Displaced Vertices from Pseudo-Dirac Dark Matter

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arXiv:1706.08985, 1803.02861

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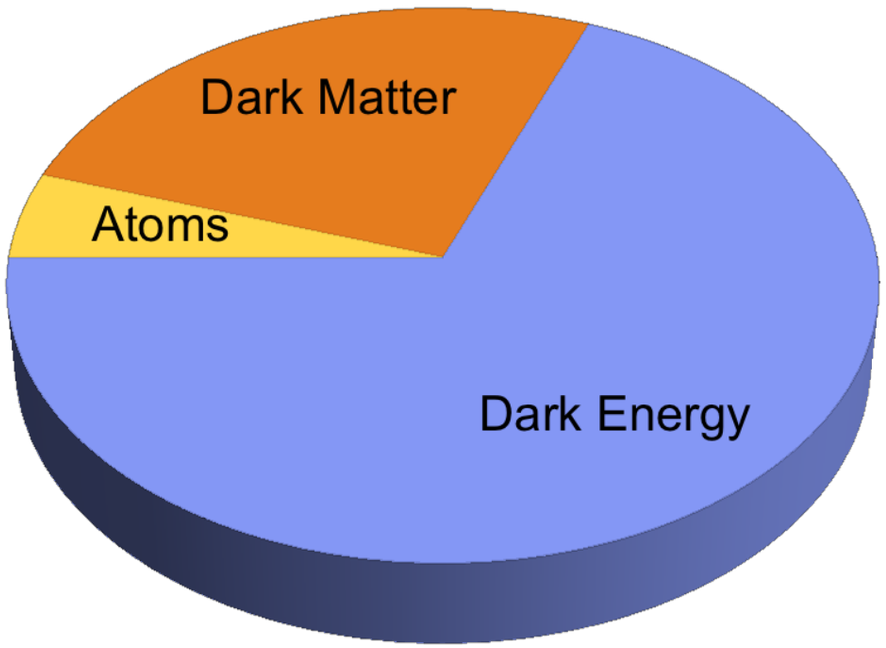
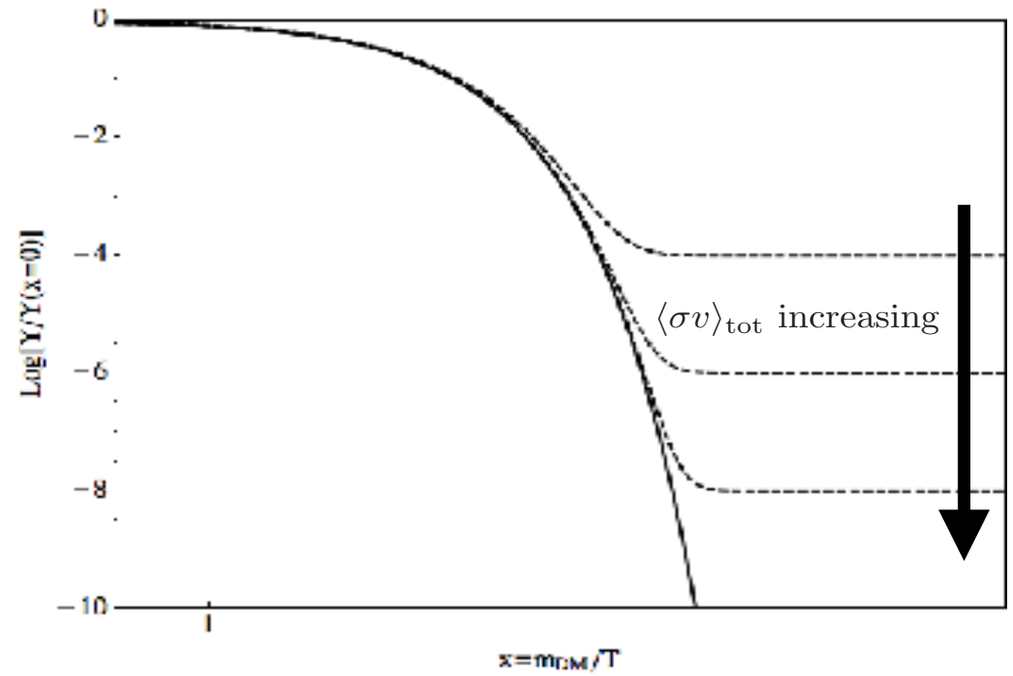
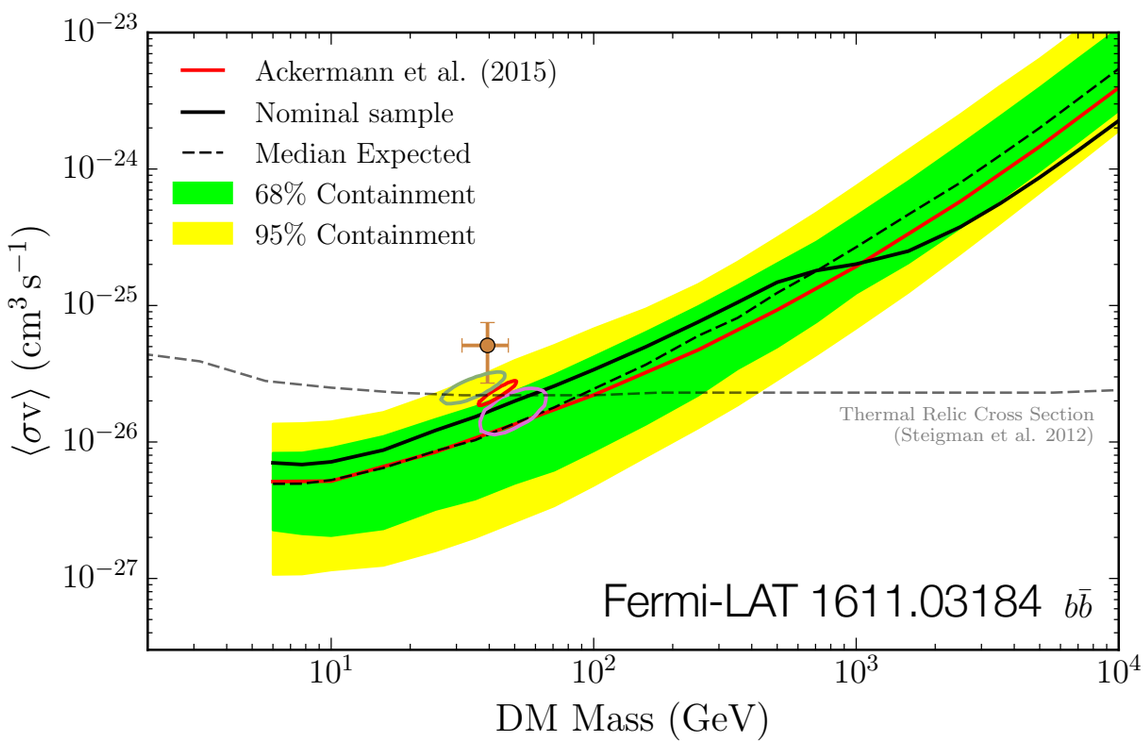
ma per seguir virtute e canoscenza
SISSA

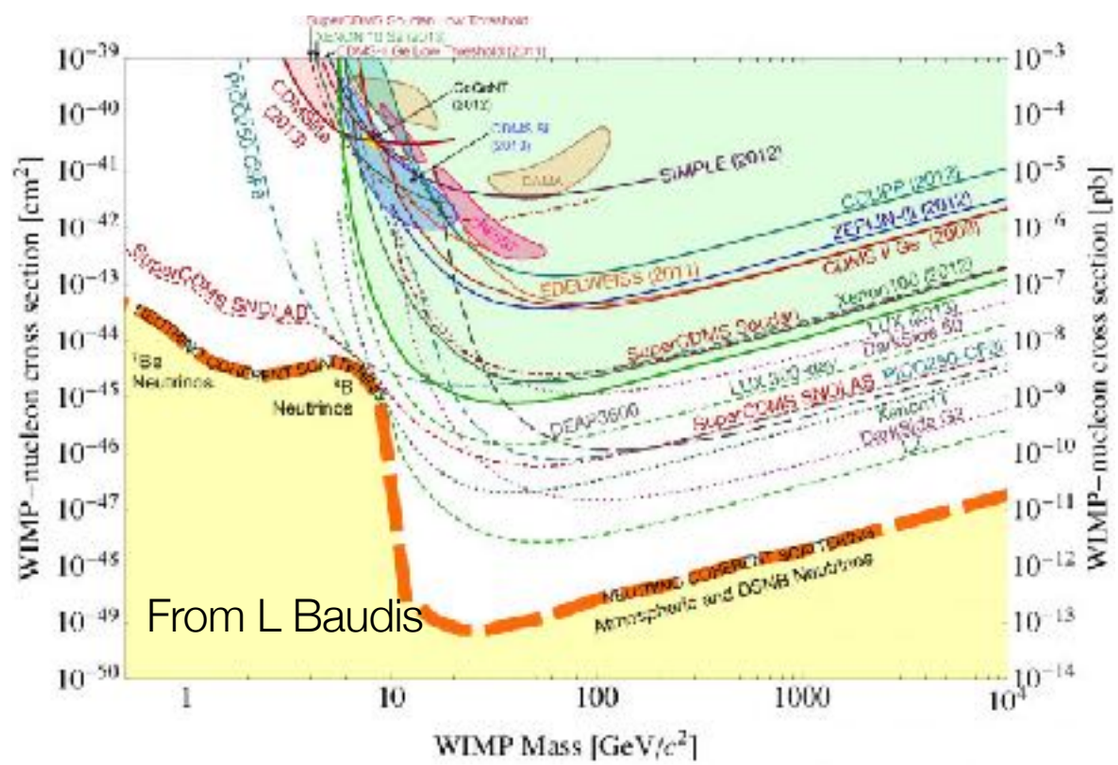
Introduction

Thomas Jacques









Introduction

Thomas Jacques

- **Pressure growing on WIMP paradigm**
  The relic density cross section is ruled out for many models

- Next steps:

  - **Continue searches for WIMP alternatives**
    Axions, freeze-in, gravitinos, sterile neutrinos, asymmetric DM…

  - **Find viable WIMP candidates**
    Models that are either overlooked or not yet ruled out

  - **Explore new signatures**

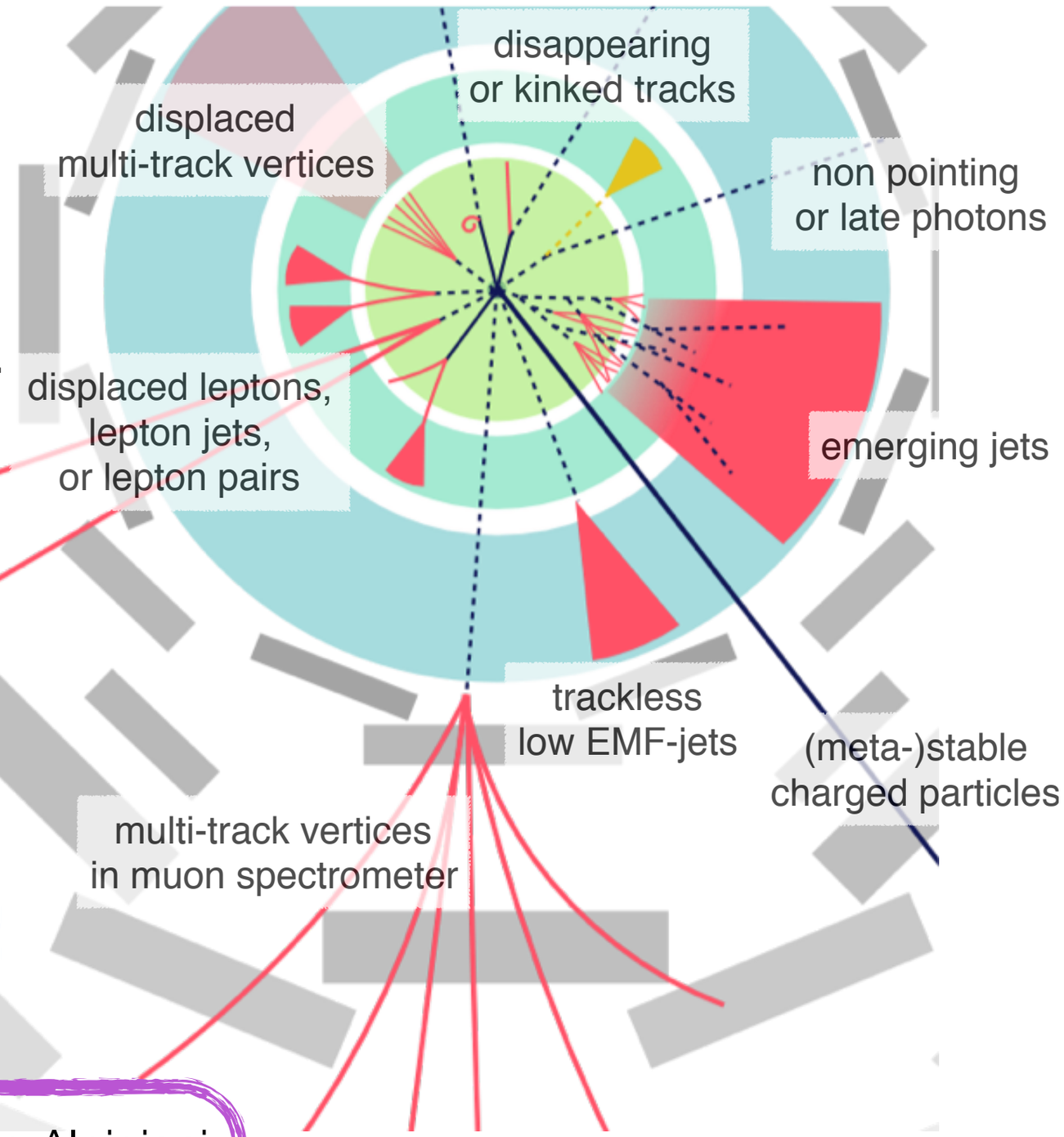
Long-lived particles (LLPs) @ LHC

Thomas Jacques

- **LLPs arise naturally**
  Many theories naturally predict new particles decaying on detector timescale; SUSY, Quirks, Hidden Valley, Monopoles… in general, anything with small couplings, heavy scales

- **Minimal SM background**
  Hardware interactions, merged vertices, track crossings

- **Wide range of signatures!**



See also talks by Heather Russell and Cristiano Alpigiani

Graphics from Heather Russell

Model 1

Pseudo-Dirac Dark Matter

Model

De Simone, Sanz, Sato
Phys.Rev.Lett. 105 (2010) 121802

Thomas Jacques

- General Lagrangian with **both Dirac & Majorana masses**

$$\mathcal{L}_0 = \bar{\Psi}(i\partial\!\!\!/ - M_D)\Psi - \frac{m_L}{2}\left(\overline{\Psi^c}P_L\Psi + \text{h.c.}\right) - \frac{m_R}{2}\left(\overline{\Psi^c}P_R\Psi + \text{h.c.}\right)$$

- Couples to Standard Model via **Z'**

$$\mathcal{L}_{\text{int}} = \bar{\Psi}\gamma^\mu(c_L P_L + c_R P_R)\Psi\, Z'_\mu + \bar{f}\gamma^\mu(c_L^{(f)} P_L + c_R^{(f)} P_R) f\, Z'_\mu$$

- **Take Pseudo-Dirac limit** ($M_D >> m_L, m_R$)

- **Get Majorana eigenstates $\chi_{1,2}$ with mass splitting << mass**
  at leading order in $|m_L - m_R| / M_D$

$$m_{1,2} = M_D \mp (m_L + m_R)/2$$

Model

Thomas Jacques

- **Interaction Lagrangian**

  Vector $\chi_1\chi_2$ coupling, axial-vector $\chi_1\chi_1$, $\chi_2\chi_2$

$$\mathcal{L}_{\rm int} = \frac{c_f}{2}\,\bar{f}\gamma^\mu\left(1-\gamma^5\right) f\, Z'_\mu$$

$$+\,\frac{c_R - c_L}{4}\,\bar{\chi}_1\gamma^\mu\gamma^5\chi_1\, Z'_\mu$$

$$+\,\frac{c_R - c_L}{4}\,\bar{\chi}_2\gamma^\mu\gamma^5\chi_2\, Z'_\mu$$

Pure axial-vector χ_1-χ_1, χ_2-χ_2 coupling

$$+\,i\,\frac{c_R + c_L}{2}\,\bar{\chi}_1\gamma^\mu\chi_2\, Z'_\mu$$

Pure vector χ_1-χ_2 coupling

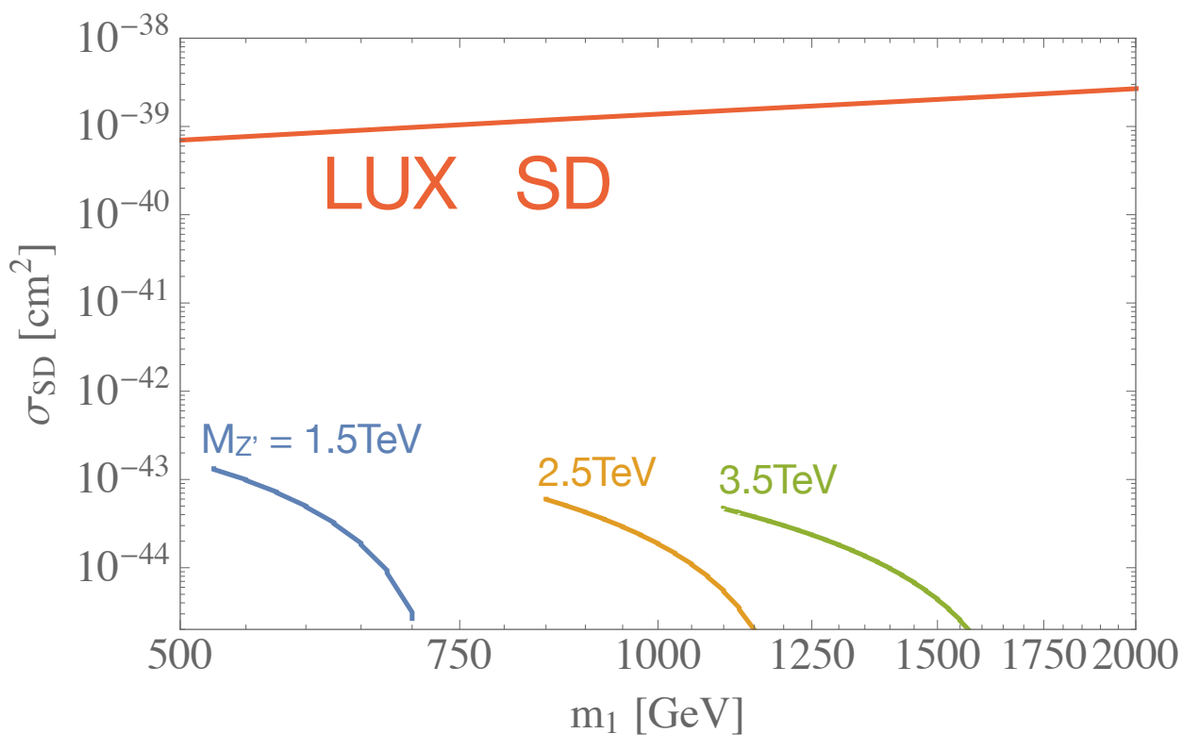
Features

Thomas Jacques

- **Thermal Relic that evades direct & indirect detection**
  For couplings that give correct relic density: direct and indirect detection constraints are weak

  - **Suppressed** direct & indirect detection rate
    from **Axial-vector** $\chi_i\chi_i Z'$ coupling

  - **Unsuppressed** $\chi_1\chi_2$ coannihilation rate
    from **Vector** $\chi_1\chi_2 Z'$ coupling



- **Displaced Vertices for Thermal Relic DM**
  Vector $\chi_1\chi_2 Z'$ coupling controls both relic density and decay length

$$\frac{\Omega h^2}{0.1194} \simeq \frac{L_0}{10\,\mathrm{cm}} \left(\frac{100\,\mathrm{GeV}}{m_1}\right)^2 \left(\frac{\Delta m}{1\,\mathrm{GeV}}\right)^5$$

Constraints

Thomas Jacques

- Summary of **coupling constraints:**
  - Assume coupling to **quarks only**

    possible coupling to leptons - future work
  - Upper limits on c_f from **dijet**

    choose max allowed value
  - Fix c_L, c_R to give correct **relic density**

    ratio c_L/c_R still free; Choose based on phenomenology
  - Impose limits on c_L, c_R to ensure small **mediator width**

    limits range of masses that can give correct relic density
  - Scan over **masses**

Choice of parameters

Thomas Jacques

- Free parameter: **c_L/c_R**
  Strong effect on phenomenology

$$\frac{c_R - c_L}{4}\,\bar{\chi}_1\gamma^\mu\gamma^5\chi_1\,Z'_\mu$$

$$\frac{c_R - c_L}{4}\,\bar{\chi}_2\gamma^\mu\gamma^5\chi_2\,Z'_\mu$$

$$i\,\frac{c_R + c_L}{2}\,\bar{\chi}_1\gamma^\mu\chi_2\,Z'_\mu$$

c_L/c_R = -1:
Pure axial-vector: No decay

c_L/c_R = 1:
Pure vector: No $\chi_2\chi_2$ production

- Best case for displaced vertices: c_L/c_R close (but not equal!) to -1
  → **Enhances $\chi_2\chi_2$ production rate and extends χ_2 decay length**

- Choose benchmarks c_L/c_R = -0.8 and 0
  'Good' and 'meh' scenarios for displaced vertices

Choice of parameters

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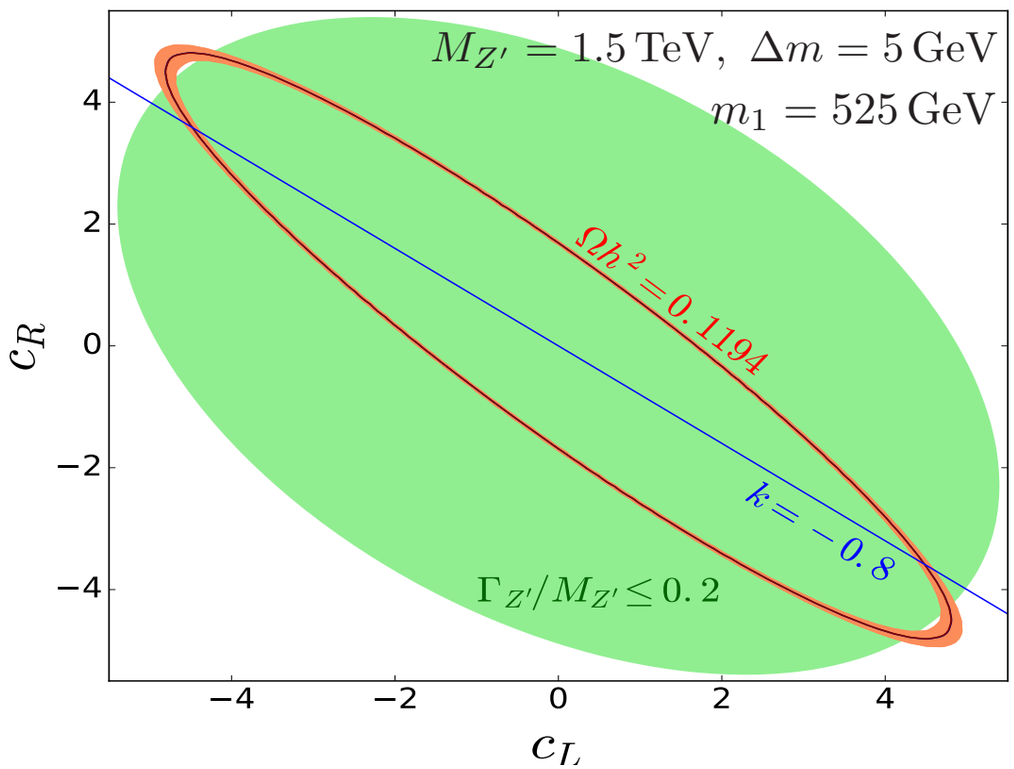

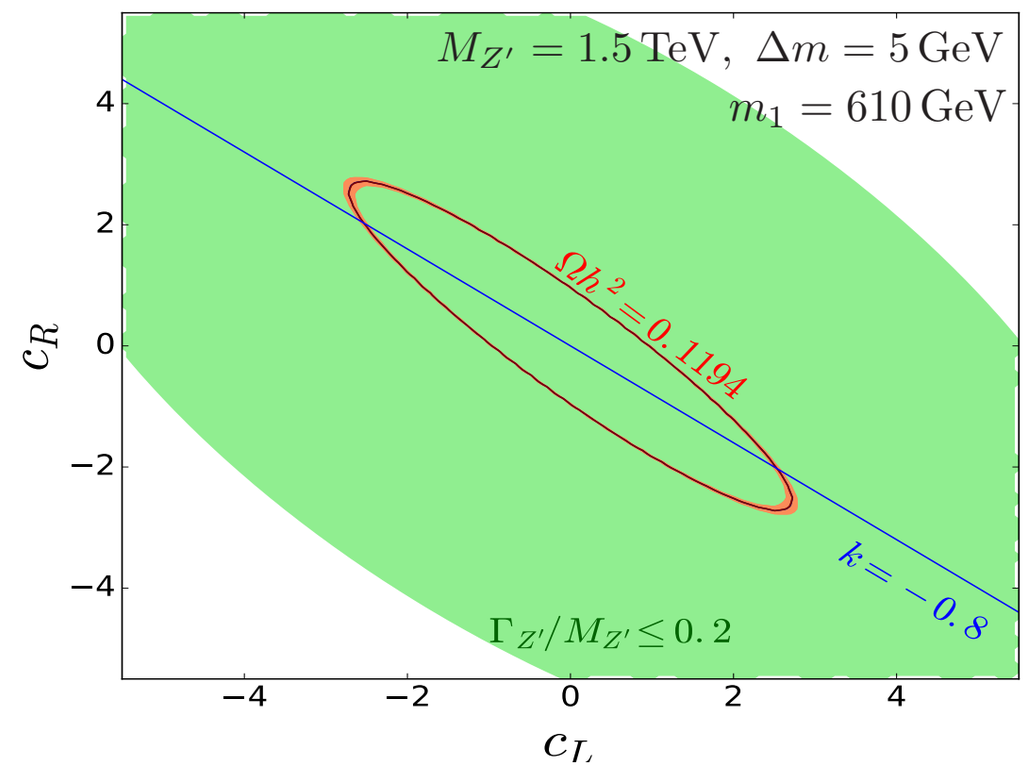

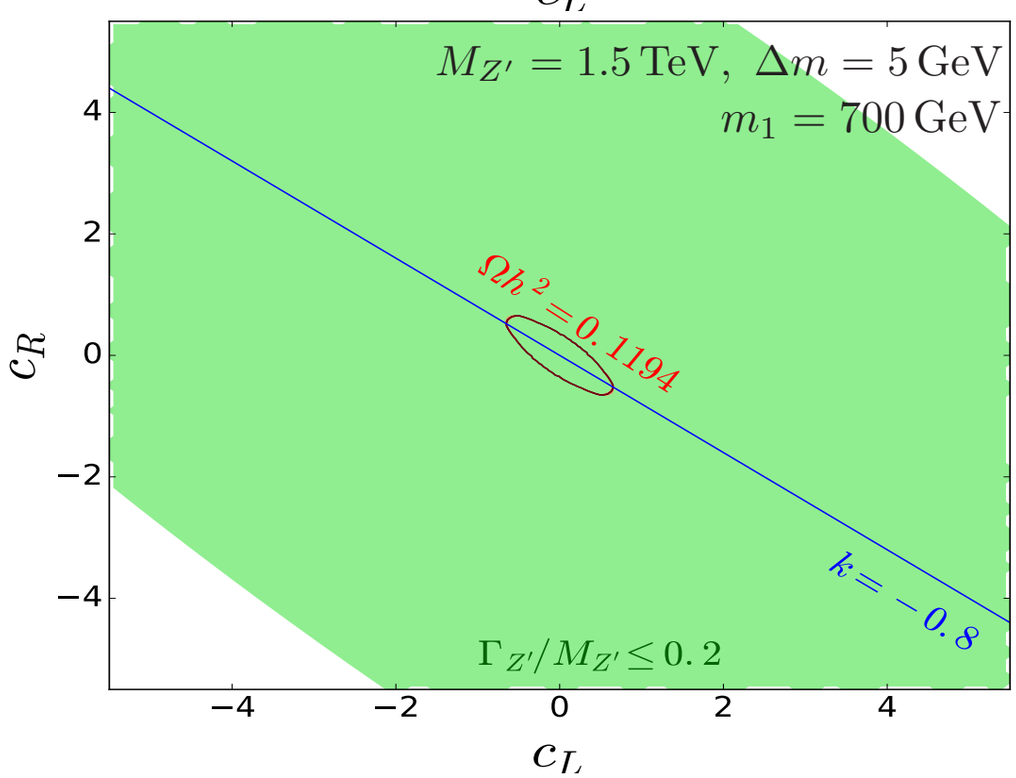

- For each (m_1, Δm, $M_{Z'}$): c_L, c_R chosen from **intercept of relic density and k contours**

  c_L, c_R appear together as $|c_L - c_R|^2$ or $|c_L + c_R|^2$, so four quadrants are equivalent

Displaced vertices

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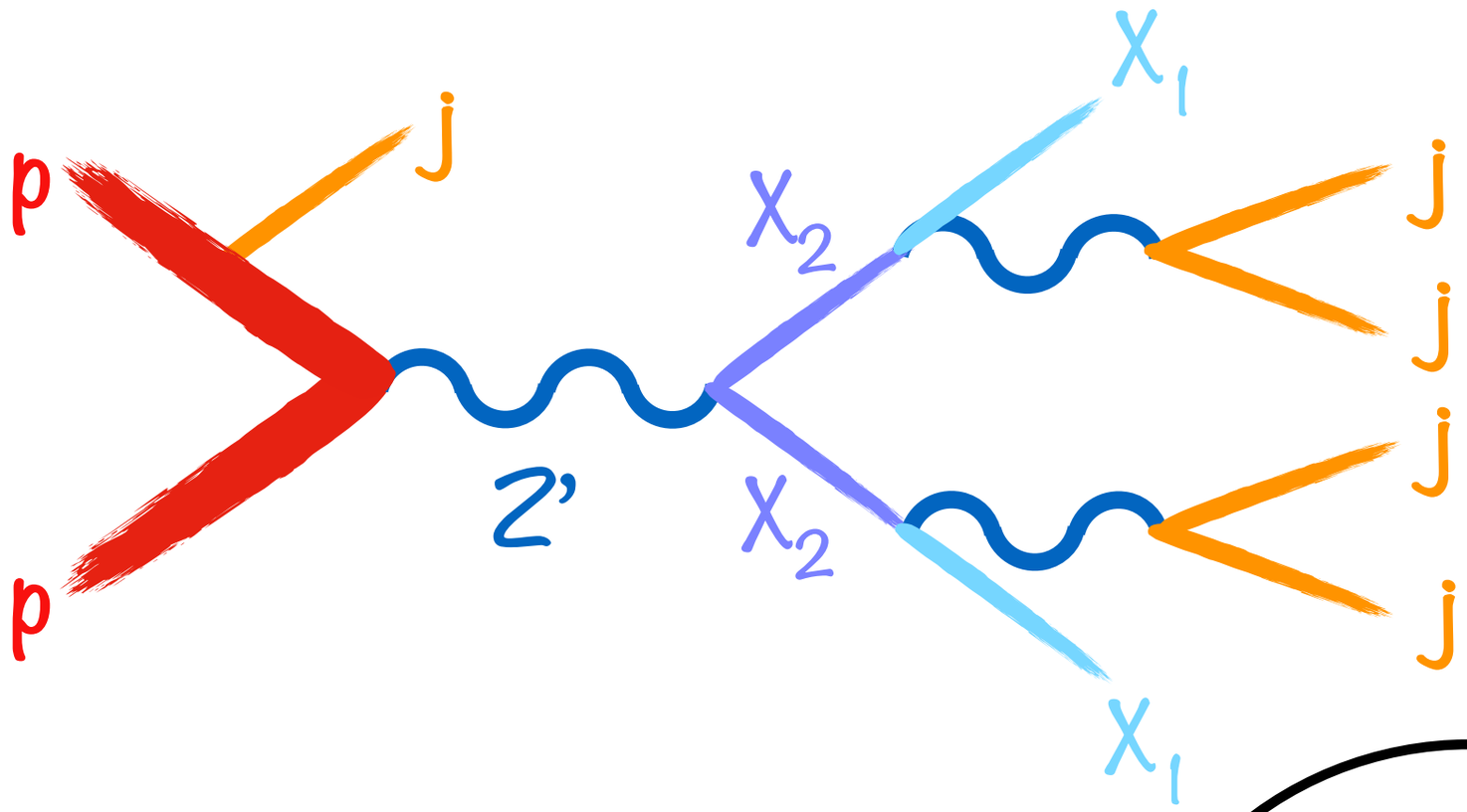
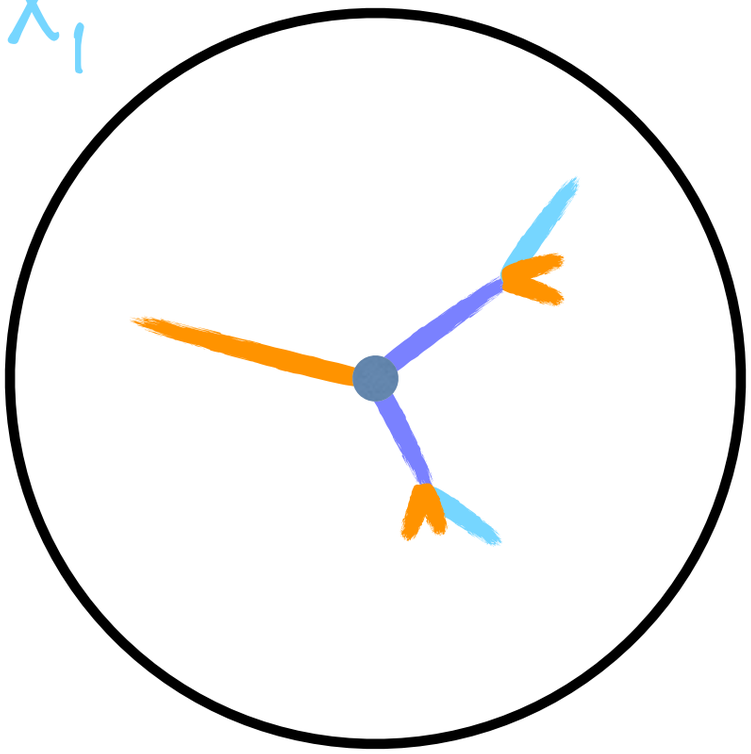


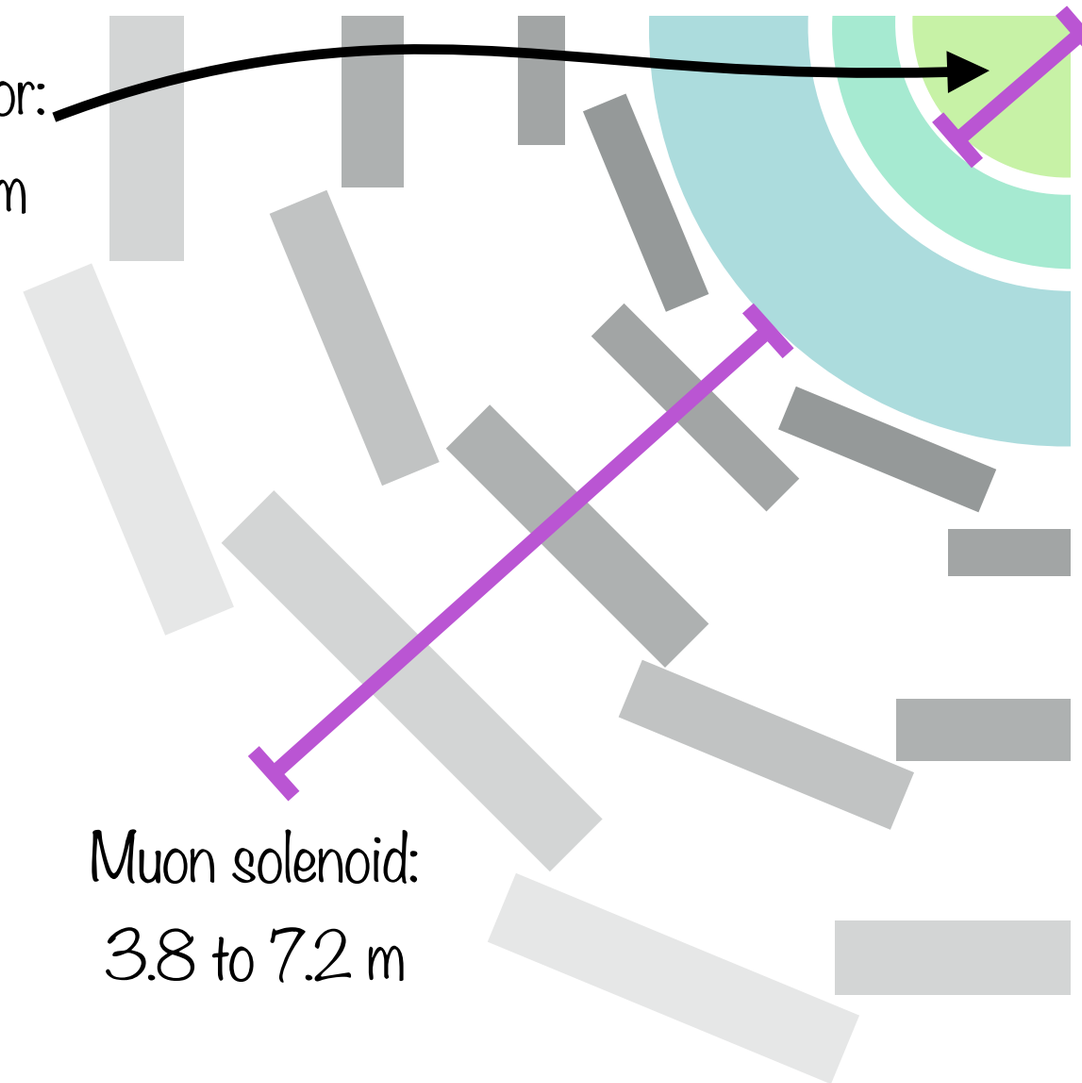
- Signal:
  - **missing energy (MET)**
    Provides trigger and reduces background
  - **hard jet**
    Increases MET, provides trigger, reduces background
  - **2 displaced vertices**
    1 DV already has minimal background;
    with 2 DV, minimal background becomes negligible



Displaced vertices

Thomas Jacques

- Follow ATLAS analysis arXiv:1504.03634:
  - Require **2 DV**
    Each in inner detector or muon solenoid
  - **Background < 10^{-3} events**
    Expected @ 8TeV, 20.3 fb^{-1}
    with jet pT > 120 GeV, MET > 200 GeV
- Scaling to 13TeV:
  - **Increase cuts** to p_T > 200 GeV, MET > 300 GeV
  - Assume **zero background up to 1000 fb^{-1}**



Displaced vertices: $c_L/c_R = 0$

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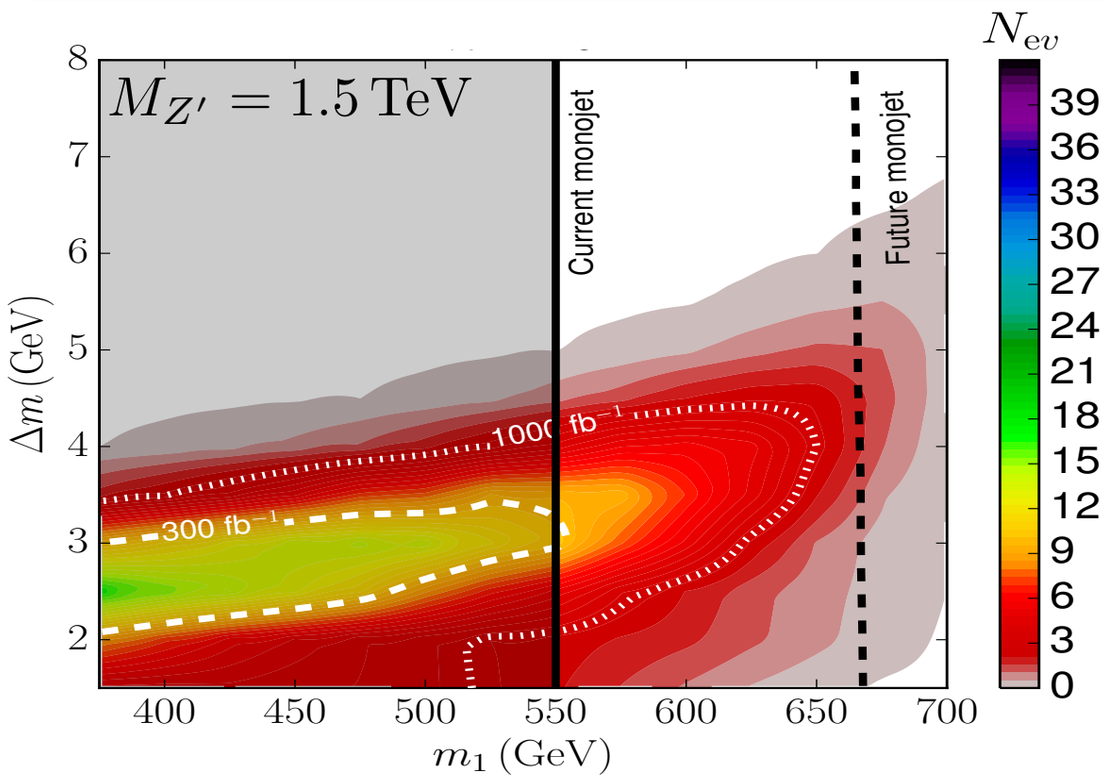

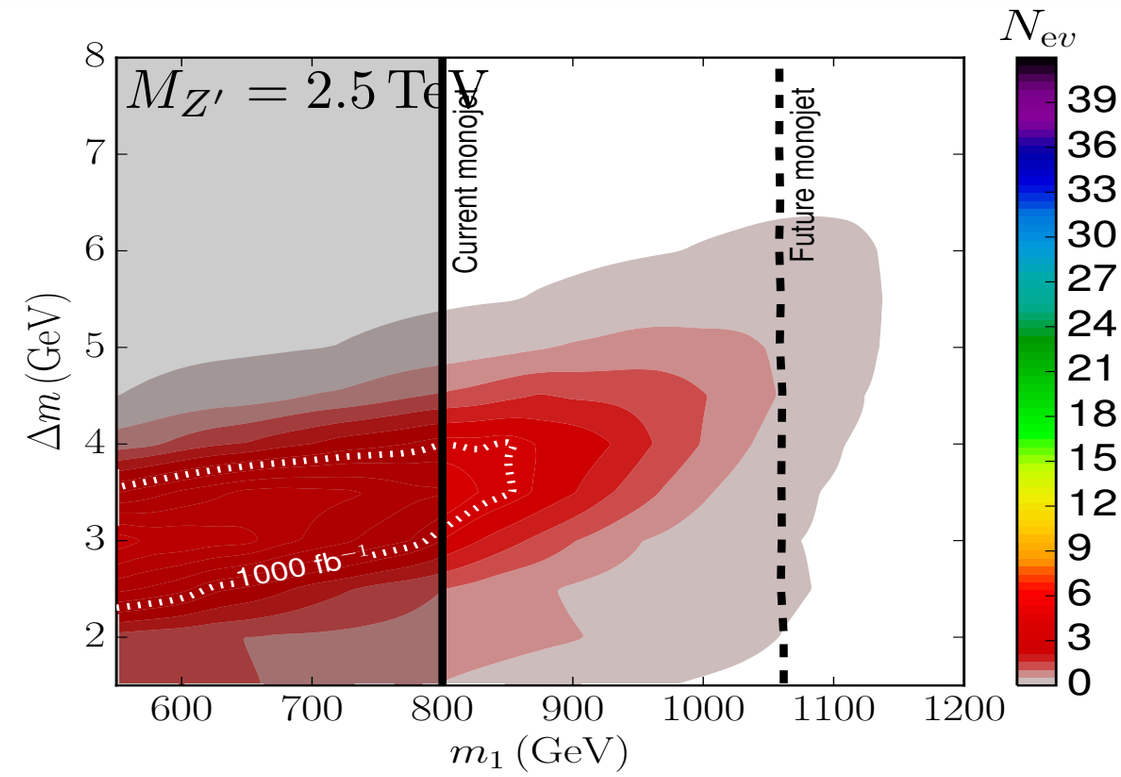

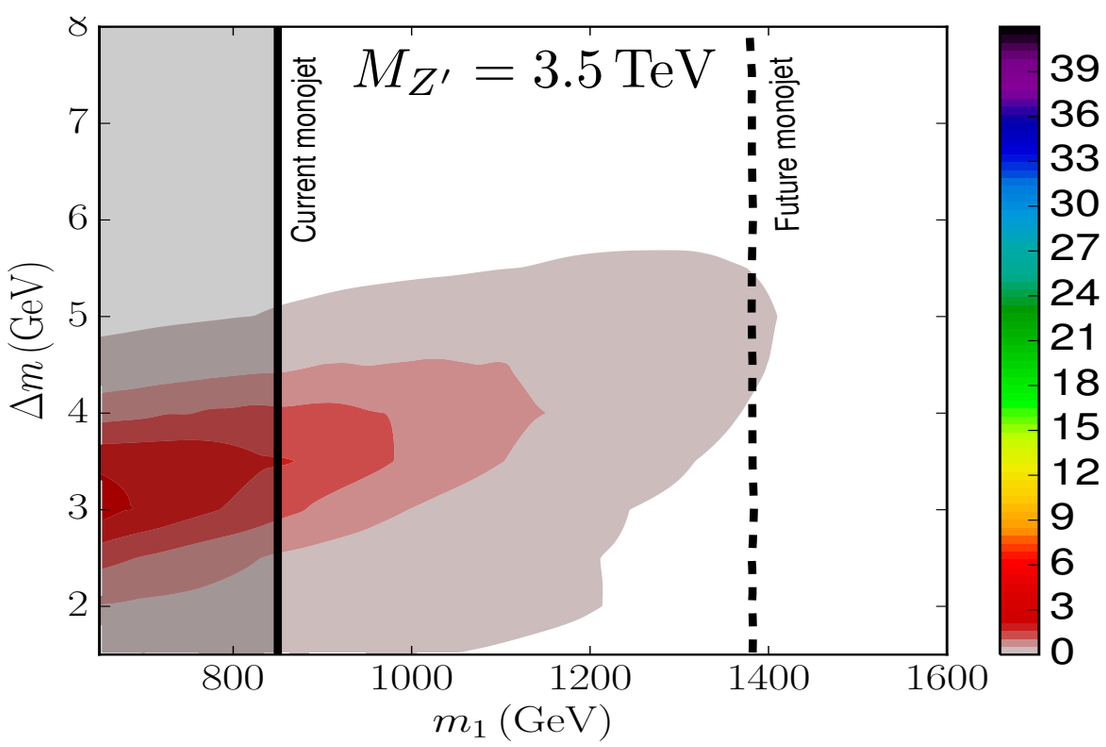

- **Equal** vector/axial vector
- Colour contours: **expected number of events @ 1000 fb^{-1}**
- White: **potential 95% exclusions** with 0 observed events
- Black: **Statistical limit of monojet**

Displaced vertices: c_L/c_R = -0.8

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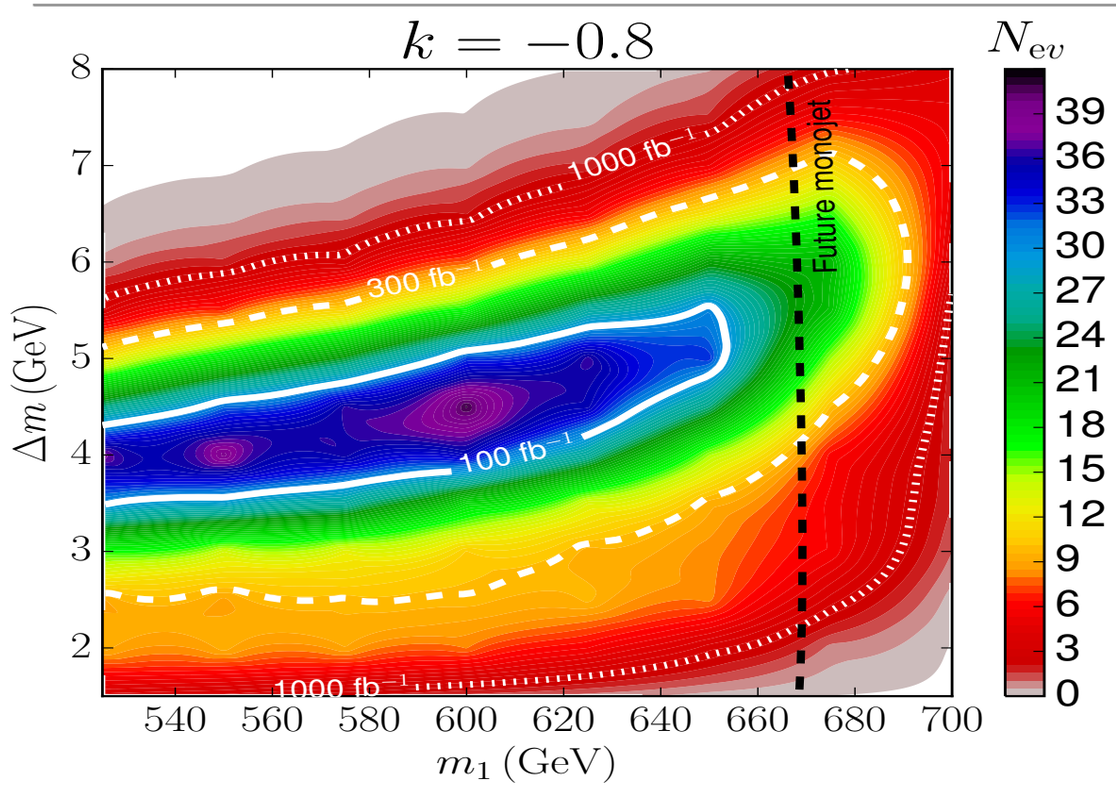
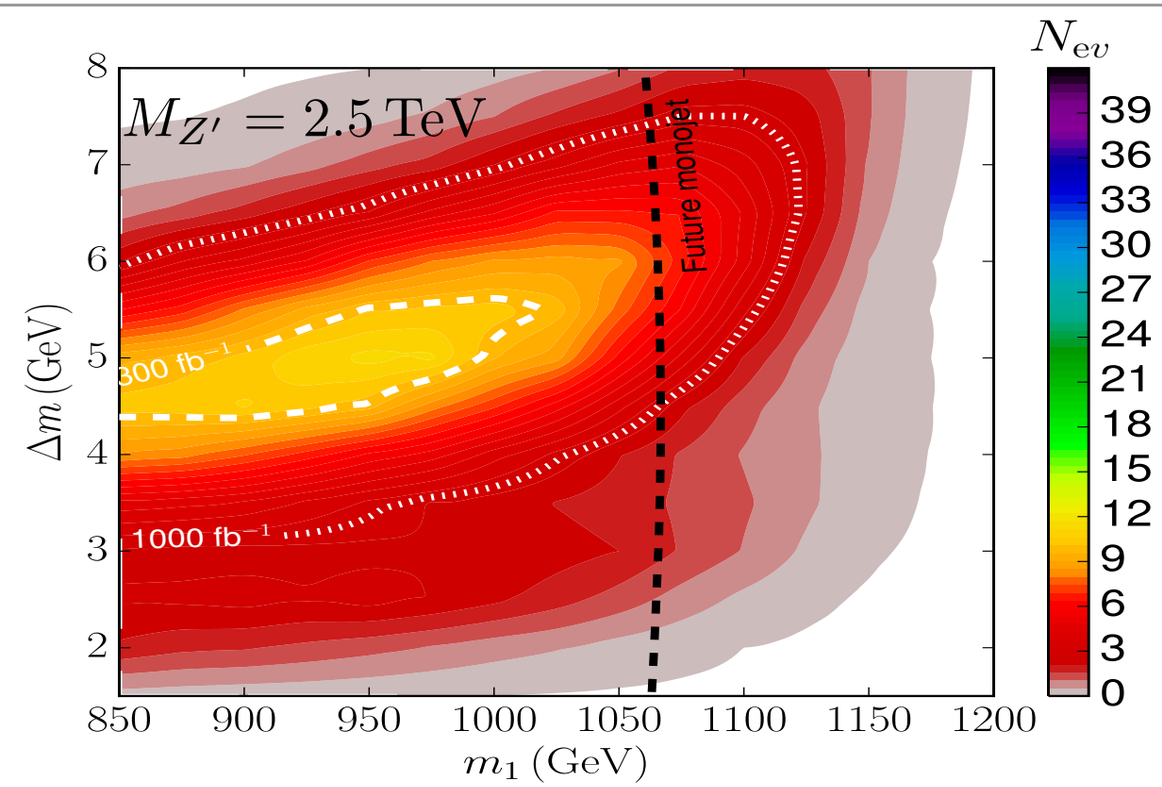
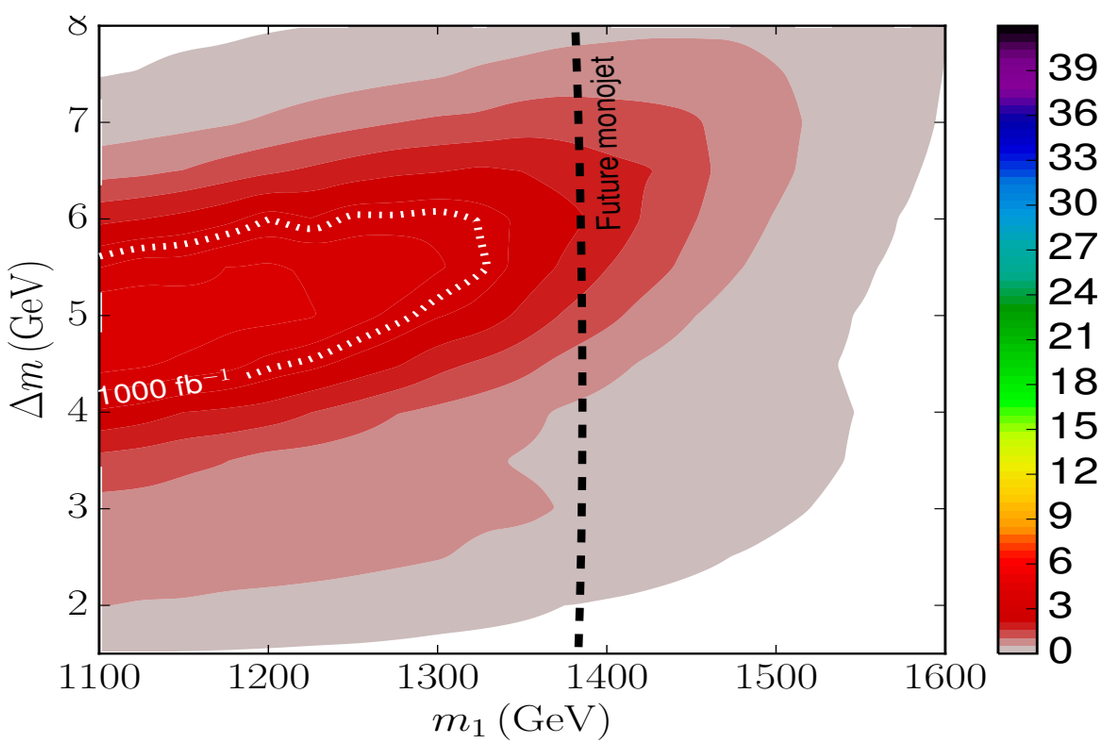






- **Mostly Axial-vector:**
  More $\chi_2\chi_2$ production, longer decay length
- Colour contours:
  expected number of events @ 1000 fb^{-1}
- White:
  potential 95% exclusions with 0 observed events
- Black: **Statistical limit of monojet**

Model 2

Colour Octet Dark Particle

Model 2

De Simone, Sanz, Sato
Phys.Rev.Lett. 105 (2010) 121802

Thomas Jacques

- Neutral DM with heavier **coloured partner**

$$\mathcal{L}_0 = \frac{1}{2}\bar{\chi}_1\left(i\partial\!\!\!/ - m_1\right)\chi_1 + \frac{1}{2}\bar{\chi}_2^a\left(iD\!\!\!/ - m_2\right)\chi_2^a$$

- Couples to Standard Model via **dipole operator**

$$\mathcal{L}_{\rm int} = \frac{d_\chi}{2m_1}\bar{\chi}_2^a\sigma^{\mu\nu}\gamma^5\chi_1 G^a_{\mu\nu}$$

- **Relic density** dominated by **QCD**
  since χ_2 self-interactions governed by QCD
  leaving m_2 and d_χ as free parameters

$$\langle\sigma v\rangle_{\chi_2\chi_2\to gg} = \frac{27\,g_S^4}{512\pi}\frac{1}{m_1^2} + \mathcal{O}(d_\chi^2)$$

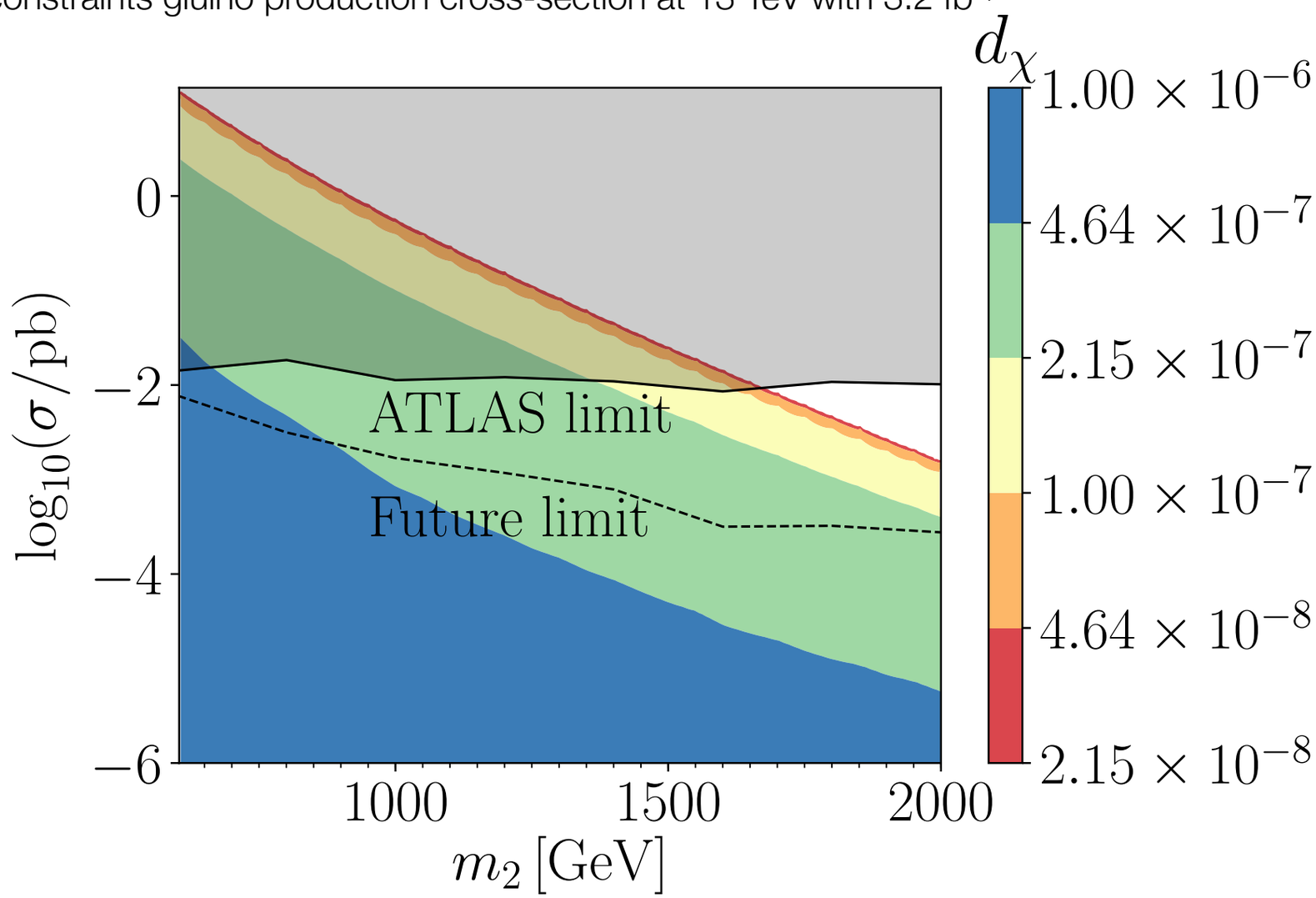
- **Decay length** controlled by d_χ: $\Gamma_{\chi_2\to\chi_1 g} = \frac{d_\chi^2}{\pi}\frac{\Delta m^3}{m_1^2}$

- $d_\chi \ll 1$ for EFT to be valid

R-hadron constraints

Thomas Jacques

- χ_2 is colour octet
  - Forms **R-hadrons**
    Hadronises with SM particles, leaving ionisation track with Velocity $\ll c$ if stable on detector timescale
  - Apply **gluino R-hadron** constraints from ATLAS 1606.05129
    Simulate R-hadrons from χ_2 pair production
    ATLAS constraints gluino production cross-section at 13 TeV with 3.2 fb^{-1}



Monojet constraints

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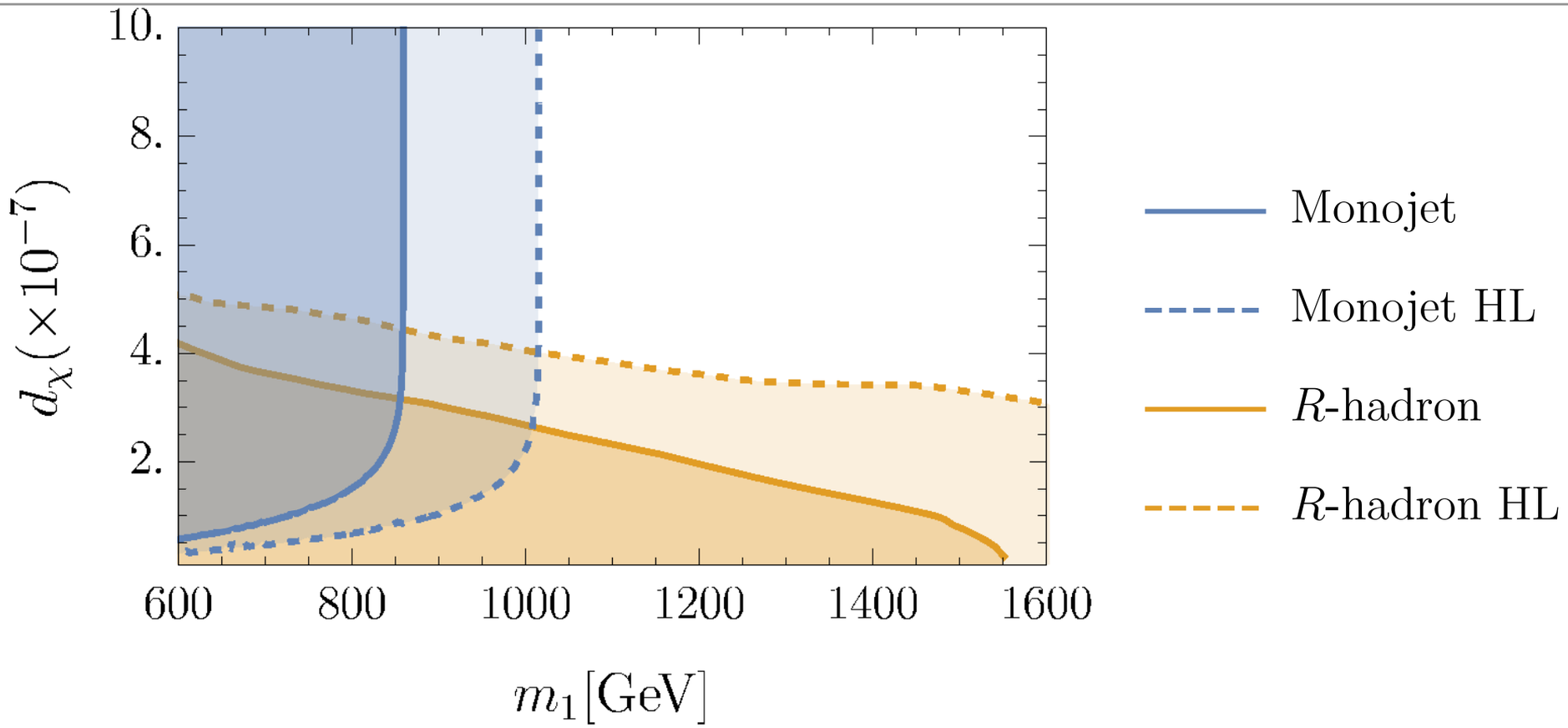


- Apply **monojet** constraints from ATLAS 1711.03301
  Applies to χ_2 which decay promptly rather than forming R-hadrons

- **Complementarity** between monojet and R-hadron constraints
  Monojet insensitive to d_χ, R-hadron insensitive to m_1

Conclusion

Thomas Jacques

- LLPs and displaced vertices are an LHC signal with growing prospects
- Pseudo-Dirac Dark Matter:
  - Avoids direct & indirect detection constraints
  - Yields correct relic abundance
  - Gives displaced vertices at LHC
- Displaced vertex signal complementary to Monojet
  Monojet initially stronger but can be overtaken at large luminosity

Backup

UV Completion

Thomas Jacques

- Z' **cannot** be U(1) gauge boson
  Explicitly broken by Majorana mass term: $\frac{m_R}{2}\left(\overline{\Psi^c} P_R \Psi + \text{h.c.}\right)$

- UV completions **do exist**
  e.g. pseudo-Dirac Bino in extended SUSY

- Proof-of-principle UV completion:
  - Z' gauge boson from **SU(2)'**:
    Ψ embedded in spontaneously broken SU(2)' doublet Θ
  - Dirac mass via **Higgs-like mechanism** from v' of new scalar Φ'
  - Majorana mass from **Weinberg operator**: $\frac{1}{\Lambda}\bar{\Theta}(i\sigma_2\Phi')(i\sigma_2\Phi')^\dagger\Theta^c$
  - **Natural mass hierarchy**: $M_D \propto v'$; $m_{L,R} \propto v'^2 / \Lambda \sim M_D\, v'/\Lambda$
  - **Anomaly free** if Z' couples to leptons
    even with vanishingly small couplings

Decay length

Thomas Jacques

- In limit Δm, $m_f << m_1, m_2$

$$L_0 \sim \frac{2.937\,\mathrm{m}}{\sum_f N_c^{(f)} (c_L + c_R)^2 \left({c_L^{(f)}}^2 + {c_R^{(f)}}^2 \right)} \left(\frac{M_{Z'}}{1\,\mathrm{TeV}} \right)^4 \left(\frac{1\,\mathrm{GeV}}{\Delta m} \right)^5$$

- In lab frame:

$$L_0^{\mathrm{lab}} = \beta\gamma L_0 = \frac{p_2}{m_2} L_0$$

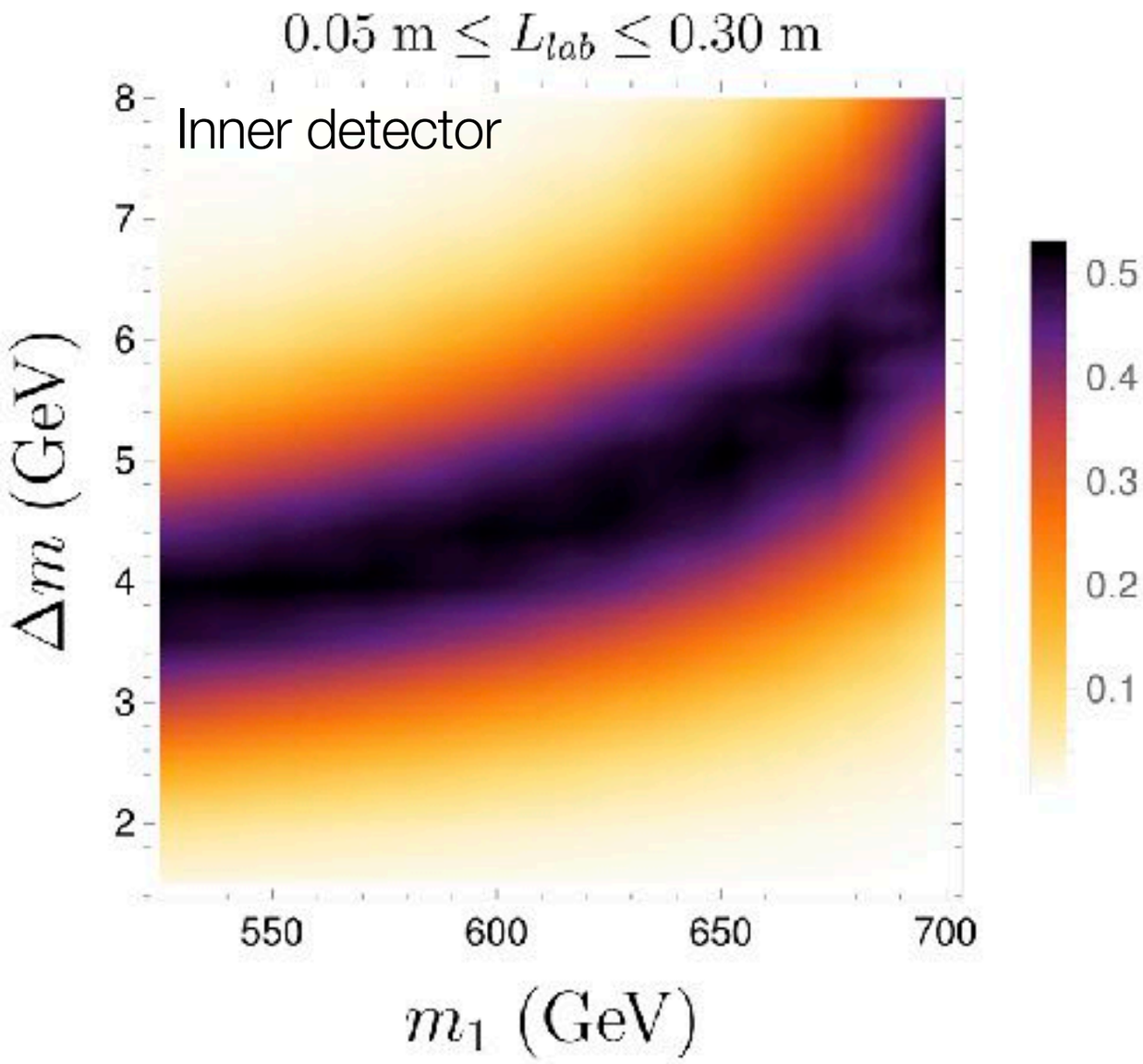
- Distribution given by:

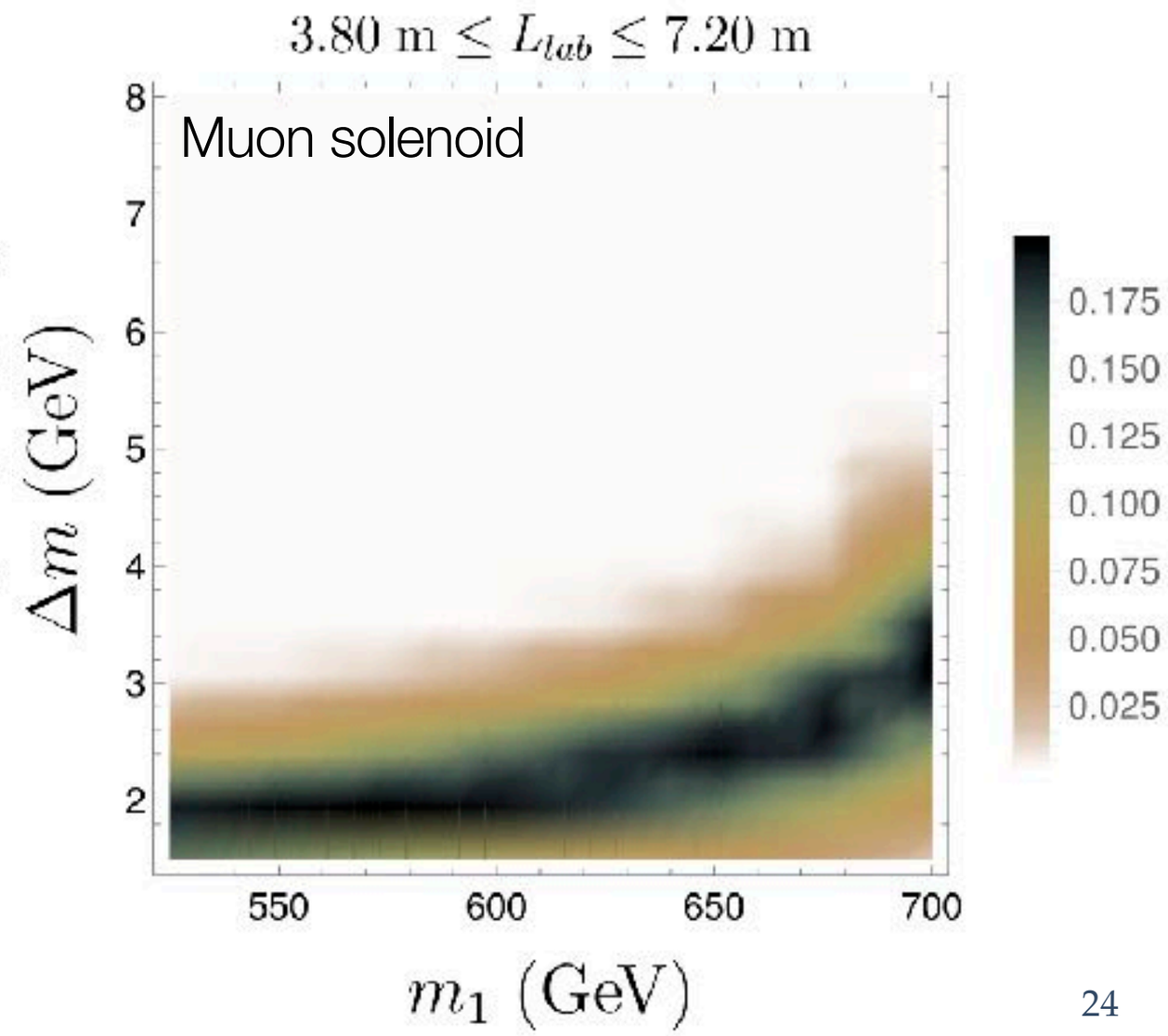
$$P(L^{\mathrm{lab}} | p_2) = e^{-L^{\mathrm{lab}}/L_0^{\mathrm{lab}}}$$

Decay probability

Thomas Jacques

- Decay probability has exponential distribution
  with mean $\hbar c/\Gamma$; Decay length $L_{\rm lab} = (\hbar/\Gamma)(p/m)$ after boost to lab frame





Constraints: Dijet

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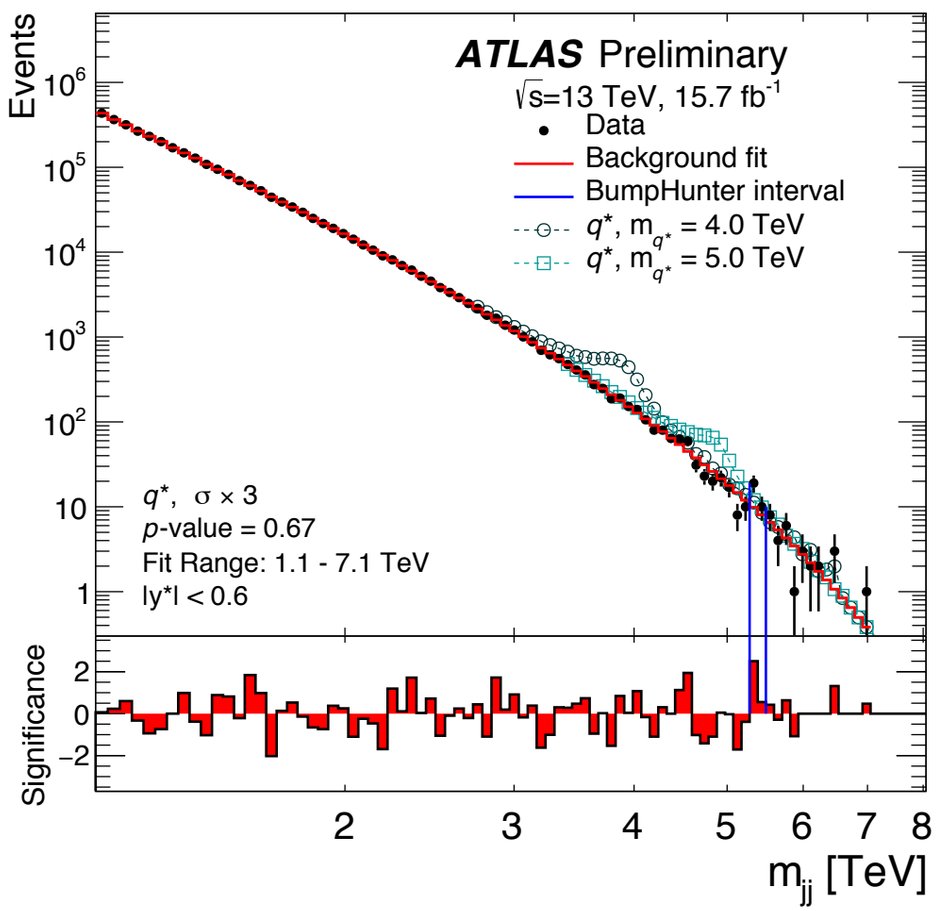

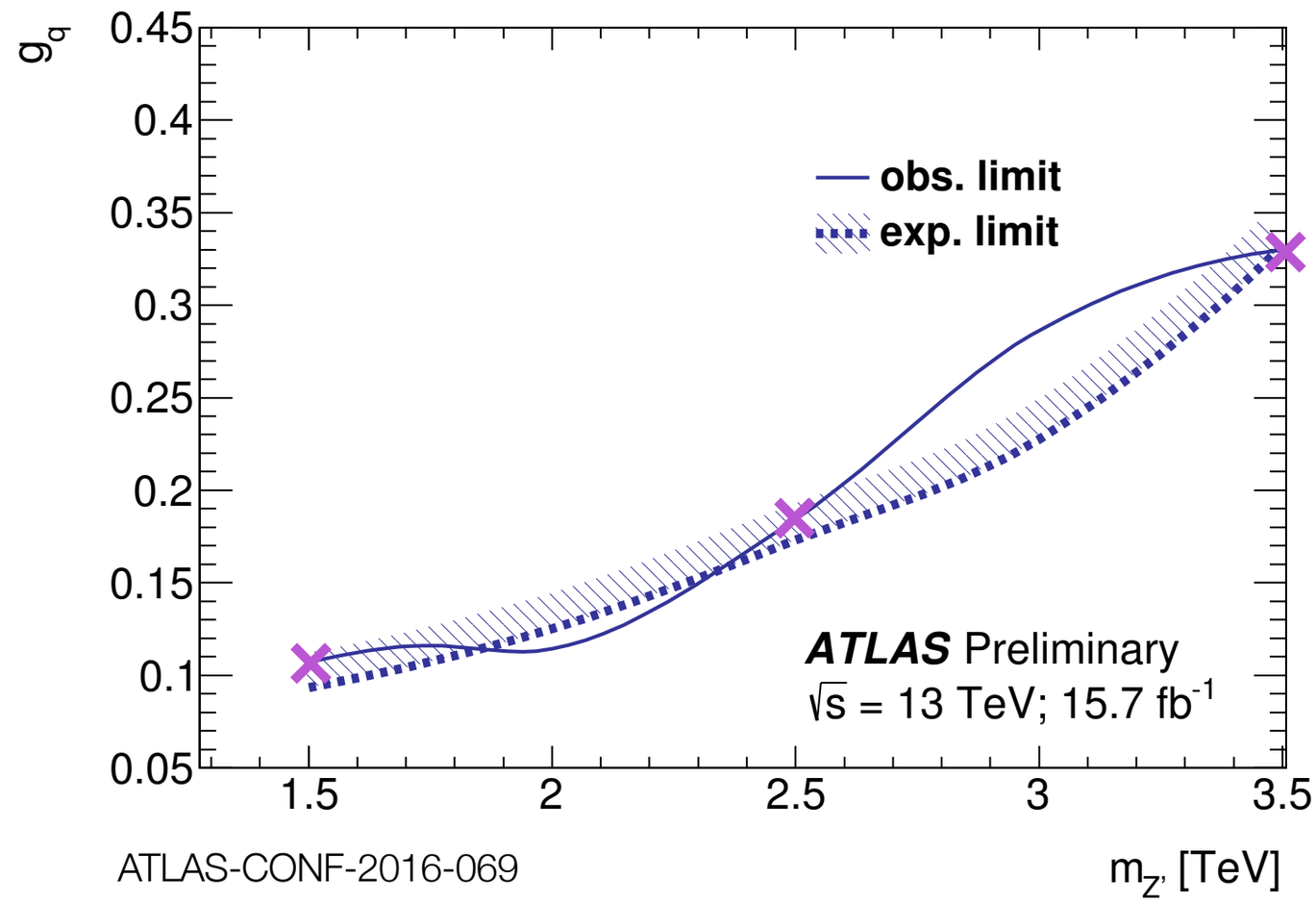

ATLAS-CONF-2016-069

- Search for **Z' decay to quark pairs**
  Strong constraint on quark-mediator coupling

- Gives **upper limit on c_f**
  Use max allowed value

Choice of parameters

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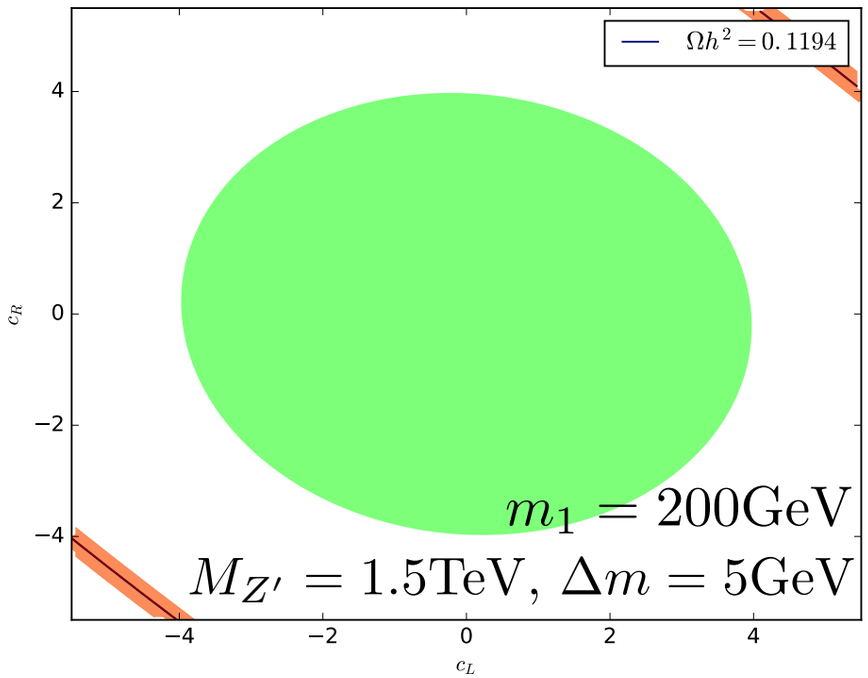


- **Lower limit on m_1 from Z' width**
  Relic density coupling gives very large Z' width

- **Upper limit from kinematics**
  require $M_{Z'} > 2m_2$

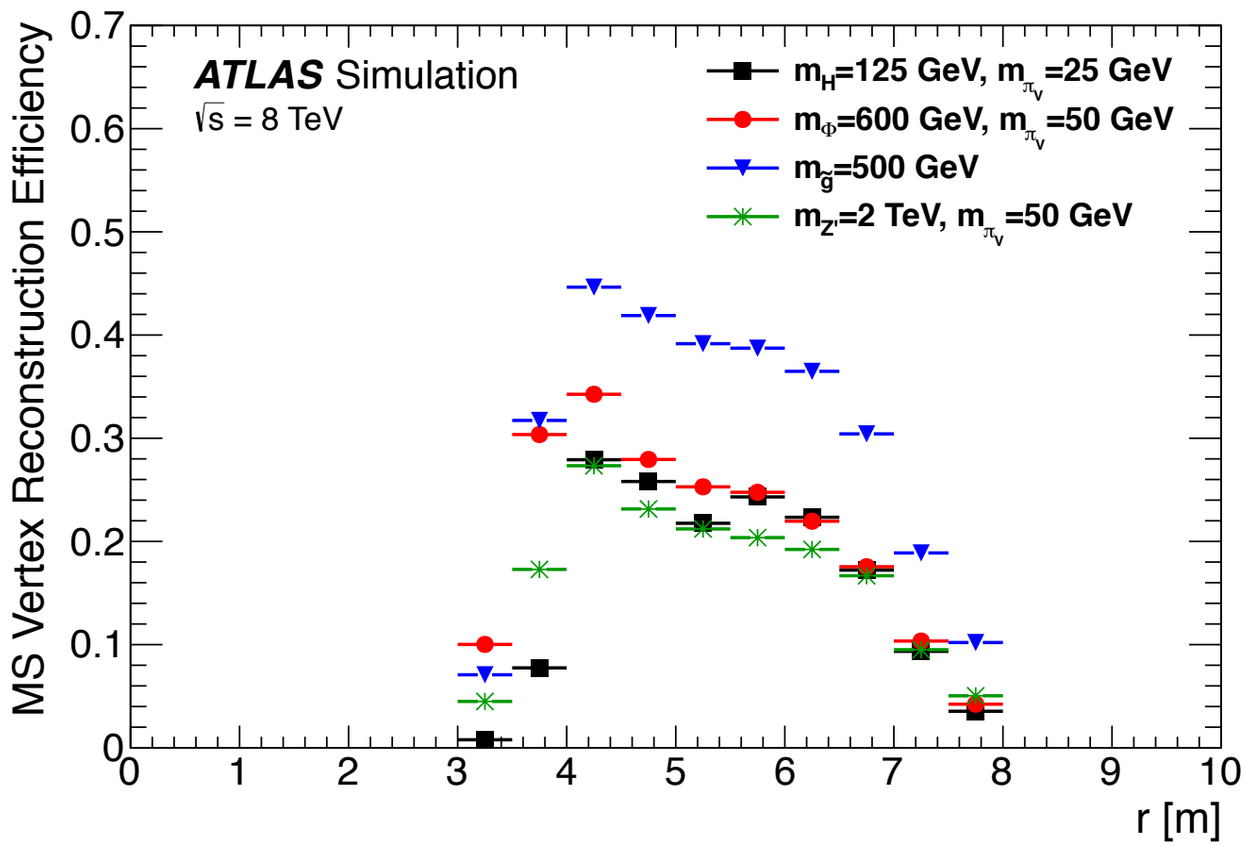
k = -0.8	$M_{Z'} = 1.5\,\text{TeV}$	$M_{Z'} = 2.5\,\text{TeV}$	$M_{Z'} = 3.5\,\text{TeV}$
$c_L^{(f)}$	0.07	0.13	0.25
$m_{1,\text{min}}$ (GeV)	525	850	1100
$m_{1,\text{max}}$ (GeV)	700	1200	1600

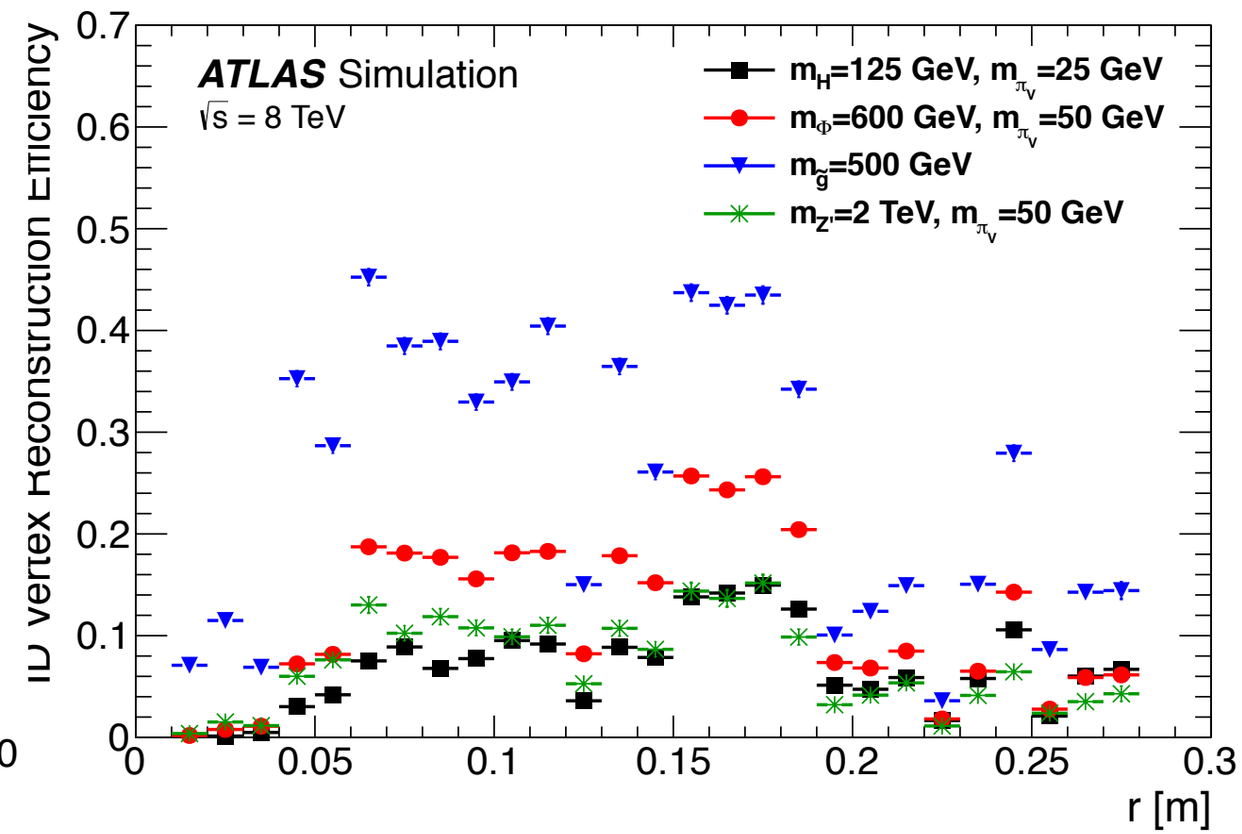
k = 0	$M_{Z'} = 1.5\,\text{TeV}$	$M_{Z'} = 2.5\,\text{TeV}$	$M_{Z'} = 3.5\,\text{TeV}$
$c_L^{(f)}$	0.07	0.13	0.25
$m_{1,\text{min}}$ (GeV)	375	550	650
$m_{1,\text{max}}$ (GeV)	700	1200	1600

Recasting and Efficiencies

Thomas Jacques

1504.03634





- Difficult to recast DV searches:

  Vertex ID efficiency ε highly model-dependent

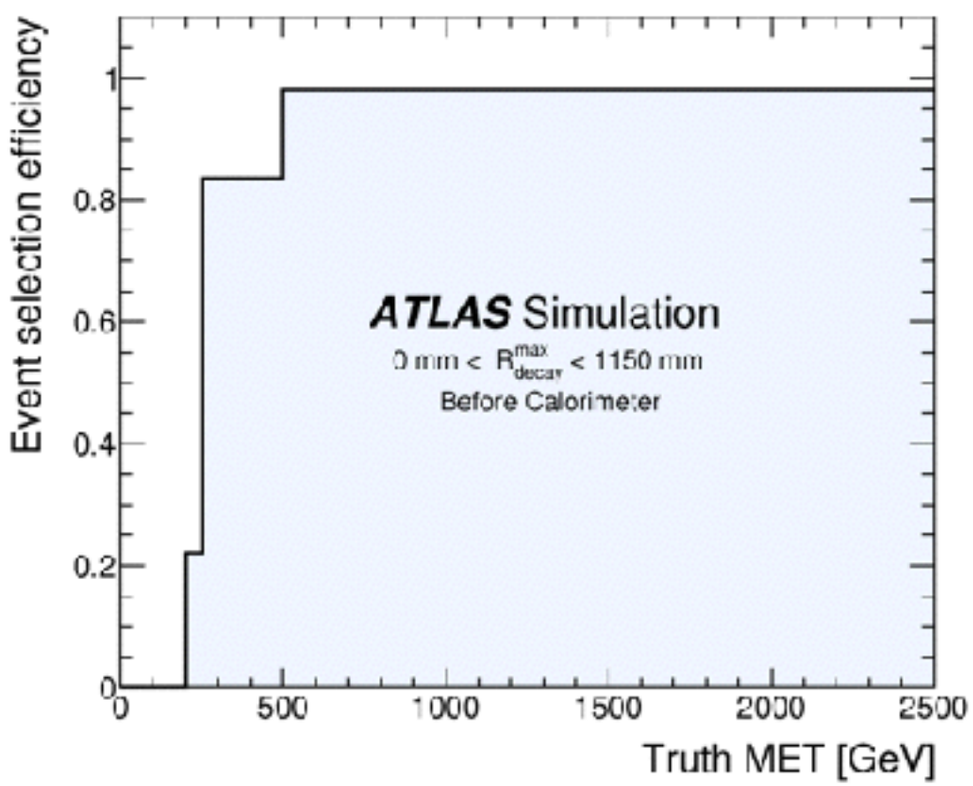
  Impossible to *precisely* recast without model-independent efficiencies as function of kinematic variables

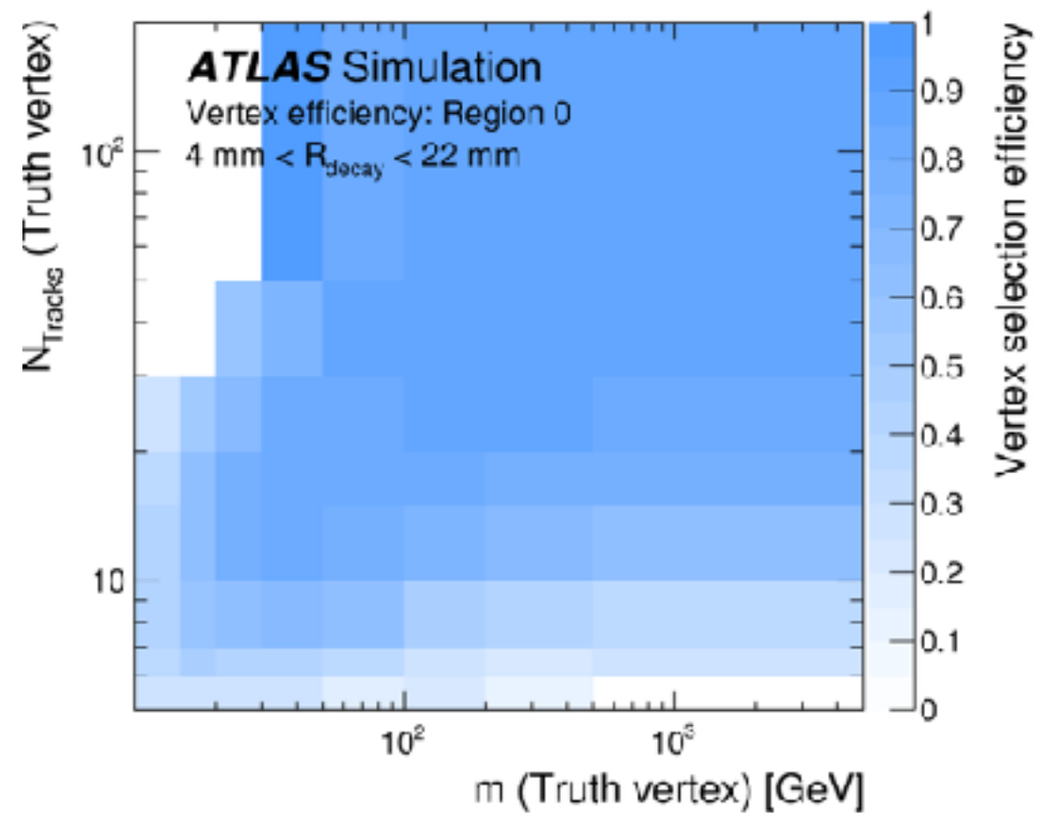
Recasting and Efficiencies

Thomas Jacques

- **Information from experiments is improving!**
  Stated goal is to provide as much info as possible to aid recasting,
  hopefully including LLP reconstruction efficiency as function of kinematic variables or at least efficiencies for wider range of simplified models and topologies

- **A good start**
  Selected event and vertex efficiencies for displaced vertices + MET



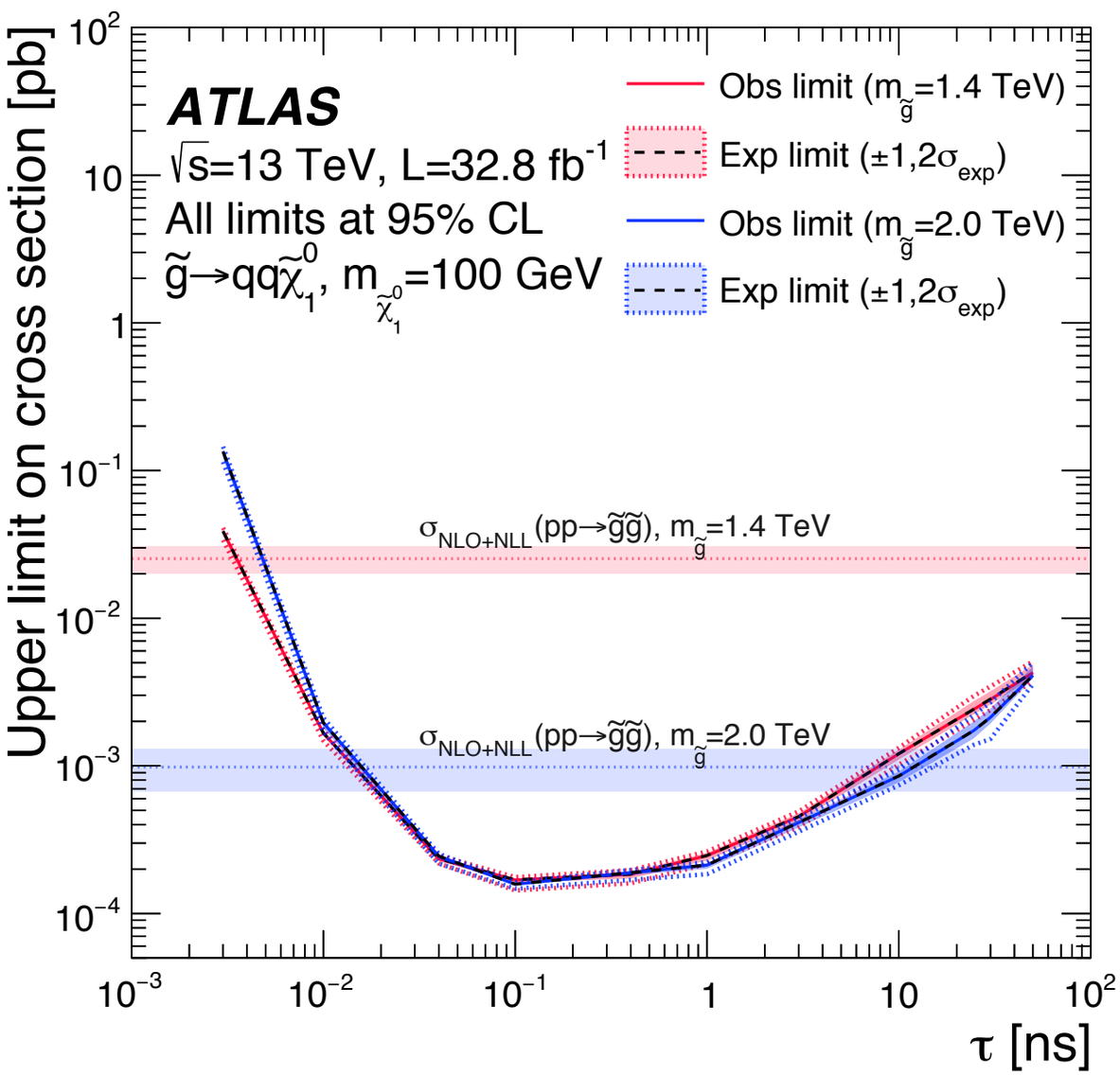


https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2016-08/

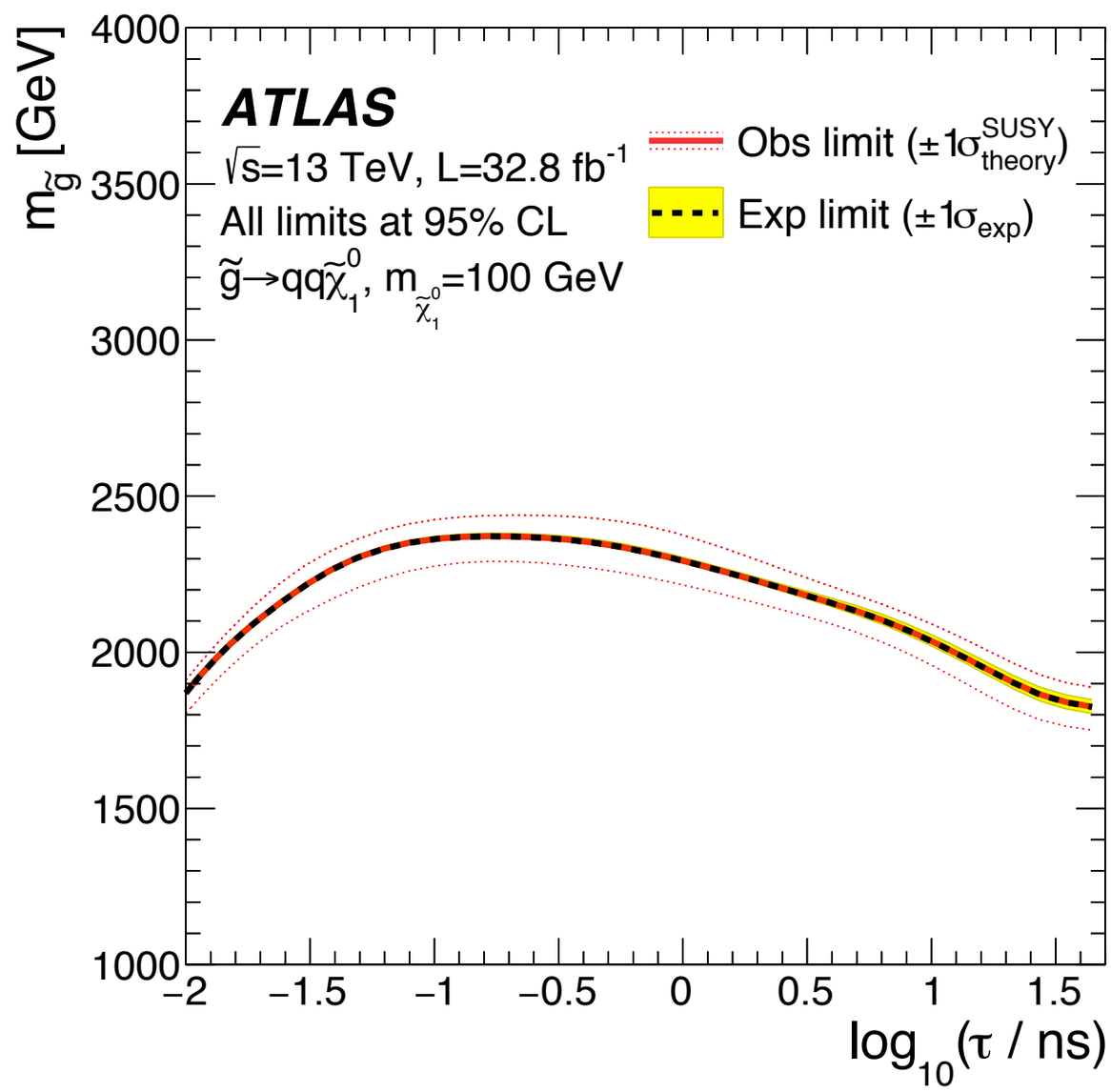
ATLAS results: DV + MET

Thomas Jacques

arXiv:1710.04901



(a) Upper limits on production cross section



(b) Lower limits on $m_{\tilde{g}}$

Monojet

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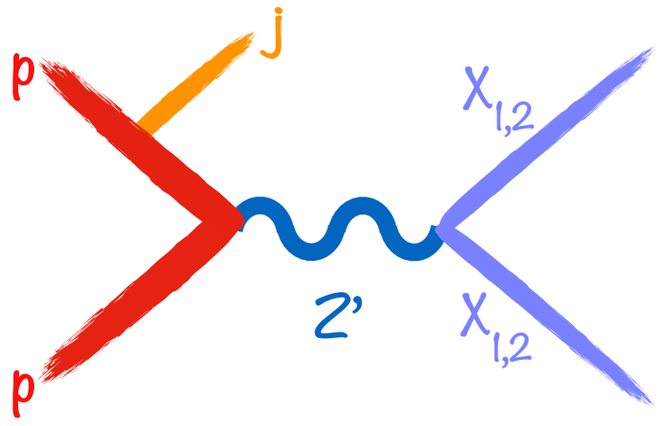

- **Use ATLAS monojet constraints**
  3.2 fb^{-1} of data
  Cuts on MET from 250 to 700 GeV
  Limit on cross-section 553 to 19 fb
- **Scale background up to 100 fb^{-1}**
  Assume same systematics
  & no observed signal;
  Limit scales to 4 fb