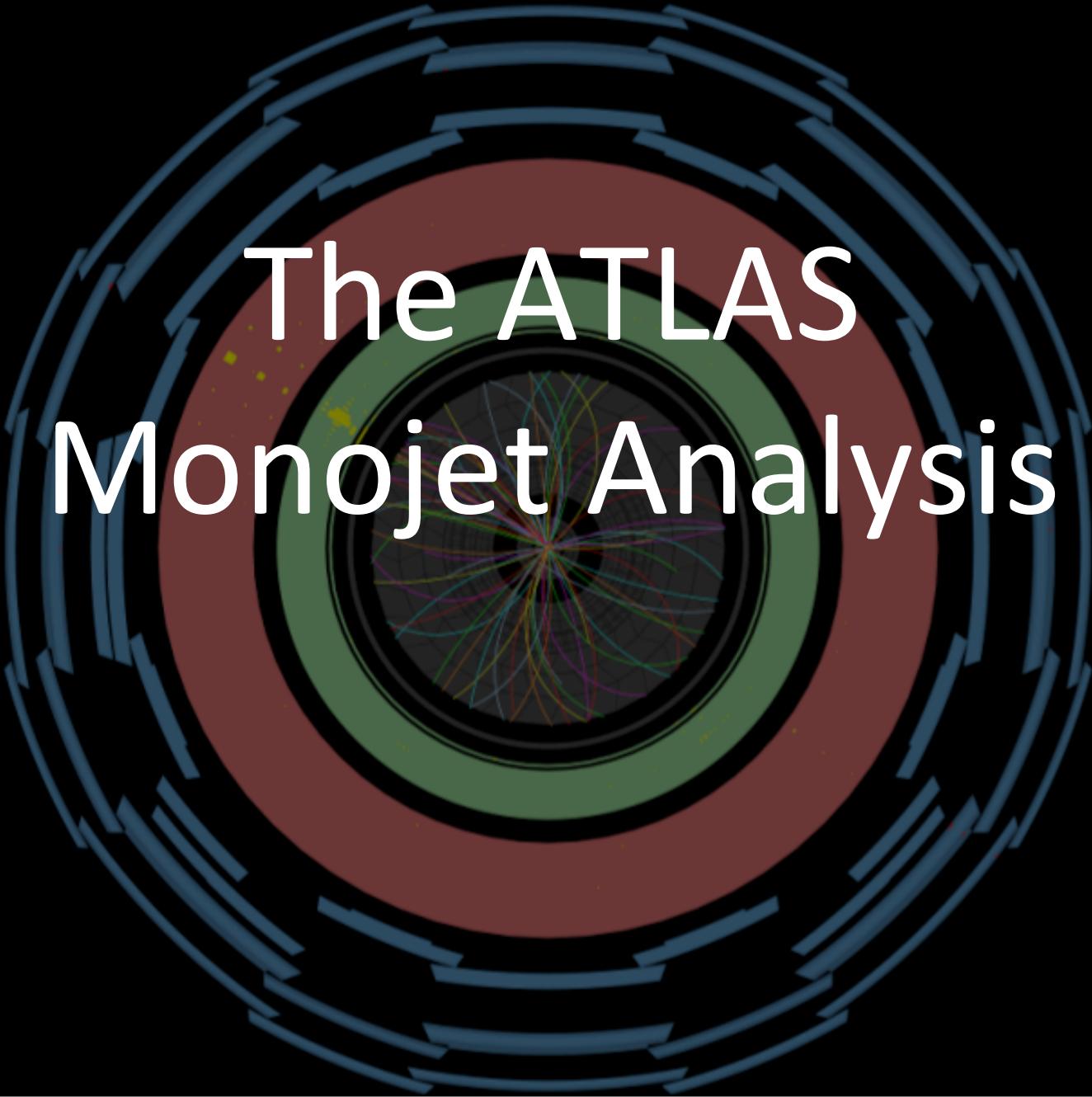
How could strong SUSY production exist but be hidden?

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?

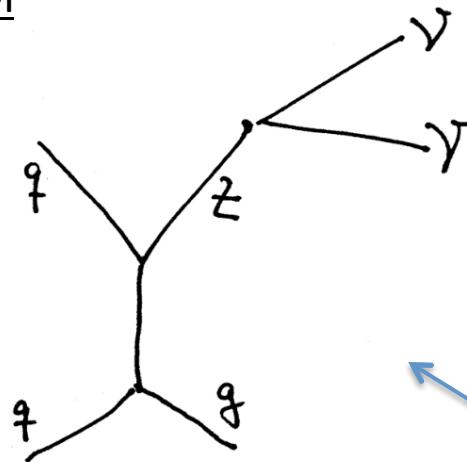
Maybe squarks and gluinos are all too heavy and only neutralinos (WIMPs) are produced?



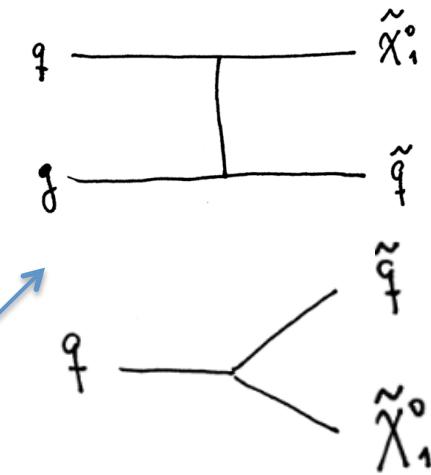
A circular diagram representing the ATLAS detector's endcap. It features concentric rings of blue curved arrows pointing clockwise, set against a black background. Inside these are three colored rings: red, green, and blue, which are slightly offset from each other. The center of the diagram is a dark gray circle containing several colored lines (red, green, blue) that radiate outwards, resembling particle trajectories.

The ATLAS Monojet Analysis

SM



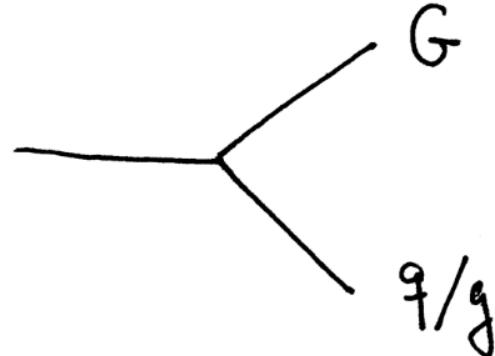
SUSY



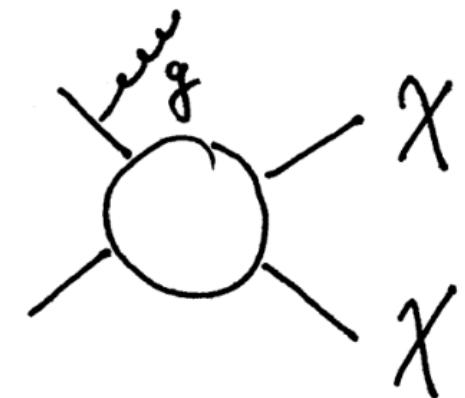
26

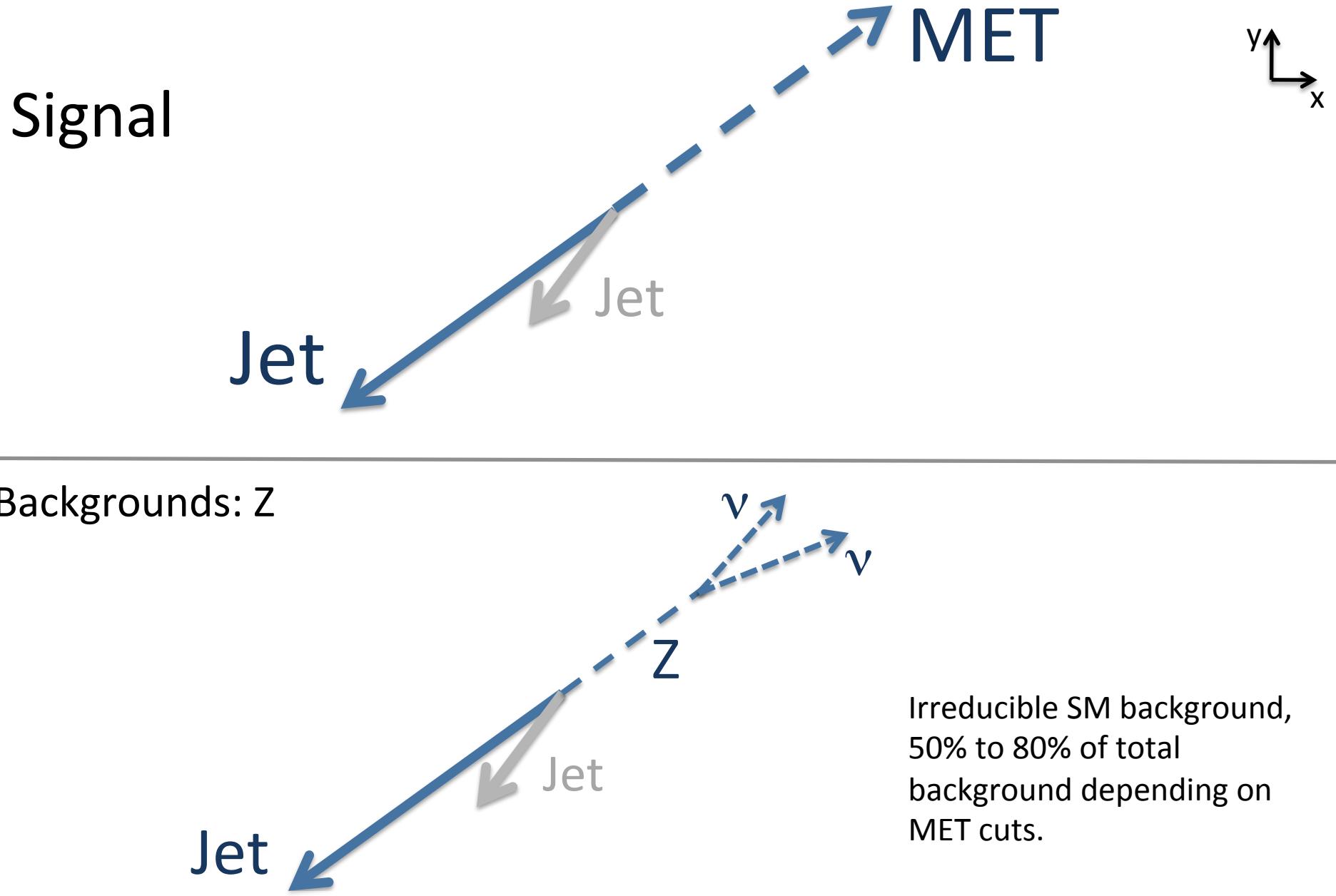
Monojets

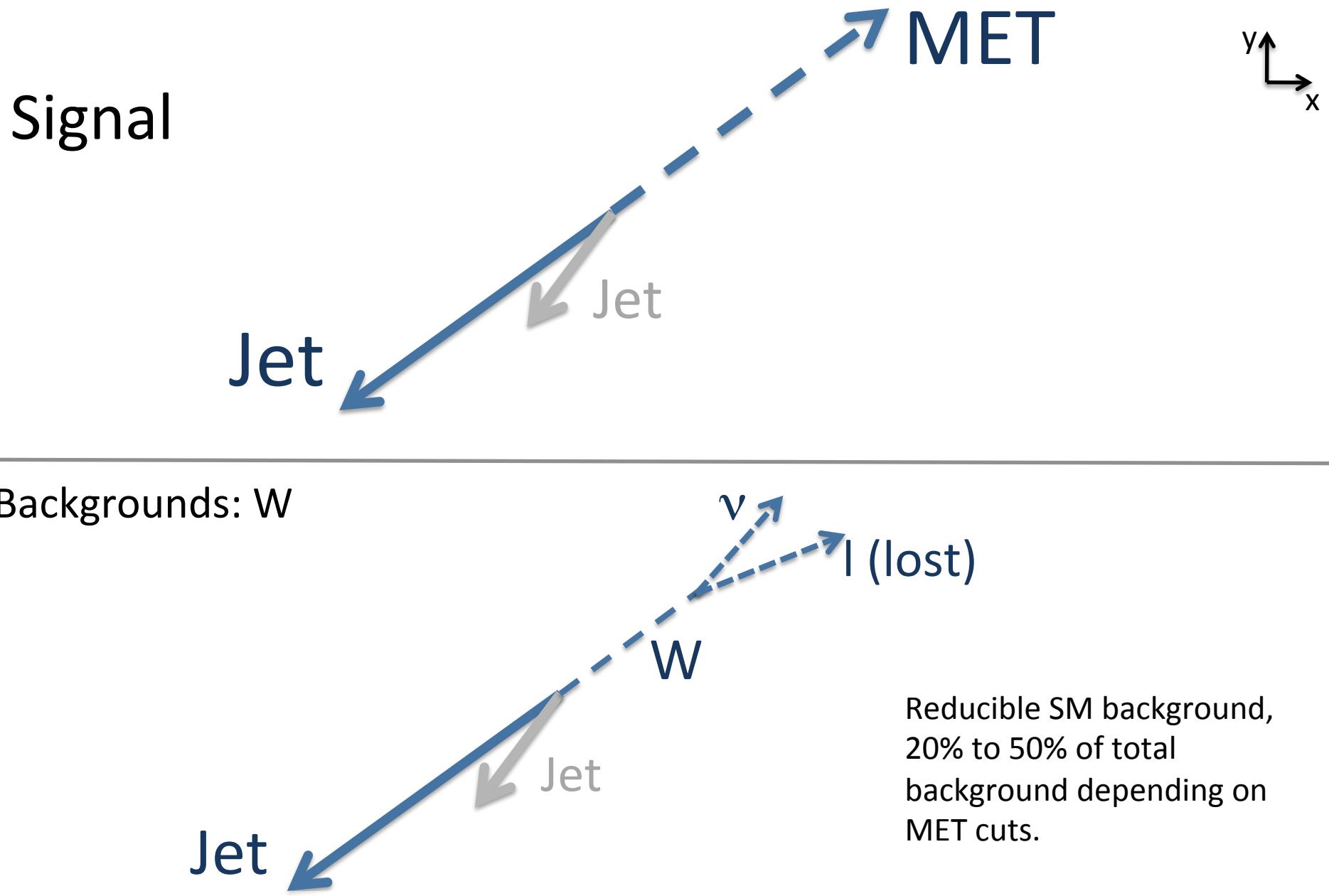
Large Extra Dimensions



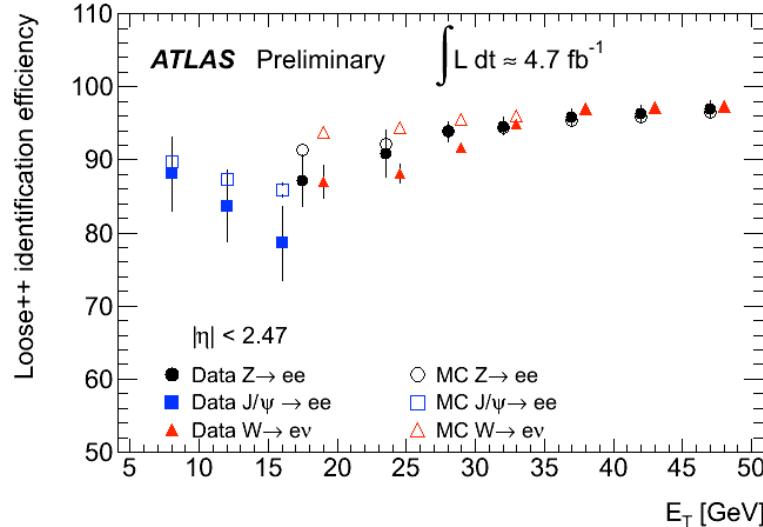
WIMP Pairs



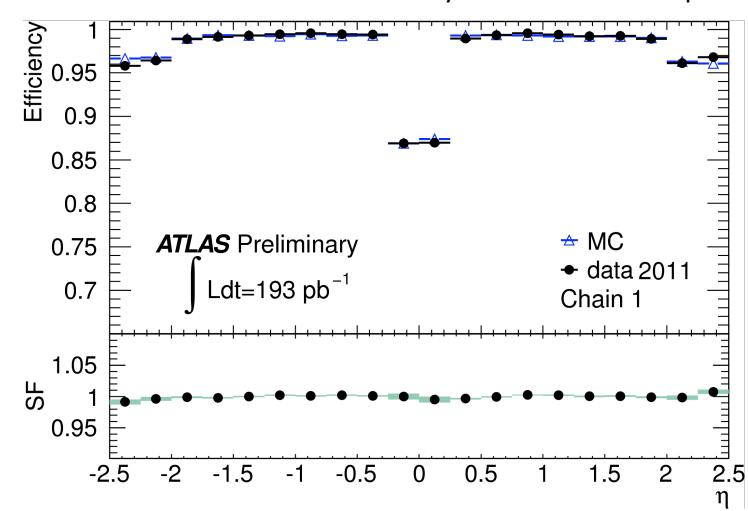




Electron reconstruction efficiency within the detector acceptance!

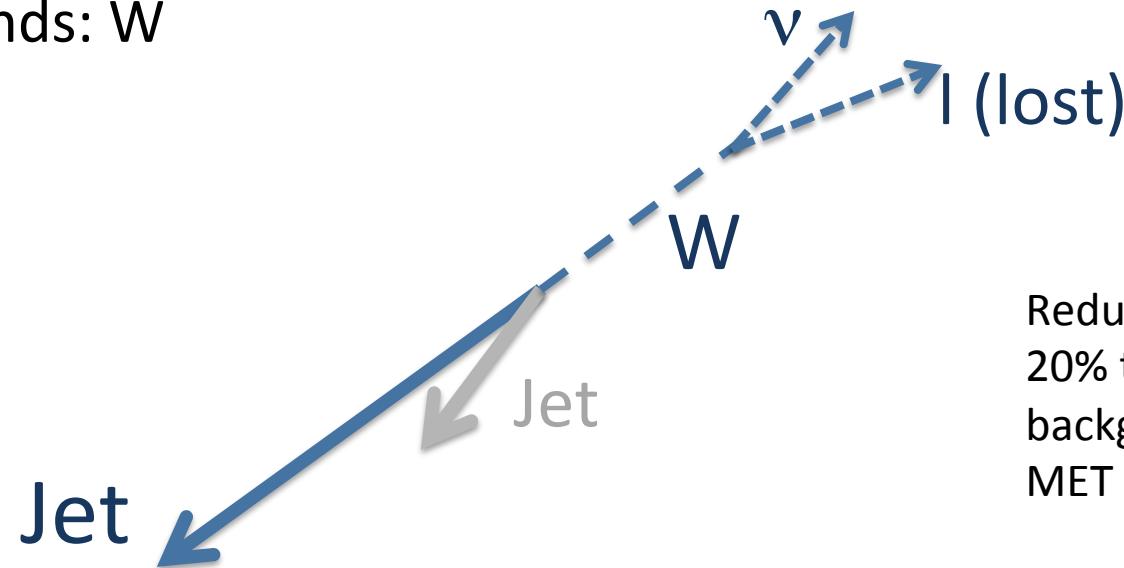


Muon reconstruction efficiency with detector acceptance

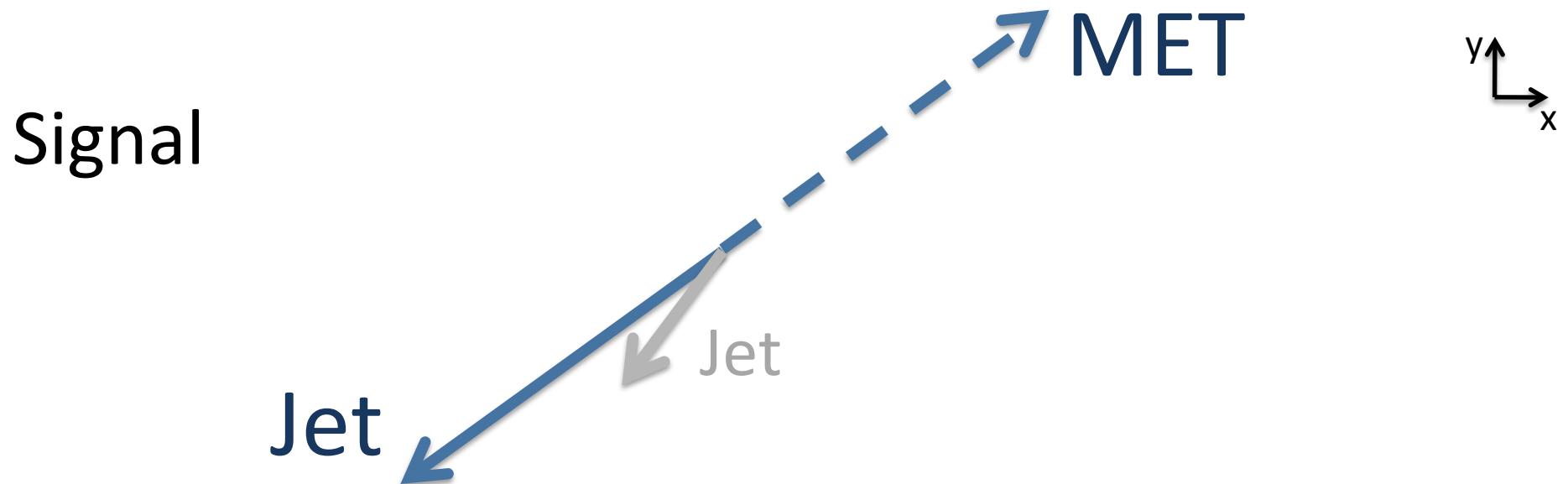


Both electrons and muons are efficiently reconstructed within the detector coverage!

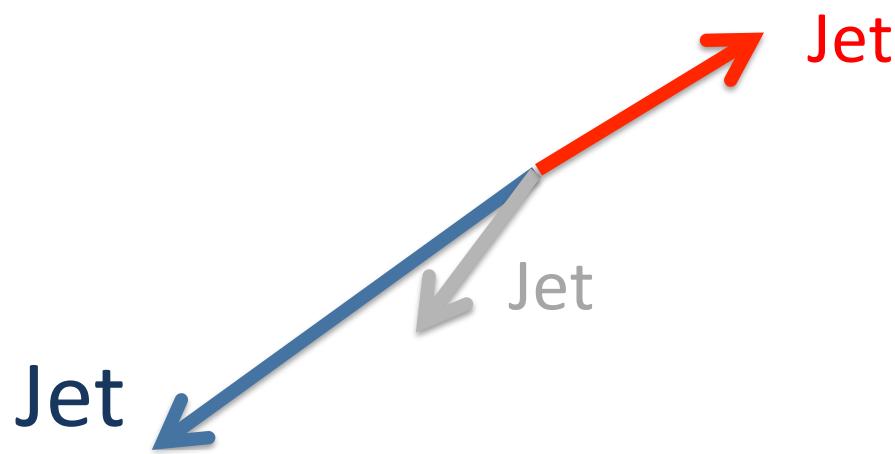
Backgrounds: W



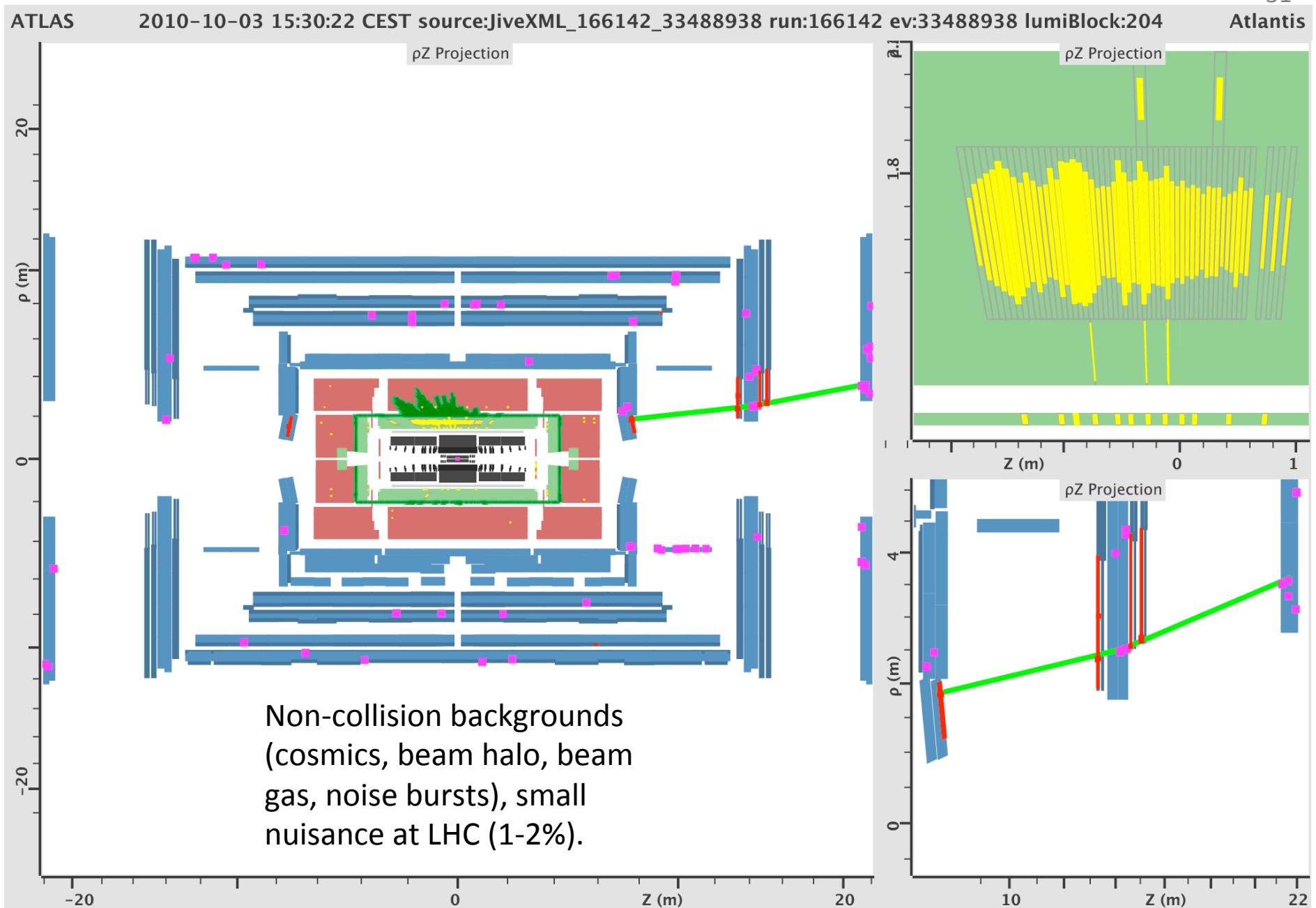
Reducible SM background,
20% to 50% of total
background depending on
MET cuts.

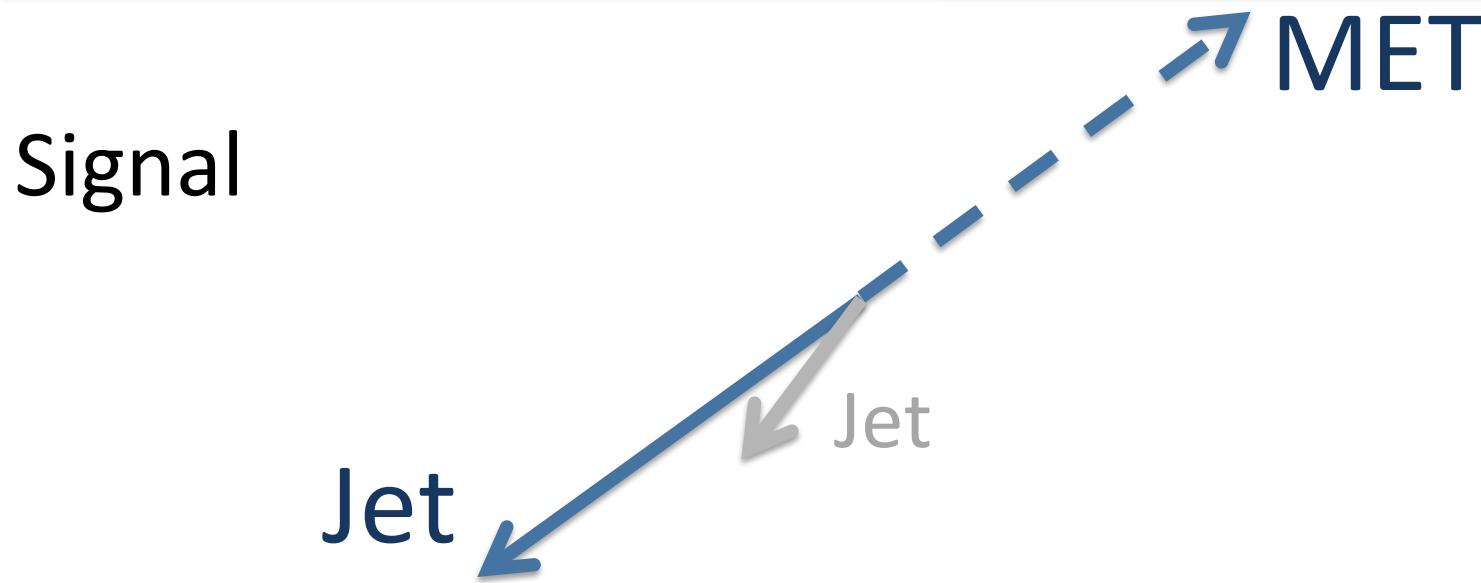


Backgrounds: multijets



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



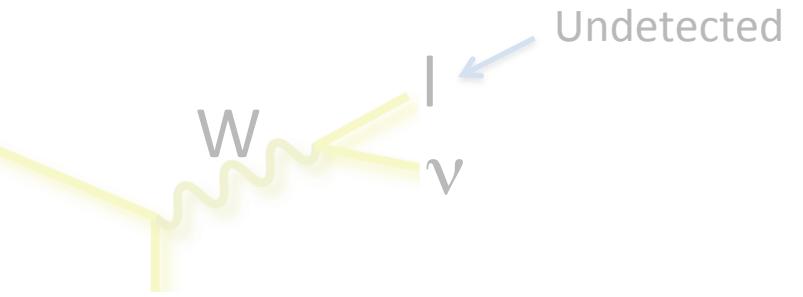


- 2010 (35pb^{-1}) and first part of 2011 (1 fb^{-1}) public
 - 5 fb^{-1} analysis released soon
- Simple selection strategy:
 - Large missing ET
 - One and only one high p_T jet
 - Check for excess beyond Standard Model backgrounds
 - Do this for a number (**MET** | **jet**) cuts (in GeV): (**120**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

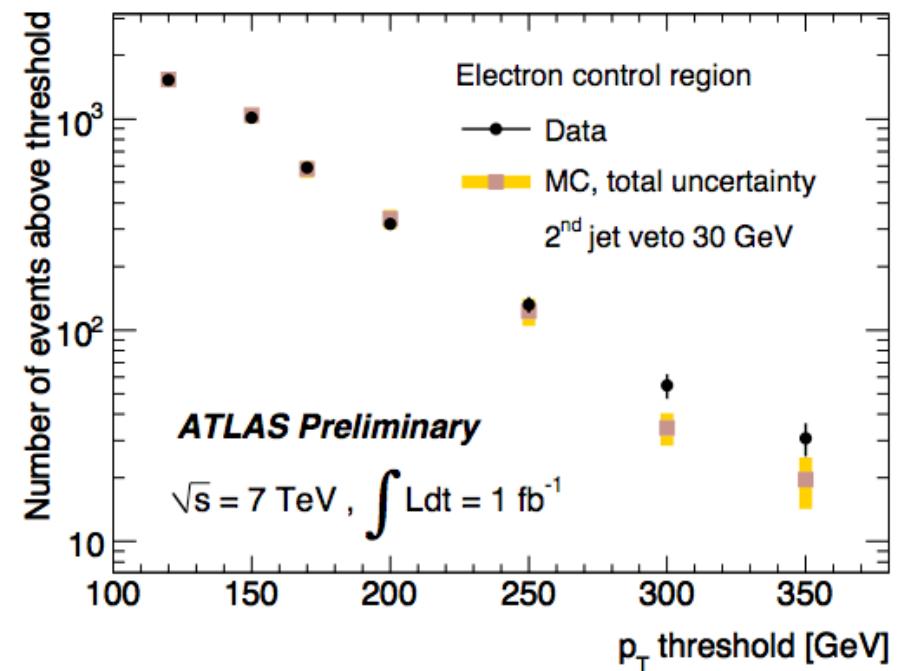
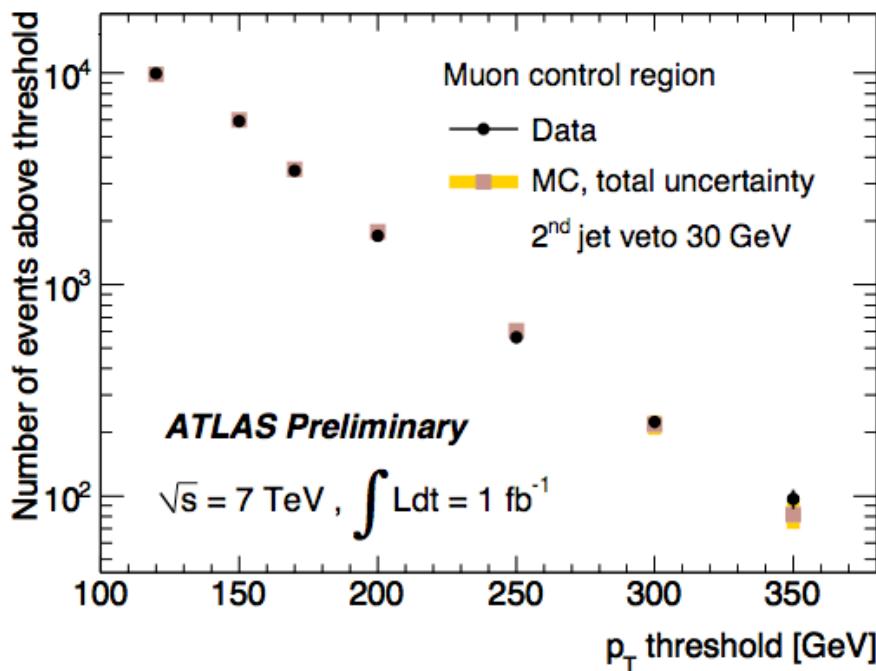
Electroweak Backgrounds

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Main backgrounds:

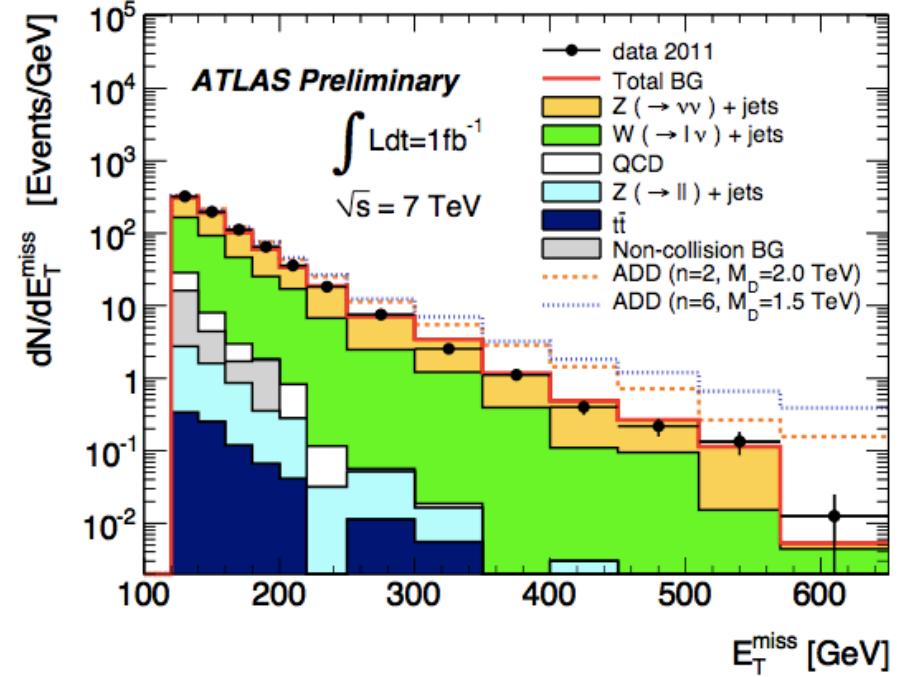
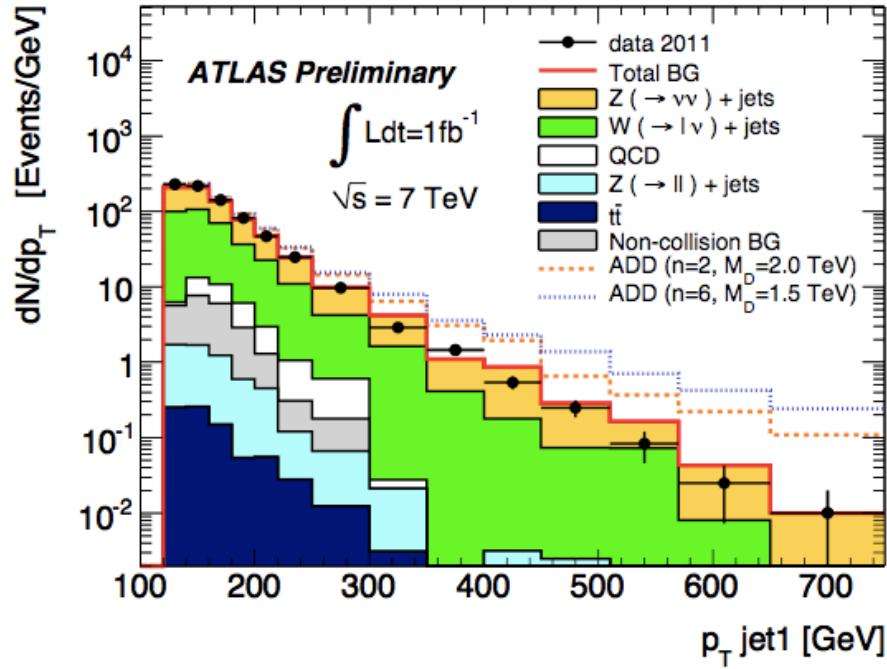


Control regions after scaling, data versus sum of MC:

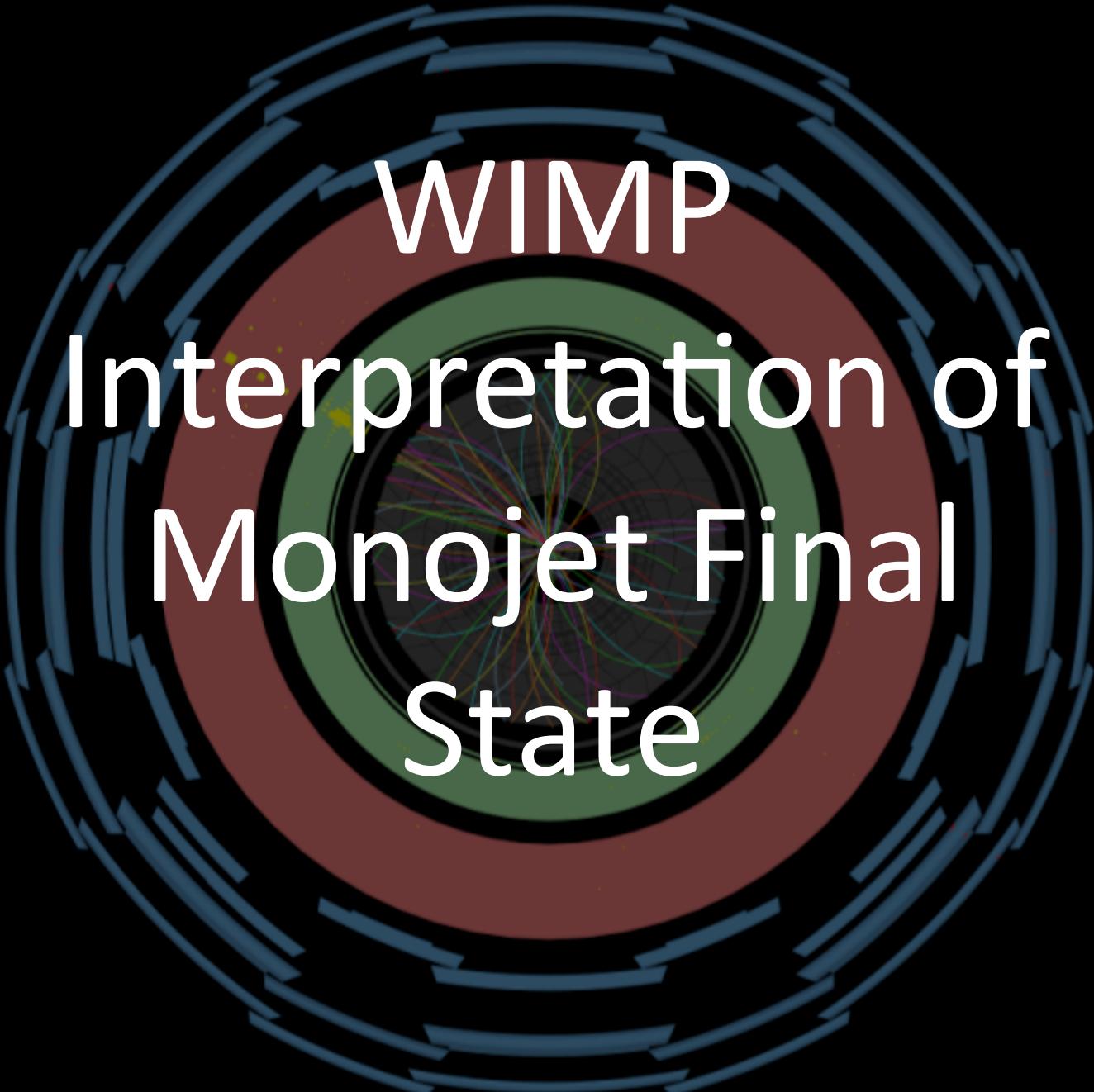


Results

34



The Standard Model holds tight...



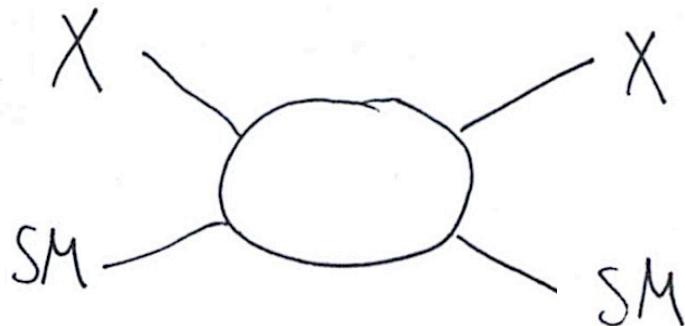
WIMP Interpretation of Monojet Final State

2: Generic WIMP Searches at Colliders

36

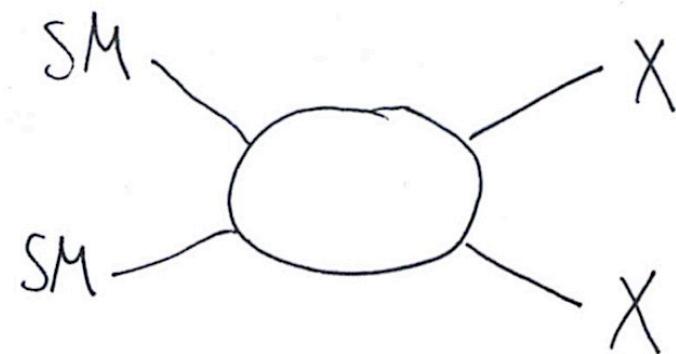
- Consider WIMP pair production at colliders, idea goes back to:
 - Birkedal et al (hep-ph/0403004)
 - Beltran et al: Maverick Dark Matter (hep-ph/1002.4137)
- Latest papers about ATLAS 1fb^{-1} result:
 - Fox et al, arxiv:1109.4398 (FNAL crew)
 - Rajamaran et al, arxiv:1108.1196 (UCI crew)
- All based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

Direct DM searches:



If this interaction exists...

Colliders:



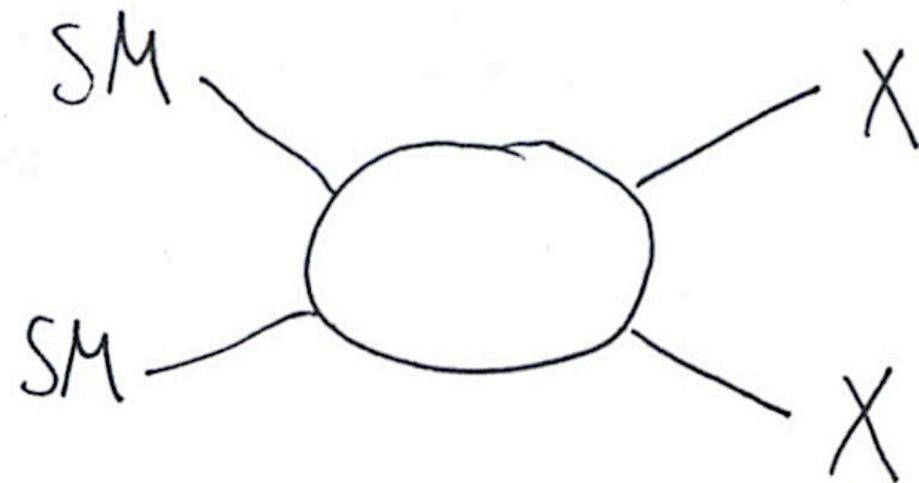
... this one must exist, too.
But can we see it?

Generic WIMP Searches at Colliders

37

Assume:

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

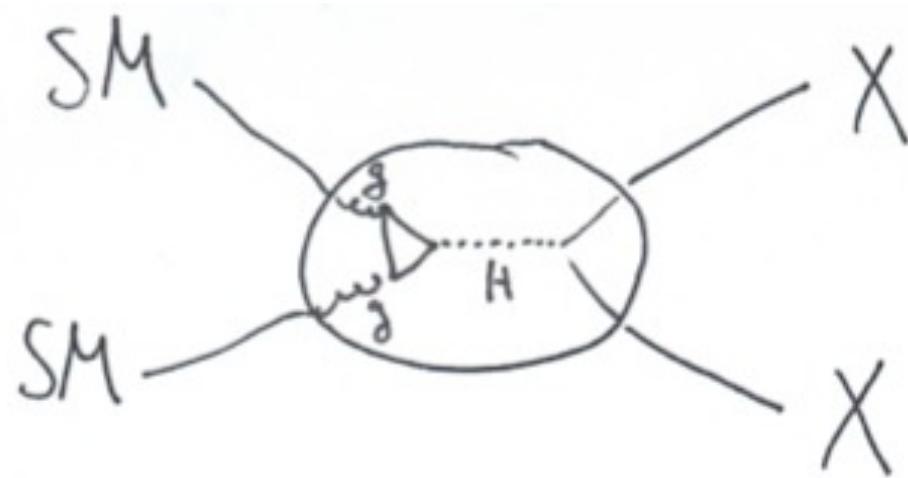


Generic WIMP Searches at Colliders

38

Assume:

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

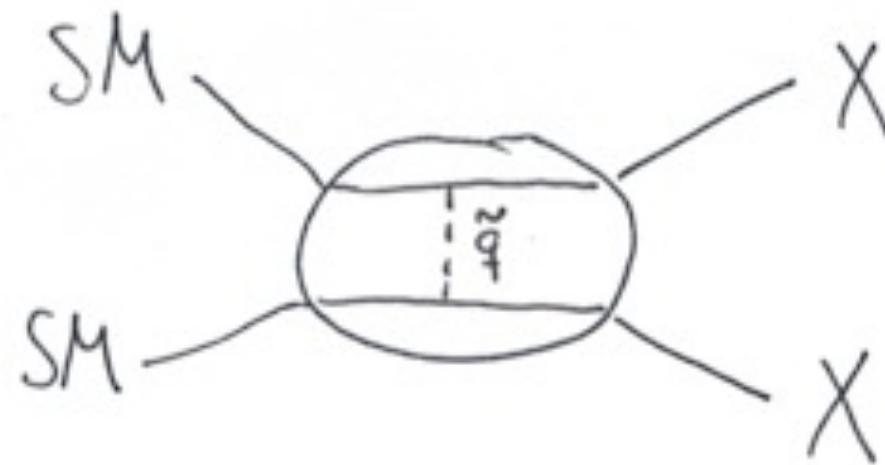


Generic WIMP Searches at Colliders

39

Assume:

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

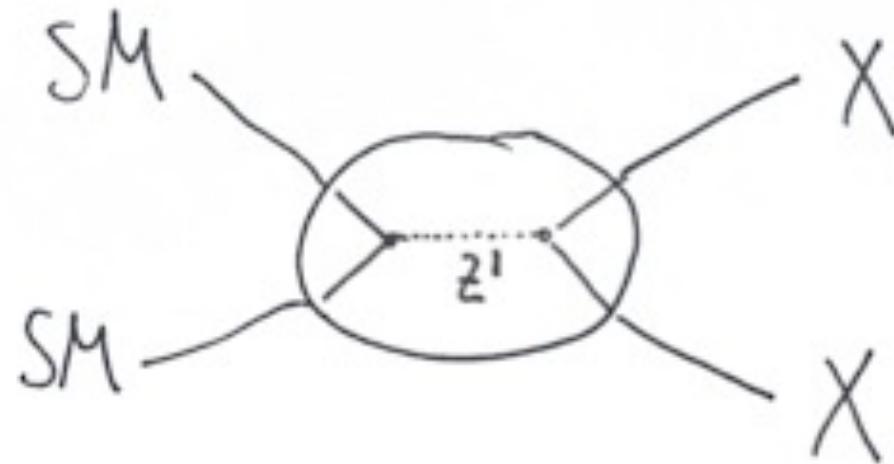


Generic WIMP Searches at Colliders

40

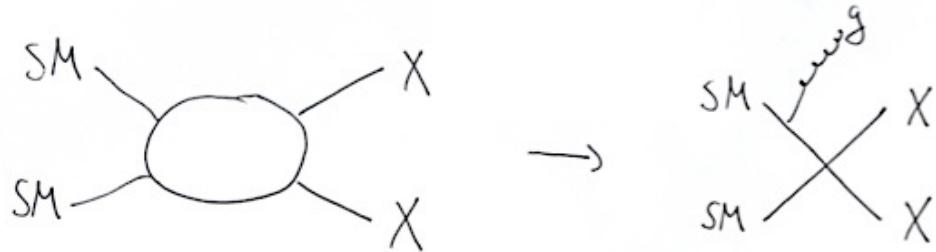
Assume:

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



Generic WIMP Searches at Colliders

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Assume:

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

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

$$G_{qij} \sim \frac{1}{\Lambda^n}$$

$$\Lambda = \frac{M_Z}{g_{q.X}}$$

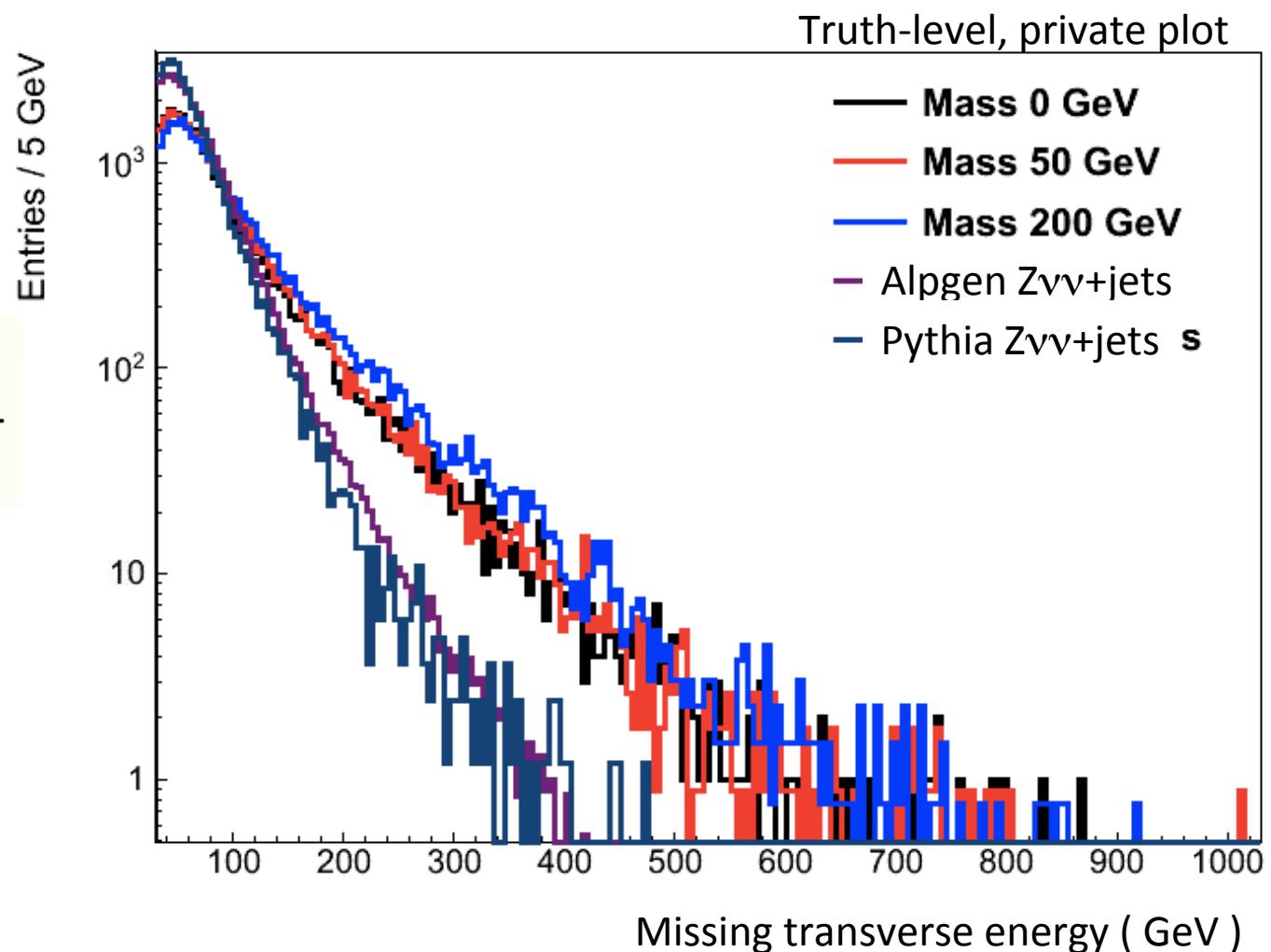
Cutoff scale

Expected signal missing ET distributions

42

- Take vector operator as example

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



Expect harder MET spectrum even for $m_\chi = 0$ GeV!

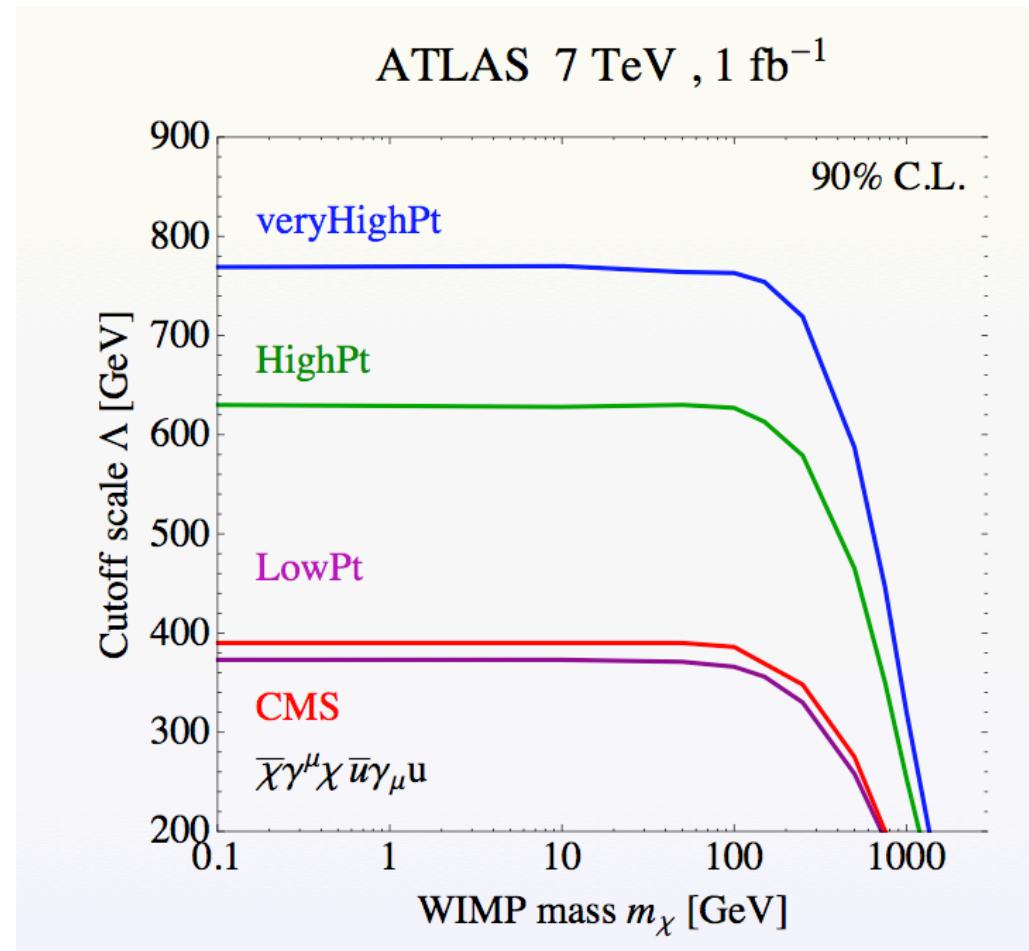
Limits on suppression scale Λ

43

- 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

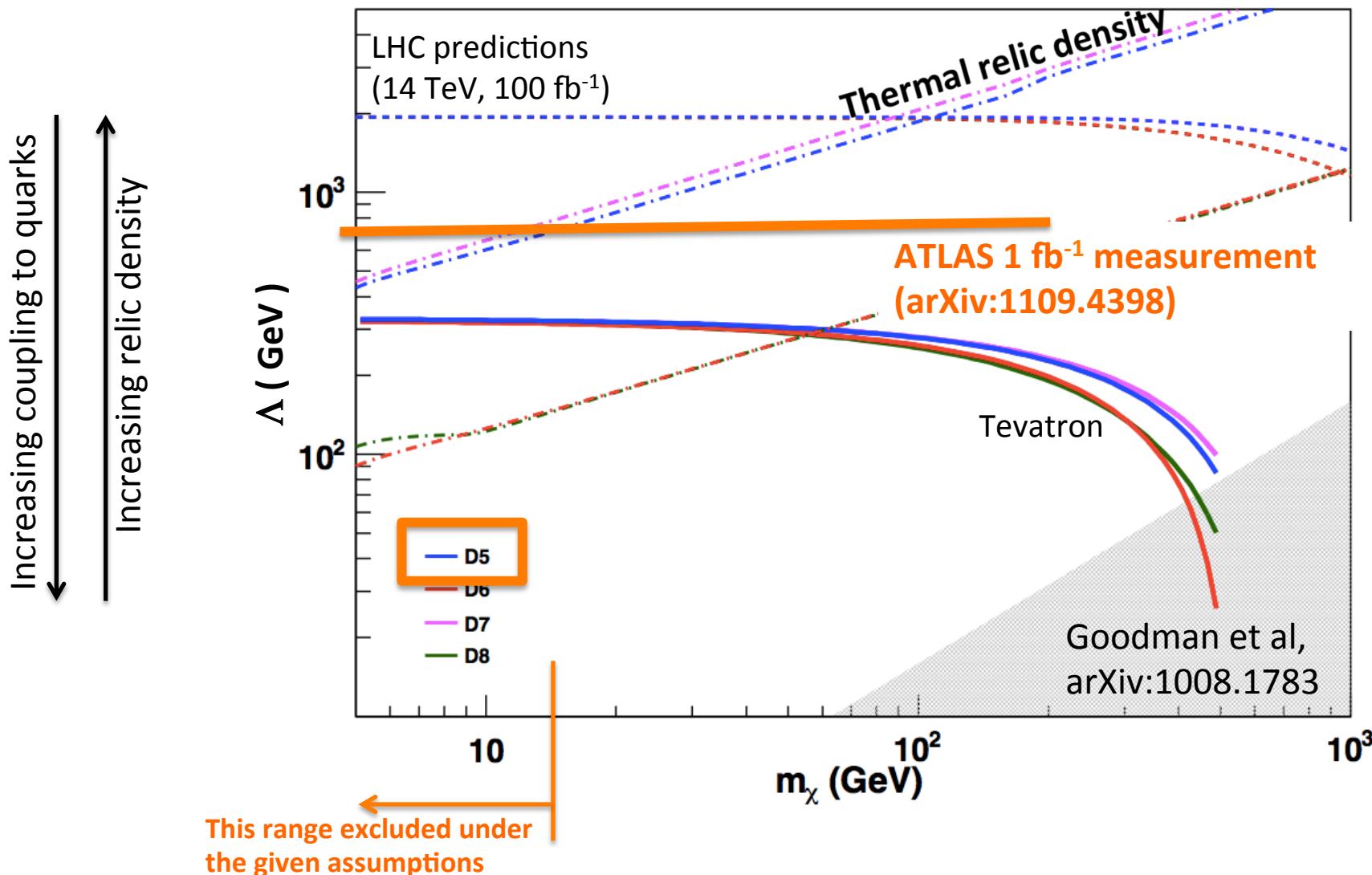


arXiv:1109.4398

Limits on suppression scale Λ

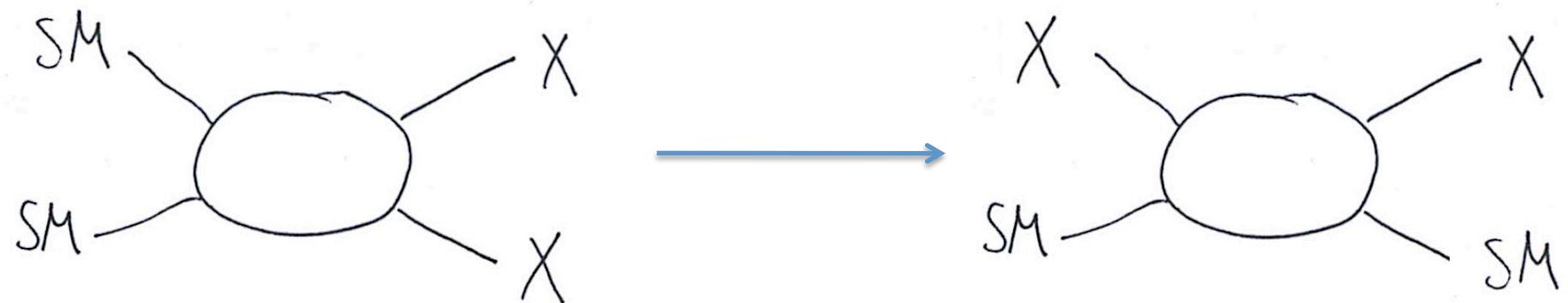
44

Compare to values of Λ consistent with thermal relic density



Limits in “direct-detection plane”

45



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

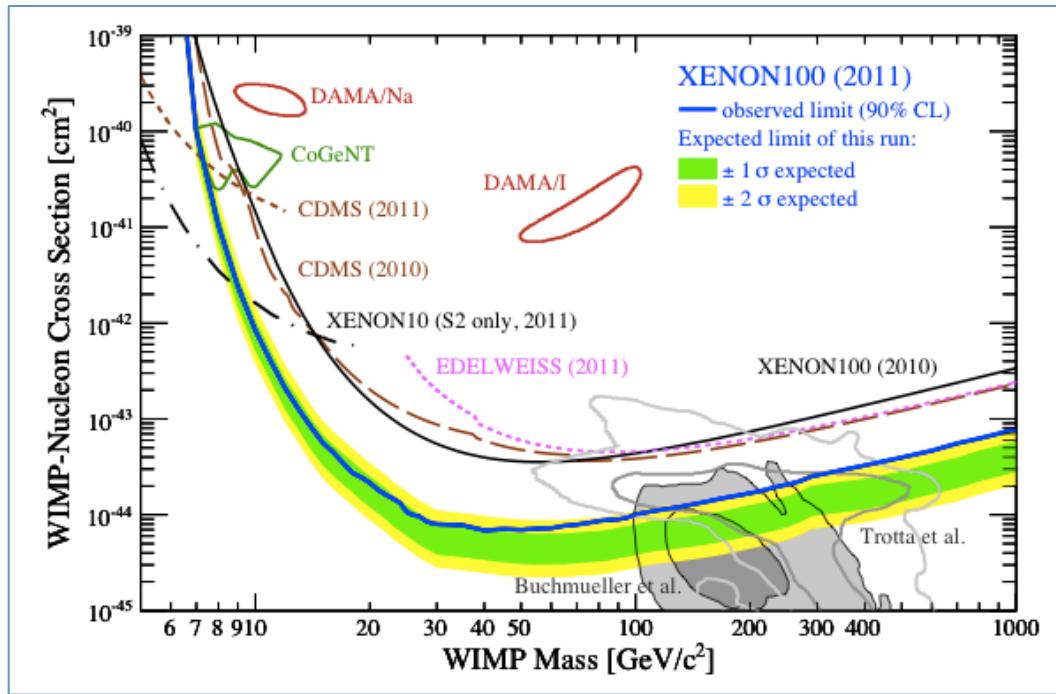
Caveats:

- 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”

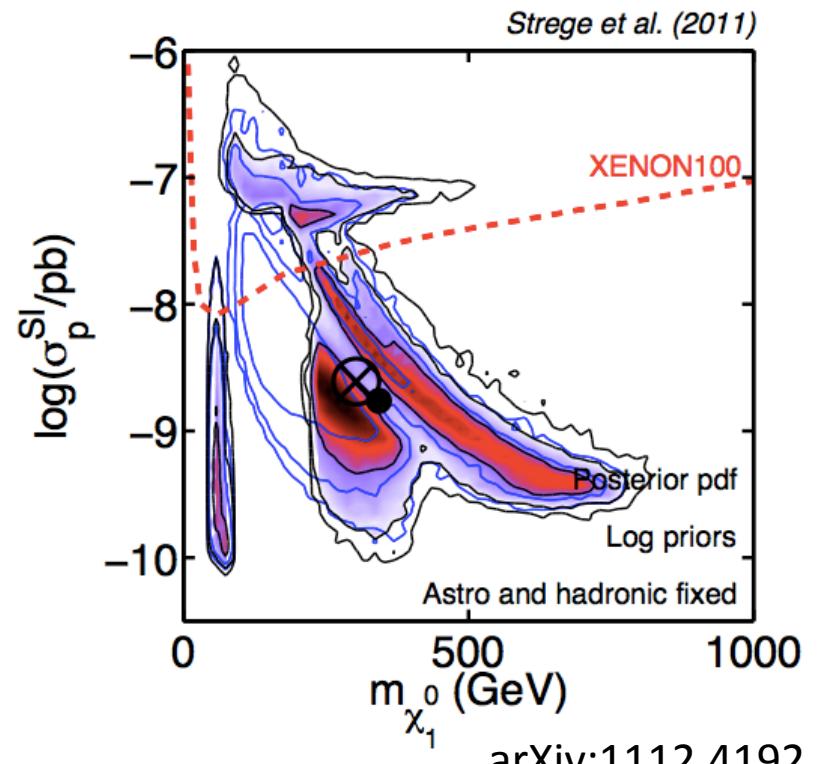
46

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



arXiv:1104.2549

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

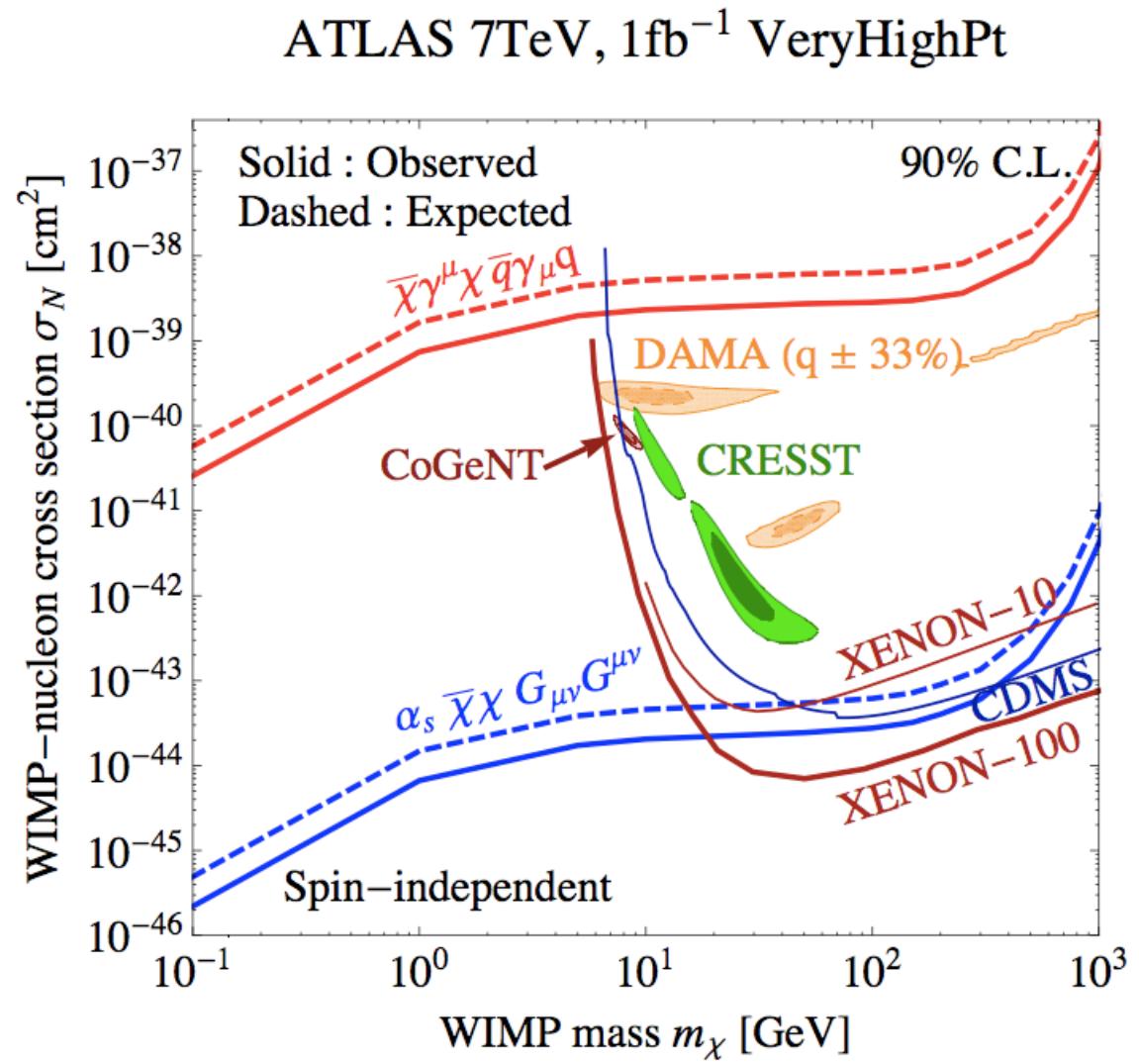


arXiv:1112.4192

One way of transferring LHC data!

Spin independent Nucleon-WIMP scattering cross section⁴⁷

- 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

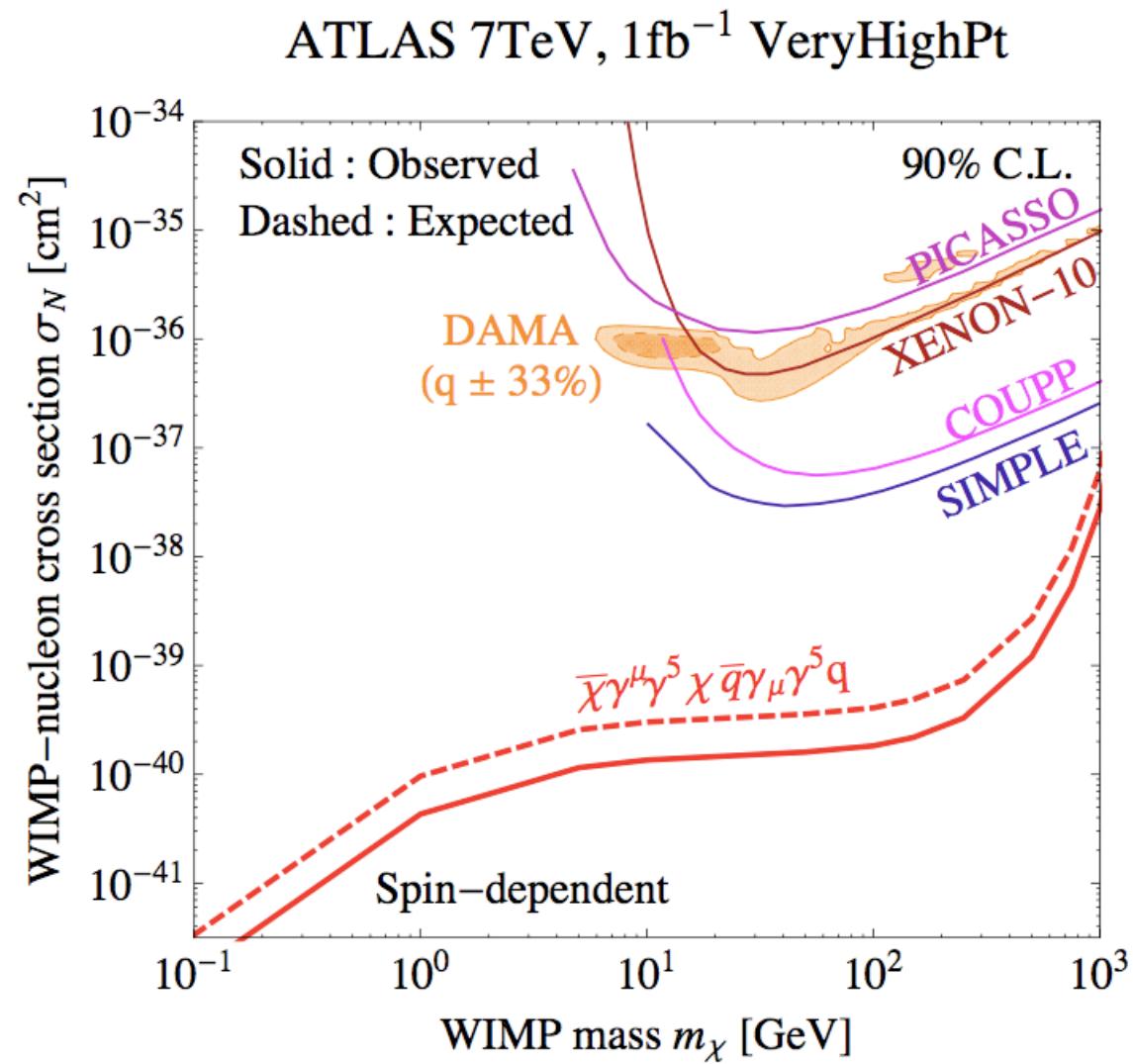


arXiv:1109.4398

Spin dependent Nucleon-WIMP scattering cross section

48

- 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

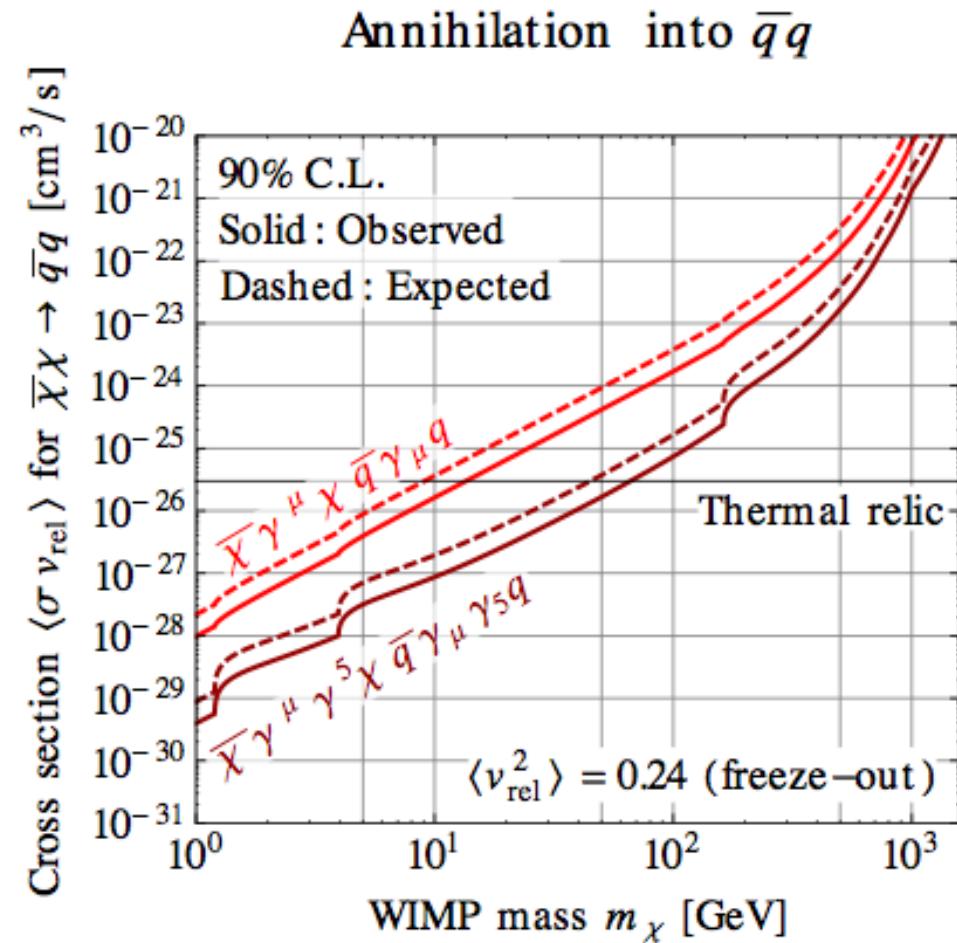


arXiv:1109.4398

LHC limits on annihilation cross section

49

- 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

50

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

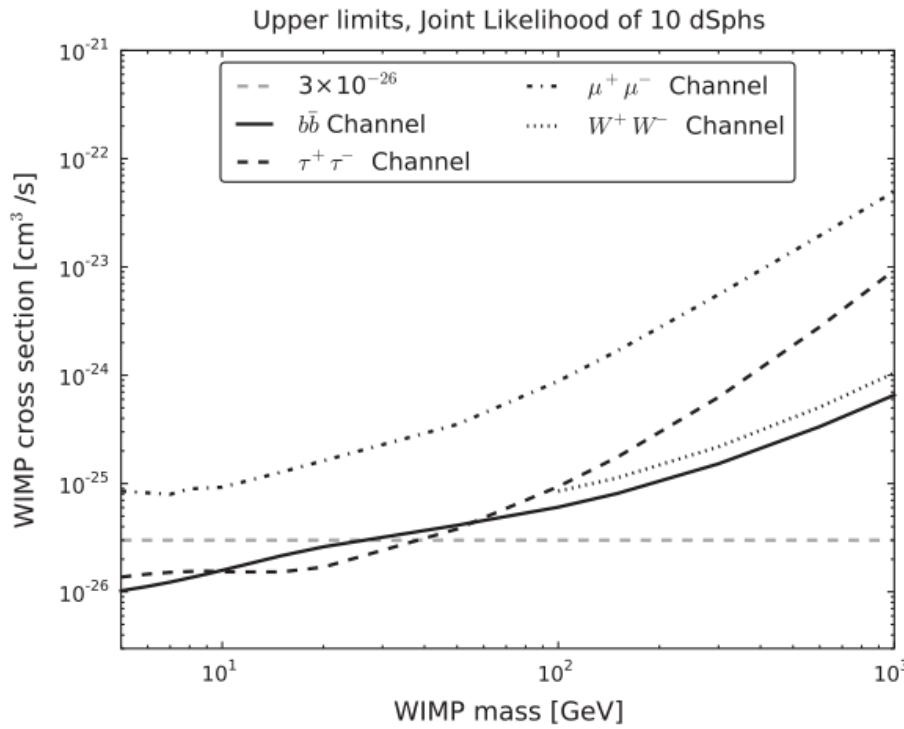
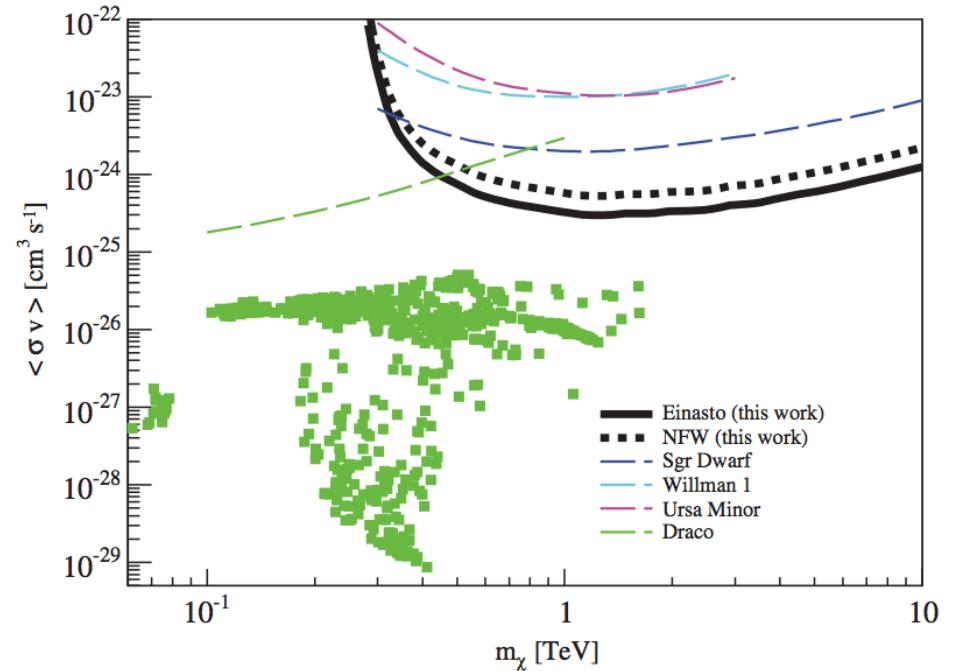


FIG. 2. Derived 95% C.L. upper limits on a WIMP annihilation cross section for the $b\bar{b}$ channel, the $\tau^+\tau^-$ channel, the $\mu^+\mu^-$ channel, and the W^+W^- channel. The most generic cross section ($\sim 3 \times 10^{-26} \text{ cm}^3 \text{s}^{-1}$ for a purely s -wave cross section)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

ATLAS Exotics Searches* - 95% CL Lower Limits (Status: Dec. 2011)

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ATLAS
Preliminary

$$\int L dt = (0.03 - 2.1) \text{ fb}^{-1}$$

$\sqrt{s} = 7 \text{ TeV}$

$L=1.0 \text{ fb}^{-1}$ (2011) [ATLAS-CONF-2011-096]	3.2 TeV	$M_D (\delta=2)$
$L=2.1 \text{ fb}^{-1}$ (2011) [Preliminary]	3.0 TeV	M_S (GRW cut-off)
$L=1.1 \text{ fb}^{-1}$ (2011) [arXiv:1111.4116]	1.23 TeV	Compact. scale 1/R (SPS8)
$L=1.1-2.1 \text{ fb}^{-1}$ (2011) [Preliminary, arXiv:1108.1582]	1.95 TeV	Graviton mass
$L=1.0 \text{ fb}^{-1}$ (2011) [ATLAS-CONF-2011-144]	575 GeV	Graviton mass
$L=1.0 \text{ fb}^{-1}$ (2011) [ATLAS-CONF-2011-123]	840 GeV	KK gluon mass

Extra dimensions

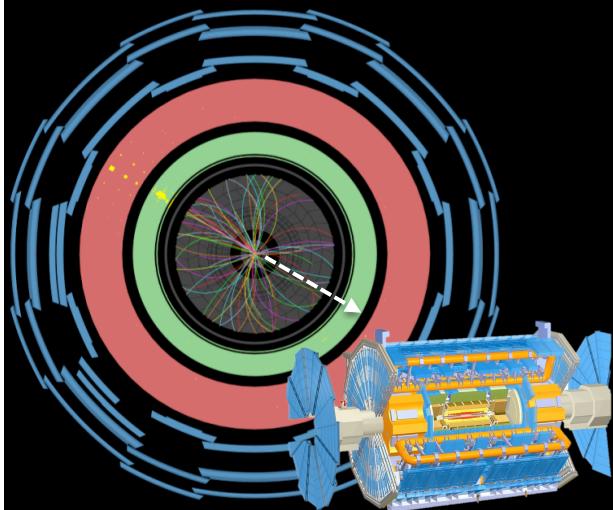
- ADD : monojet
- Large ED (ADD) : diphoton
- UED : $\gamma\gamma + E_{T,\text{miss}}$
- RS with $k/M_{\text{Pl}} = 0.1$: $\gamma\gamma$, ee, $\mu\mu$ combined, $m_{\gamma\gamma, \text{ee}, \mu\mu}$
- RS with $k/M_{\text{Pl}} = 0.1$: ZZ resonance, m_{ZZ}
- RS with $g_{\text{qqqKK}}/g_s = -0.20$: $H_T + E_{T,\text{miss}}$
- Quantum black hole (QBH I) : $m_{\text{dijet}} = \Gamma(x)$
- QBH : High-mass
- ADD BH ($M_{\text{Pl}}/M_{\text{BH}} = 3$) : SS dimension
- ADD BH ($M_{\text{Pl}}/M_{\text{BH}} = 3$) : qqq contact interaction : $F(m_{\text{dijet}})$
- ADD BH ($M_{\text{Pl}}/M_{\text{BH}} = 3$) : qql contact interaction : $F(m_{\text{dijet}})$
- ADD BH ($M_{\text{Pl}}/M_{\text{BH}} = 3$) : SSM
- Scalar LQ pairs ($\beta=1$) : kin. vars. in eejj, evjj
- Scalar LQ pairs ($\beta=1$) : 1st gen. LQ mass
- 4-th gen. : coll. mass in $Q_1 Q_2 \rightarrow W_1 W_2$
- 4-th gen. : T mass ($m(A_0) < 140 \text{ GeV}$)
- Major. neutr. (LRSIM, no mixing) : Z-lep + jets
- Major. neutr. (LRSIM, no mixing) : τ mass ($m(\rho_+/\omega_T) - m(\pi_T) = 100 \text{ GeV}$)
- Major. neutr. (LRSIM, no mixing) : N mass ($m(W_R) = 1 \text{ TeV}$)
- H $^\pm$ (DY prod., BR H $^\pm \rightarrow l\nu$) : H $^\pm$ mass
- Excited quarks : dijet resonance, m_{dijet}
- Axigluons : m_{dijet}
- Color octet scalar : m_{dijet}
- Vector-like quark : CC, m_{lvq}
- Vector-like quark : NC, m_{llq}
- Axigluon mass : 3.32 TeV
- Scalar resonance mass : 1.82 TeV
- Q mass (coupling $\kappa_{qQ} = v/m_Q$) : 900 GeV
- Q mass (coupling $\kappa_{qQ} = v/m_Q$) : 760 GeV

- 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!



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

Future



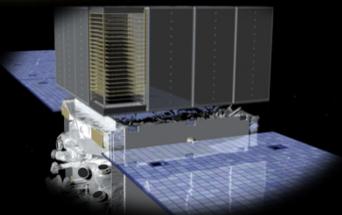
LHC physics

- 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

Fermi, CTA



VHE γ -rays

- Indirect Dark Matter searches

