Dark Matter Searches at Large Hadron Collider

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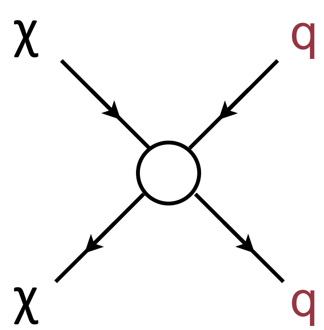
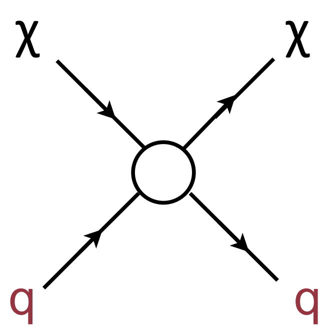
DARK MATTER DETECTION

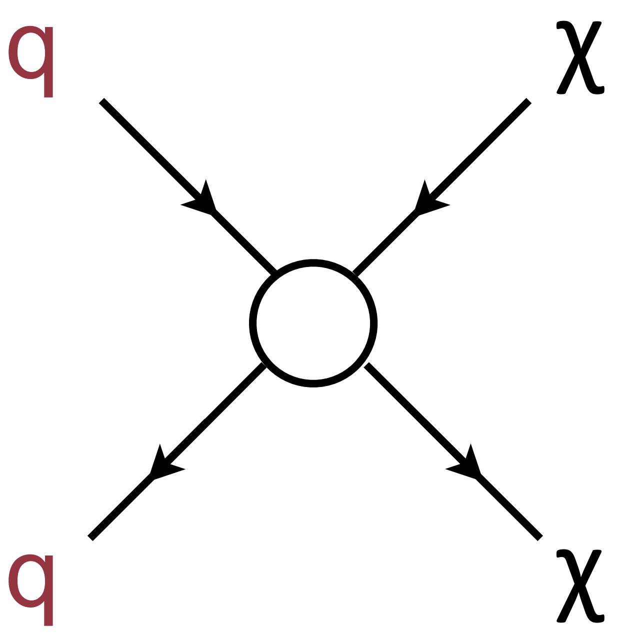
- Indirect detection
  - search for production of DM annihilation
  - high energy photons, particle-anti-particle pairs
  - search for ultra-relativistic objects produced in galactic halo
  - observatory on earth-bound or with satellites



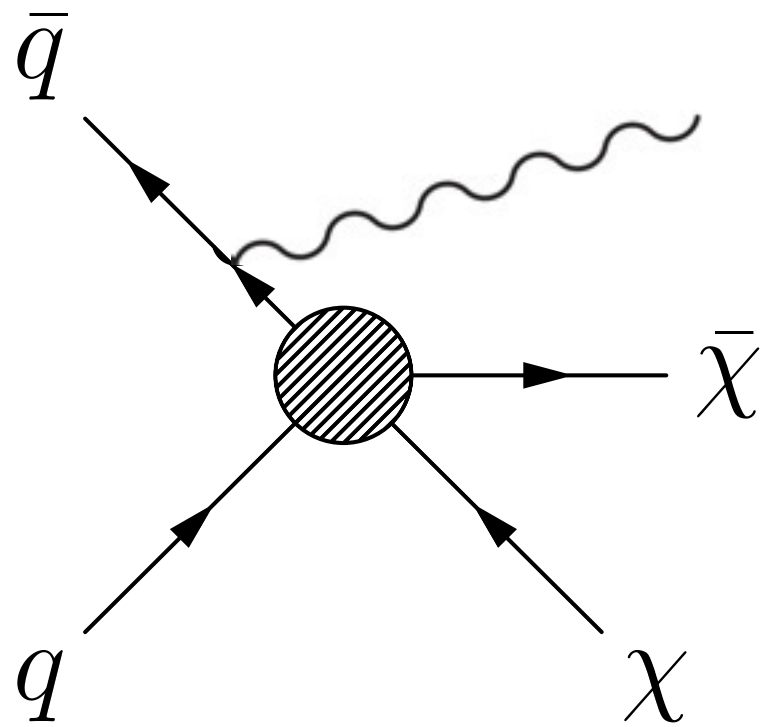
- Direct detection
  - Observe recoil of dark matter from nucleus

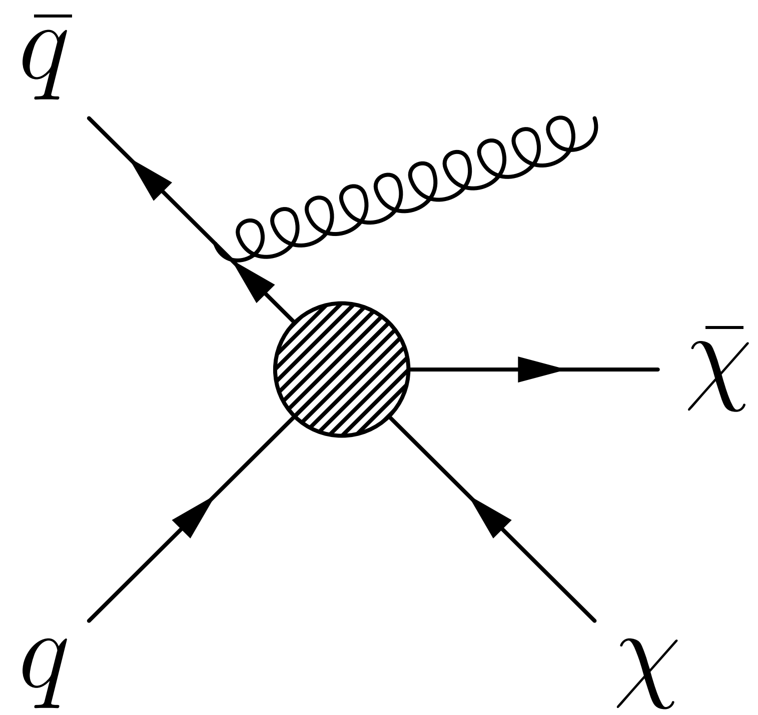


- Pair production at LHC
  - large missing energy in the detector
  - need to identify (“tag”) events of interest



DARK MATTER PRODUCTION AT LHC



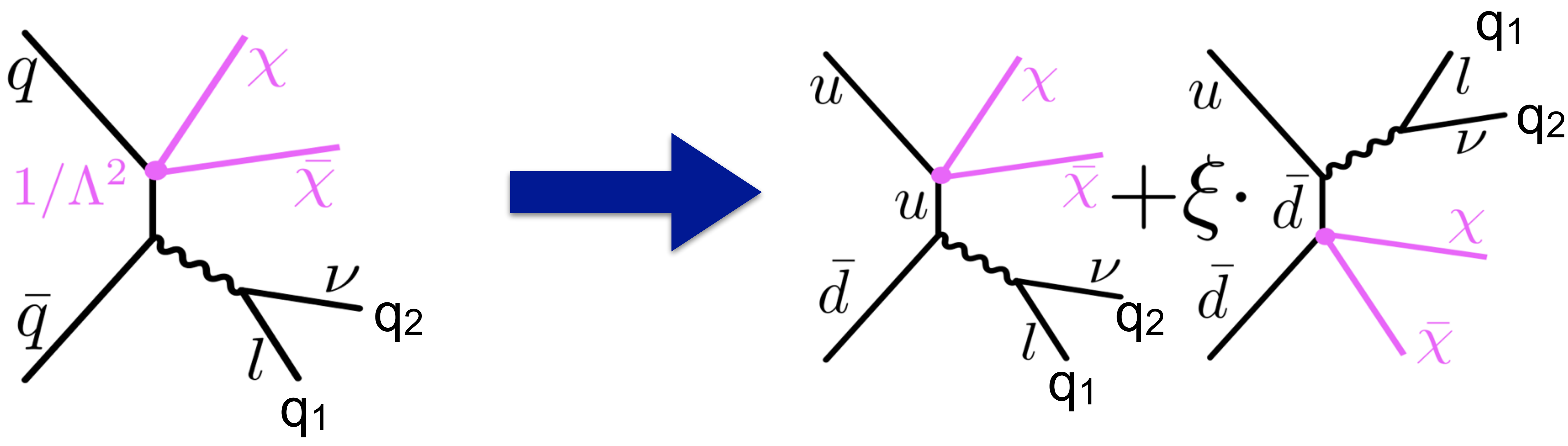


γ/W/Z + MET

gluon(jet) + MET

- EW bosons and gluons can be radiated by initial partons
- Presence of high energy photon/W/Z or jet(s) *in addition* to large missing transverse energy
- Gluon radiation at higher rate than EW bosons
  – strong interaction vs. electroweak

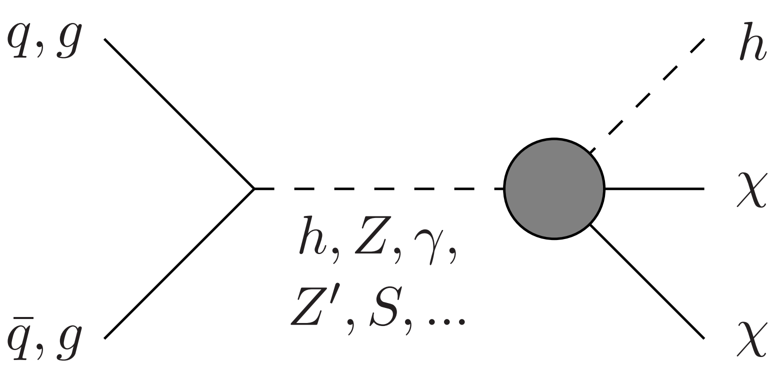
MONO-W + MET



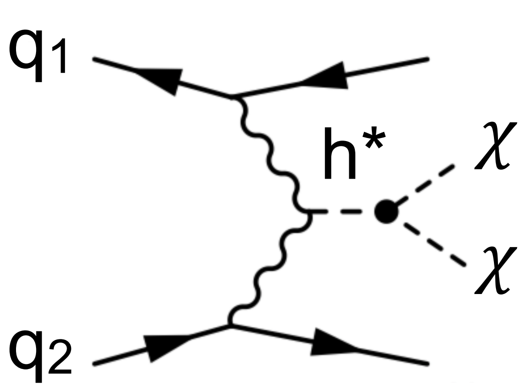
- W being charged can distinguish between u and d quarks
  - Need to account for interference
- Leptonic W decays
  - pro: clean high-pt lepton signature; single-lepton trigger
  - con: small branching ratio
- Hadronic W decays
  - pro: large branching ratio
  - con: large SM backgrounds

Higgs Portal to Dark Matter

- Discovery of Higgs has opened new doors to Dark matter
- New searches proposed to investigate coupling of dark matter candidates to Higgs boson
- mono-Higgs: Higgs + missing energy through new operator
  - produced via both quarks and gluons

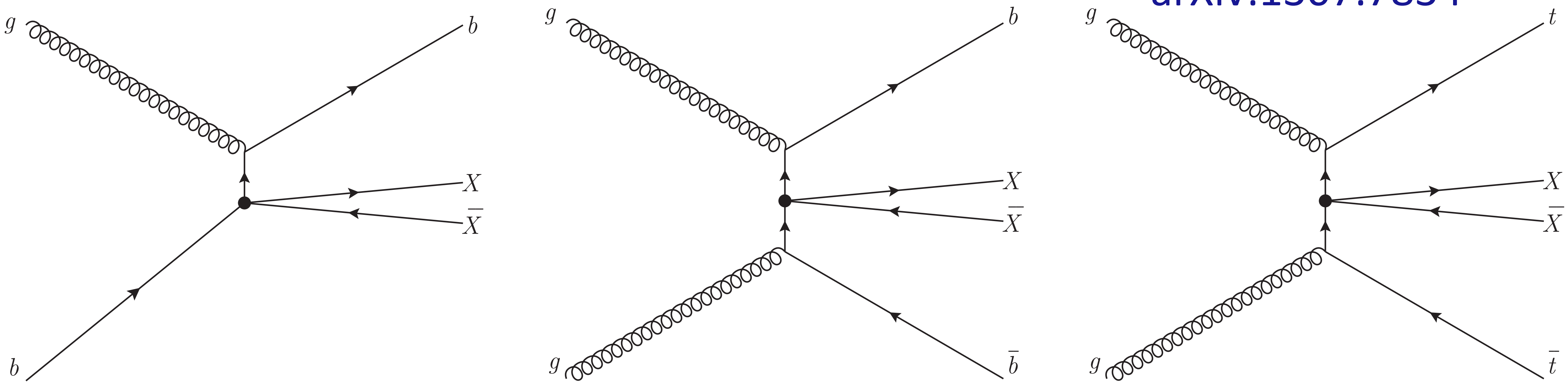


- Higgs mediation: dark matter candidate couples only to Higgs and no other SM particle
  - $m_{DM} < m_H/2$: Higgs decay to DM pair
    - Currently branching ratio of invisible Higgs decays < ~60%
      - ➡ expect to reach BR < 0.2-0.3 with 3000 fb^{-1}
  - $m_{DM} > m_H/2$: DM pair from virtual Higgs
    - Distinctive signature with forward jets



THINKING OUT OF THE BOX: MONO-b/t

arXiv:1307.7834

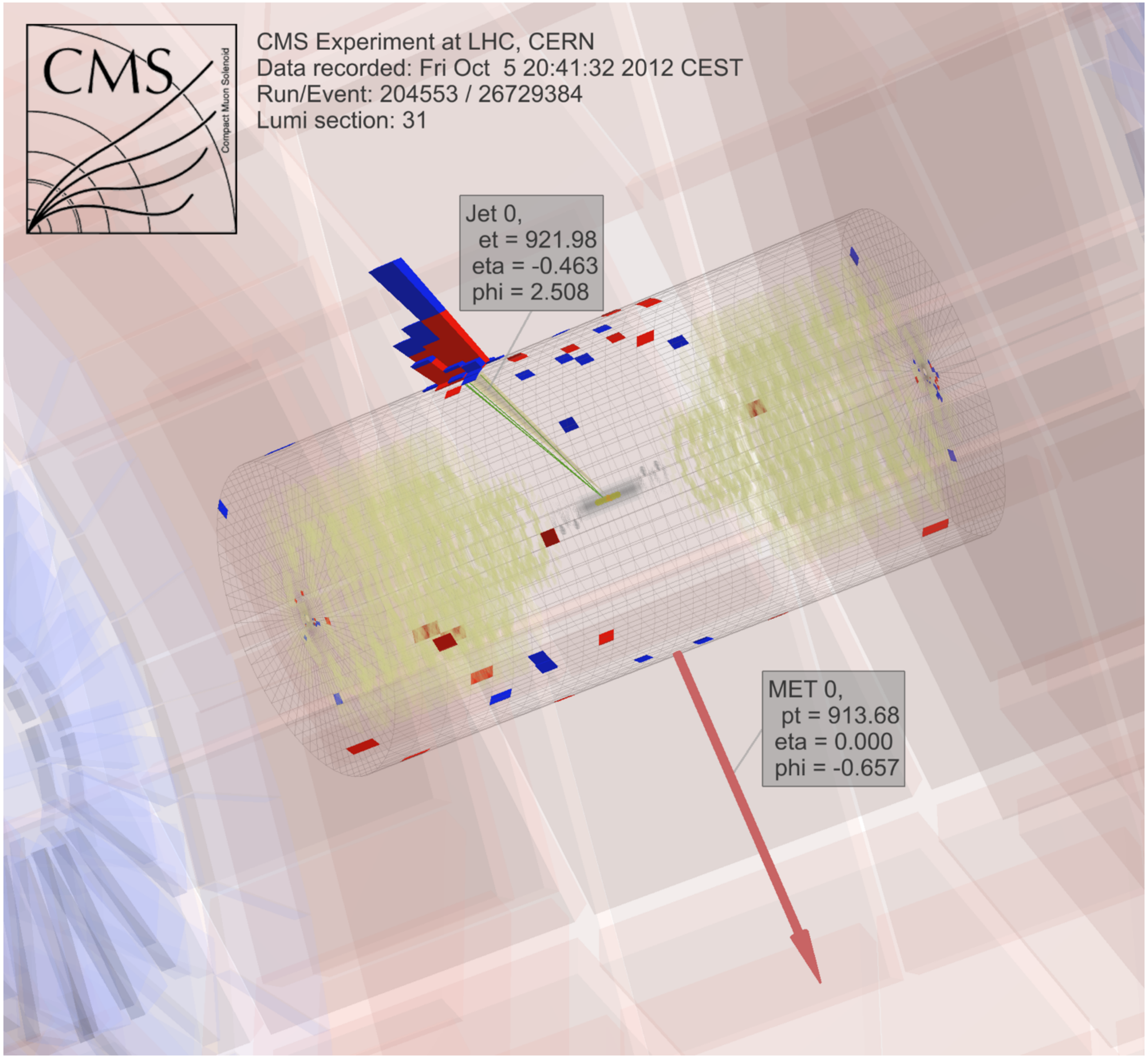


- Important for a scalar mediator operator
  - Structure constrained by flavor violation
- Enhanced coupling for third generation quark
  - coupling proportional to mass
- Dedicated analysis exploiting boosted top and b-tag more competitive than generic mono-jet search
- Efforts underway in ATLAS
  - reinterpretation of existing SUSY results performed by theorists

Summary of Current Searches

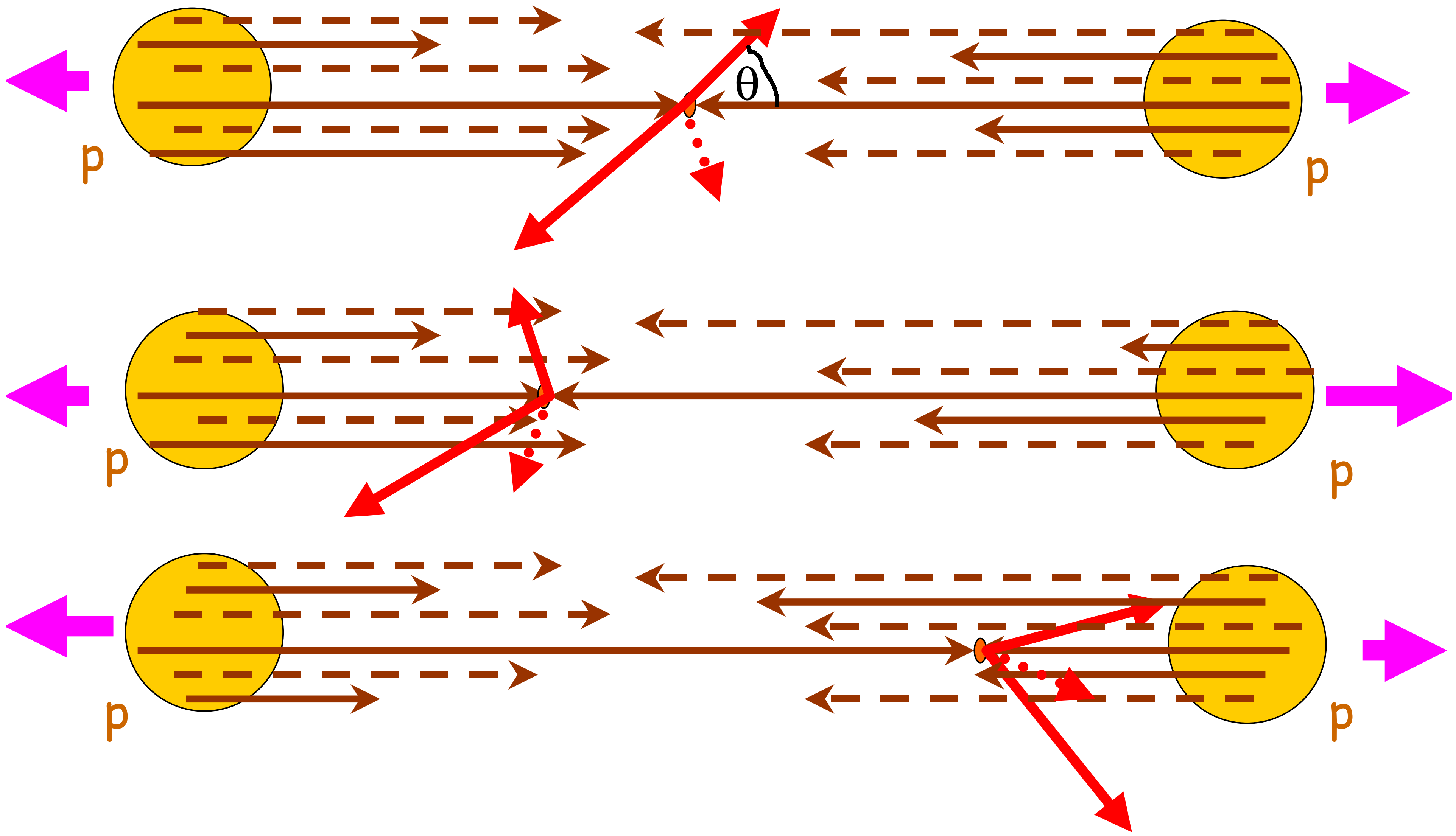
- mono-jet
  - strongest constraints
- mono-photon
  - more challenging for background estimation
  - less powerful: EW vs. strong interaction
- mono-W/Z leptonic
  - clean signature and simple trigger
  - penalized by W/Z branching fraction
- mono-W/Z hadronic
  - larger statistics with larger background

Mono-Jet Candidate



KINEMATICS AT LHC

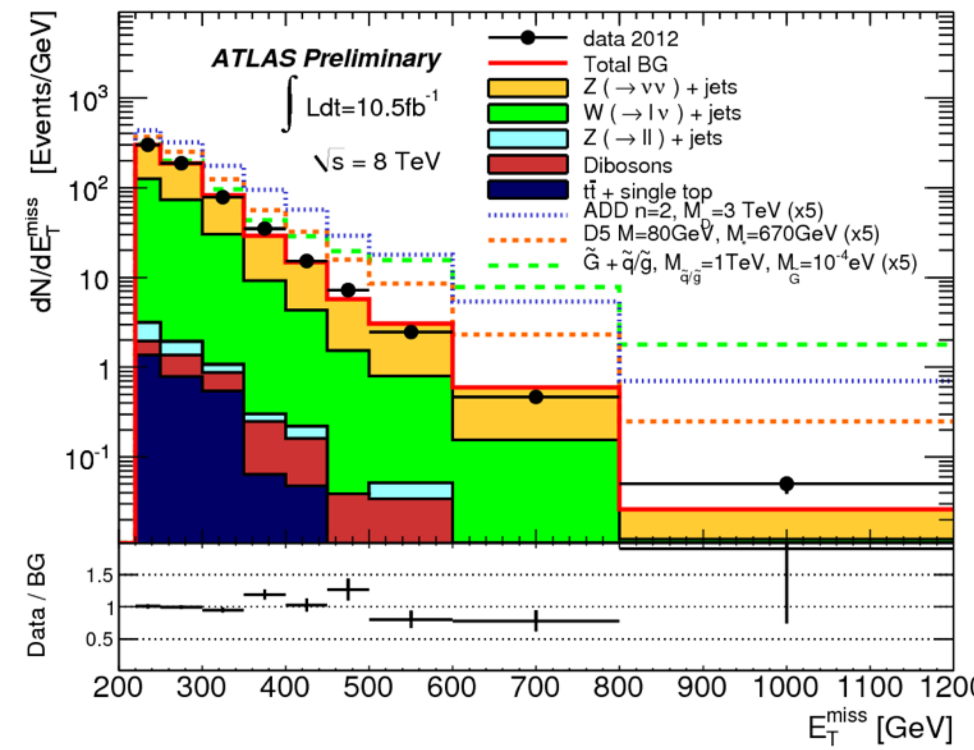
$$p_1 = x_1 \cdot E_{beam} \qquad\qquad p_2 = x_2 \cdot E_{beam}$$



- No a-priori knowledge of longitudinal boost: xi different and unknown at each collision
- Conservation of 4-momentum in transverse plane
  - measure momenta and energy of interacting particles
  - compute momenta of escaping particles

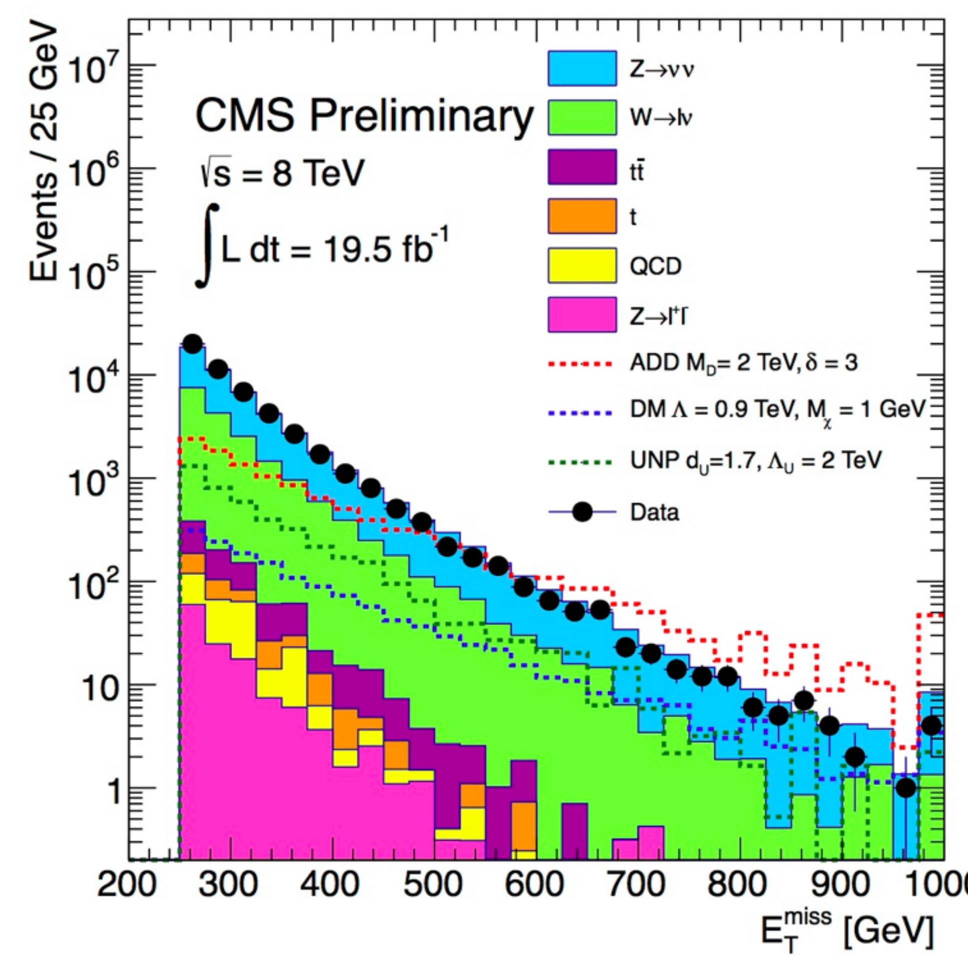
Mono-Jet Search

- Pair produced Dark Matter
  - missing energy and radiated jet(s)
  - similar strategy also for photons



- Event selection
  - leading jet p_T > ~120 GeV
  - topological cut to reduce QCD, e.g. opening of two jets
  - veto events with isolated leptons

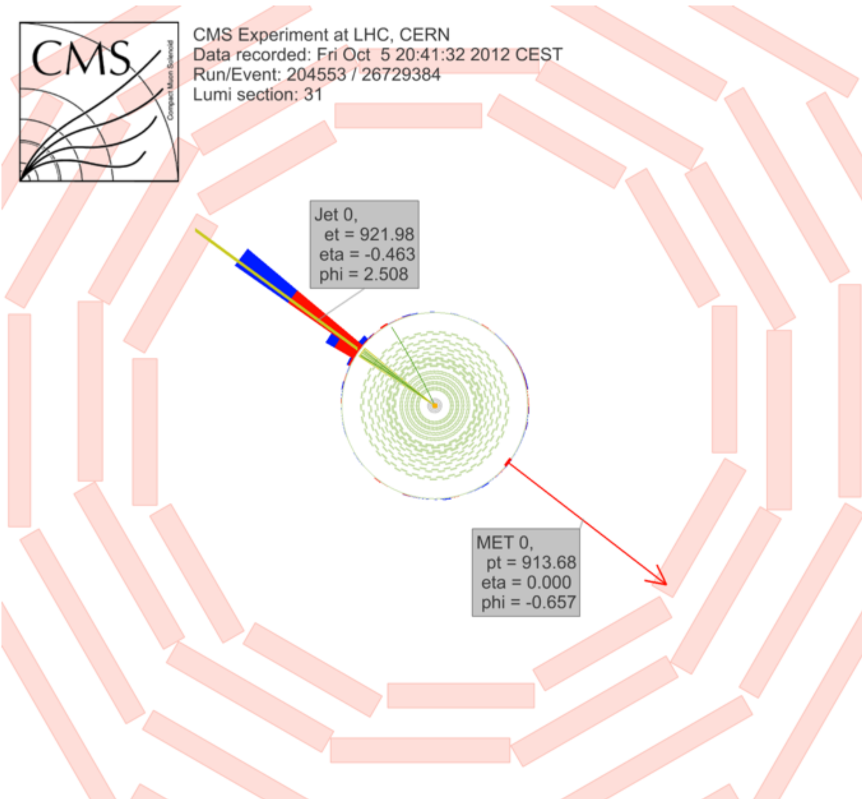
- Background determination
  - mainly from data
    - Z(νν) + jets from measurement of Z + jets
    - W(lν) + jets from measurement of W + jets
  - MC only for very small backgrounds
    - ttbar, QCD, non-collision



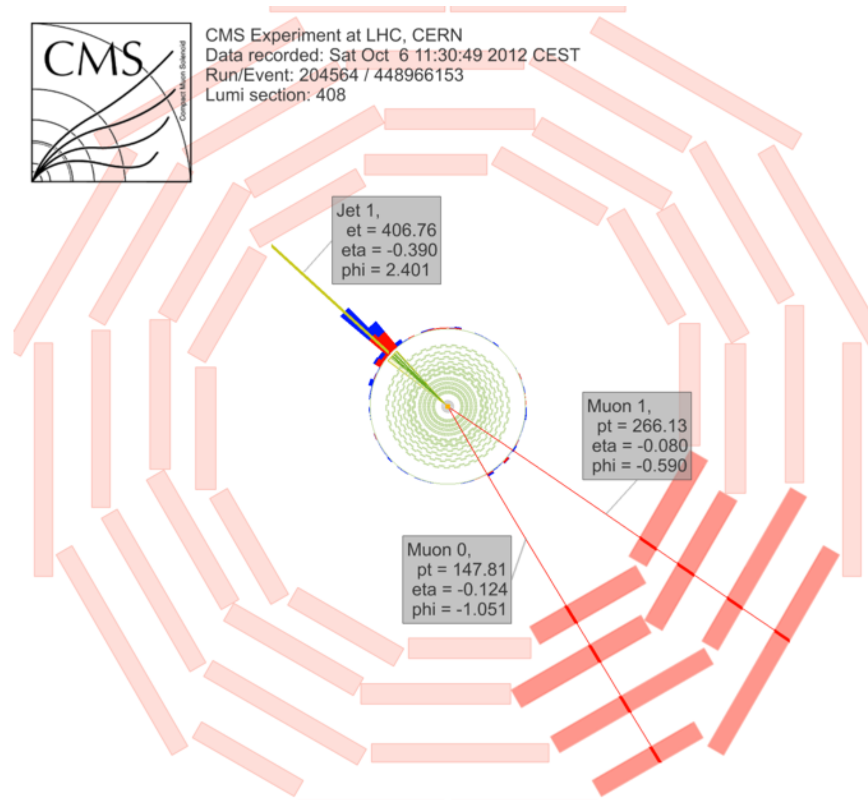
- Count events with MET > 350-400 GeV

BACKGROUNDS

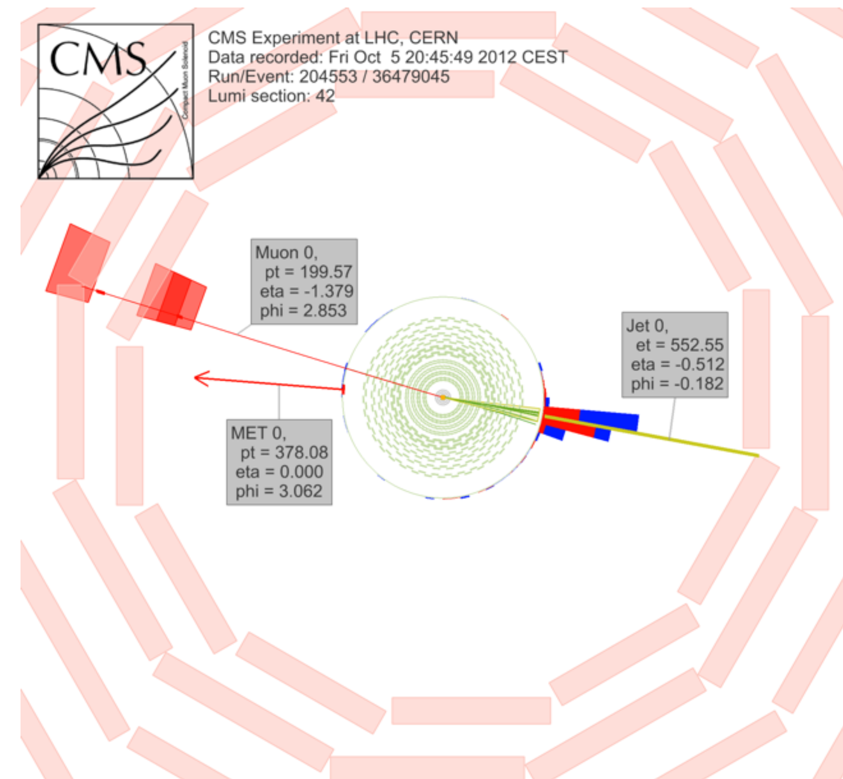
Signal



Z(νν)+jets: ~65% estimated from data



W(lν)+jets: ~30% estimated from data



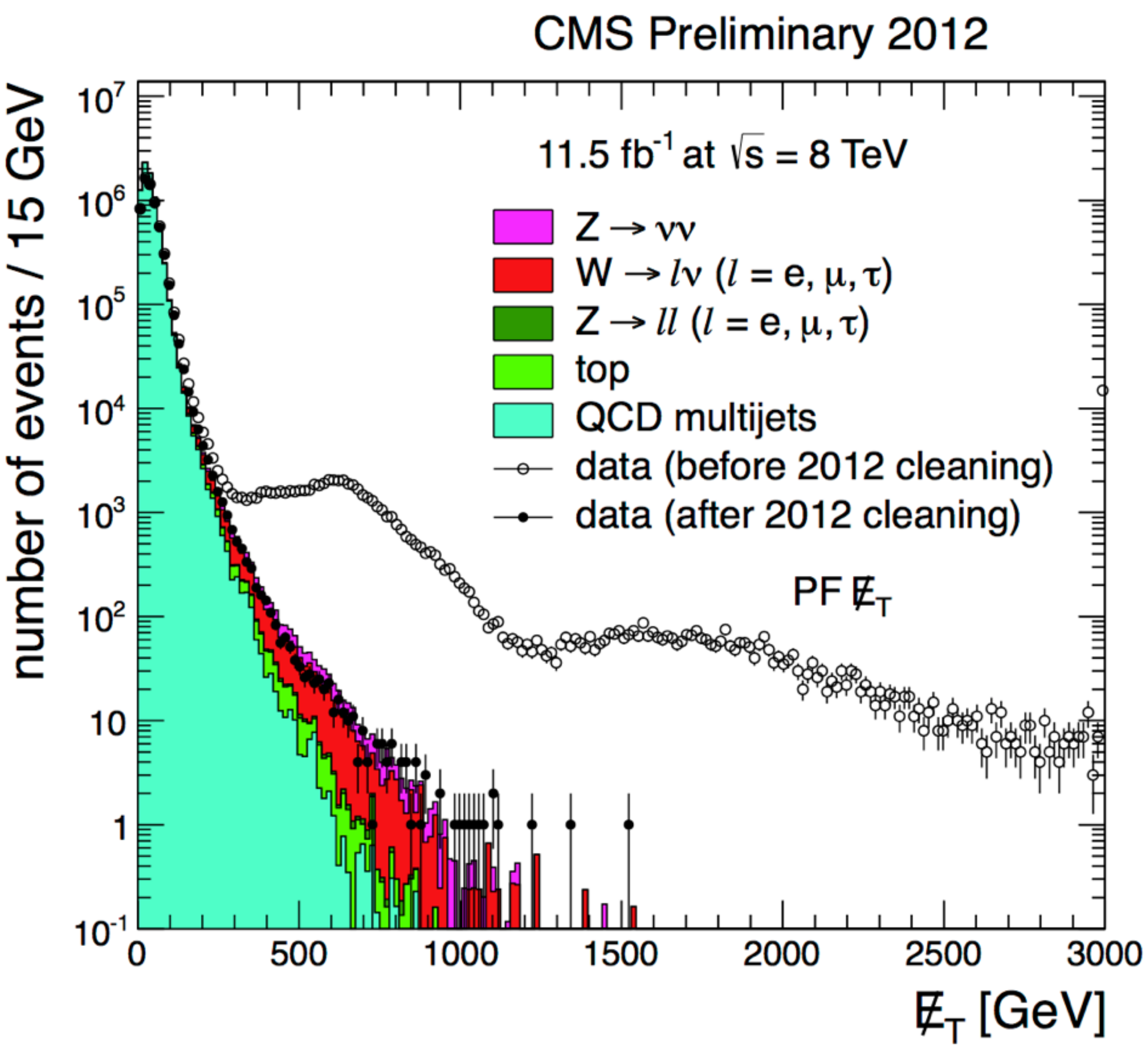
Background Composition

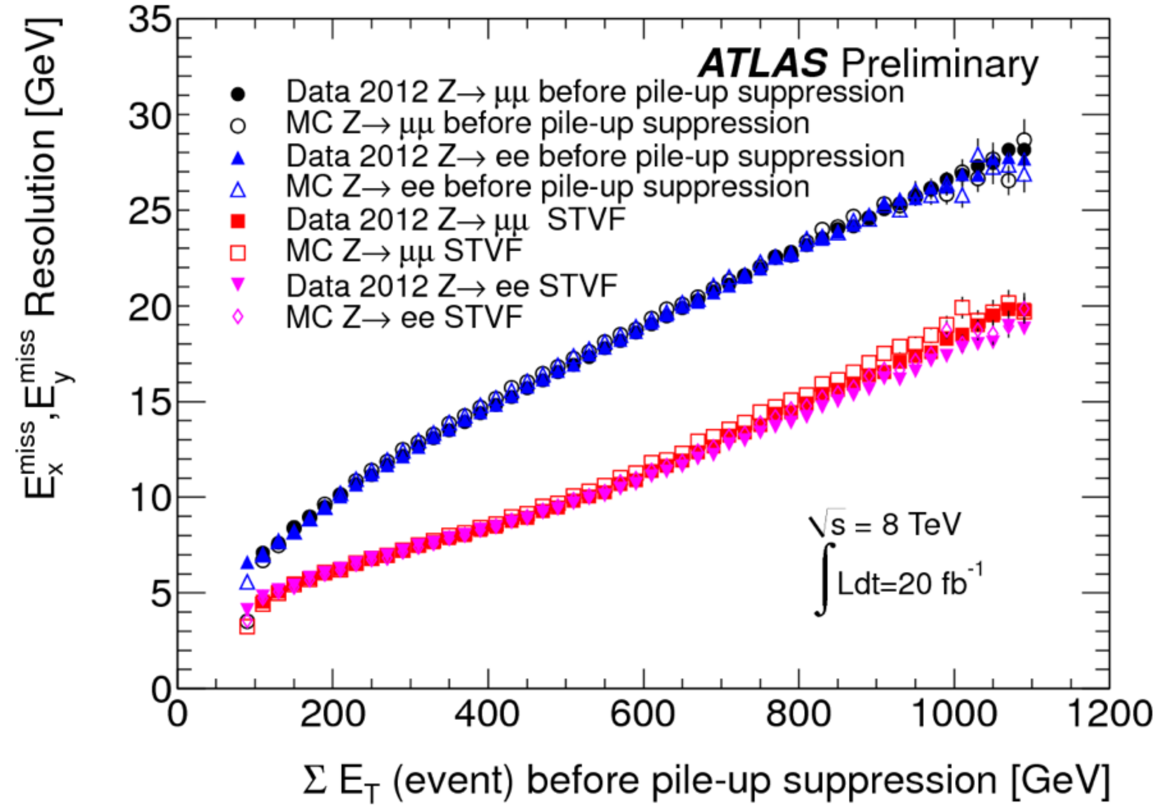
E_T^{miss} (GeV) $\rightarrow$	> 250	> 300	> 350	> 400	> 450	> 500	> 550
$Z(\nu\nu)$+jets	30600 ± 1493	12119 ± 640	5286 ± 323	2569 ± 188	1394 ± 127	671 ± 81	370 ± 58
W+jets	17625 ± 681	6042 ± 236	2457 ± 102	1044 ± 51	516 ± 31	269 ± 20	128 ± 13
$t\bar{t}$	470 ± 235	175 ± 87.5	72 ± 36	32 ± 16	13 ± 6.5	6 ± 3.0	3 ± 1.5
$Z(\ell\ell)$+jets	127 ± 63.5	43 ± 21.5	18 ± 9.0	8 ± 4.0	4 ± 2.0	2 ± 1.0	1 ± 0.5
Single t	156 ± 78.0	52 ± 26.0	20 ± 10.0	7 ± 3.5	2 ± 1.0	1 ± 0.5	0 ± 0
QCD Multijets	177 ±88.5	76 ±38.0	23 ±11.5	3 ±1.5	2 ±1.0	1 ± 0.5	0 ± 0
Total SM	49154 ± 1663	18506 ± 690	7875 ± 341	3663 ± 196	1931 ± 131	949 ± 83	501 ± 59
Data	50419	19108	8056	3677	1772	894	508

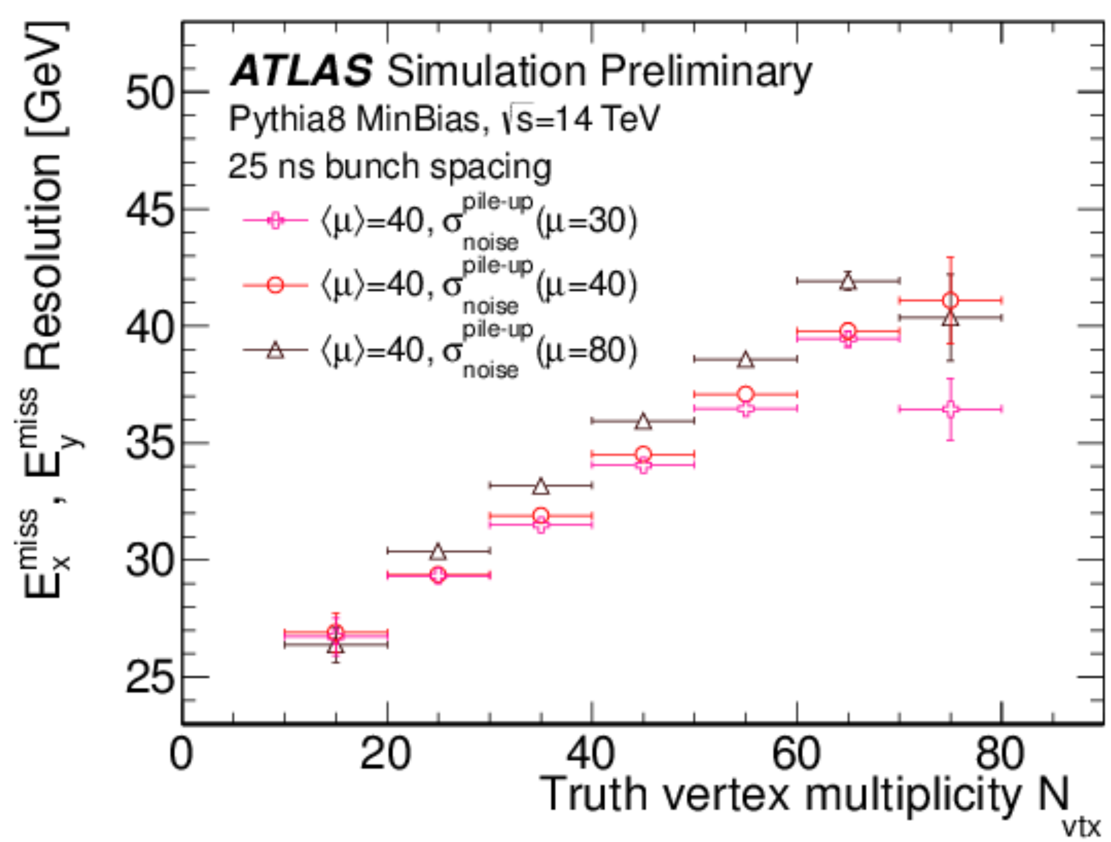
Systematic Uncertainty

E_T^{miss} (GeV)	> 250	> 300	> 350	> 400	> 450	> 500	> 550
Statistics (N^{obs})	1.7	2.6	3.9	5.6	7.6	10.9	14.6
Background (N^{bgd})	0.8	0.6	0.8	0.2	0.0	0.0	0.0
Acceptance (A)	2.0	2.0	2.0	2.1	2.1	2.2	2.4
Selection efficiency (ϵ)	2.0	2.0	2.1	2.2	2.4	2.7	3.1
Total	4.5	4.9	5.8	7.1	8.9	12.1	15.6

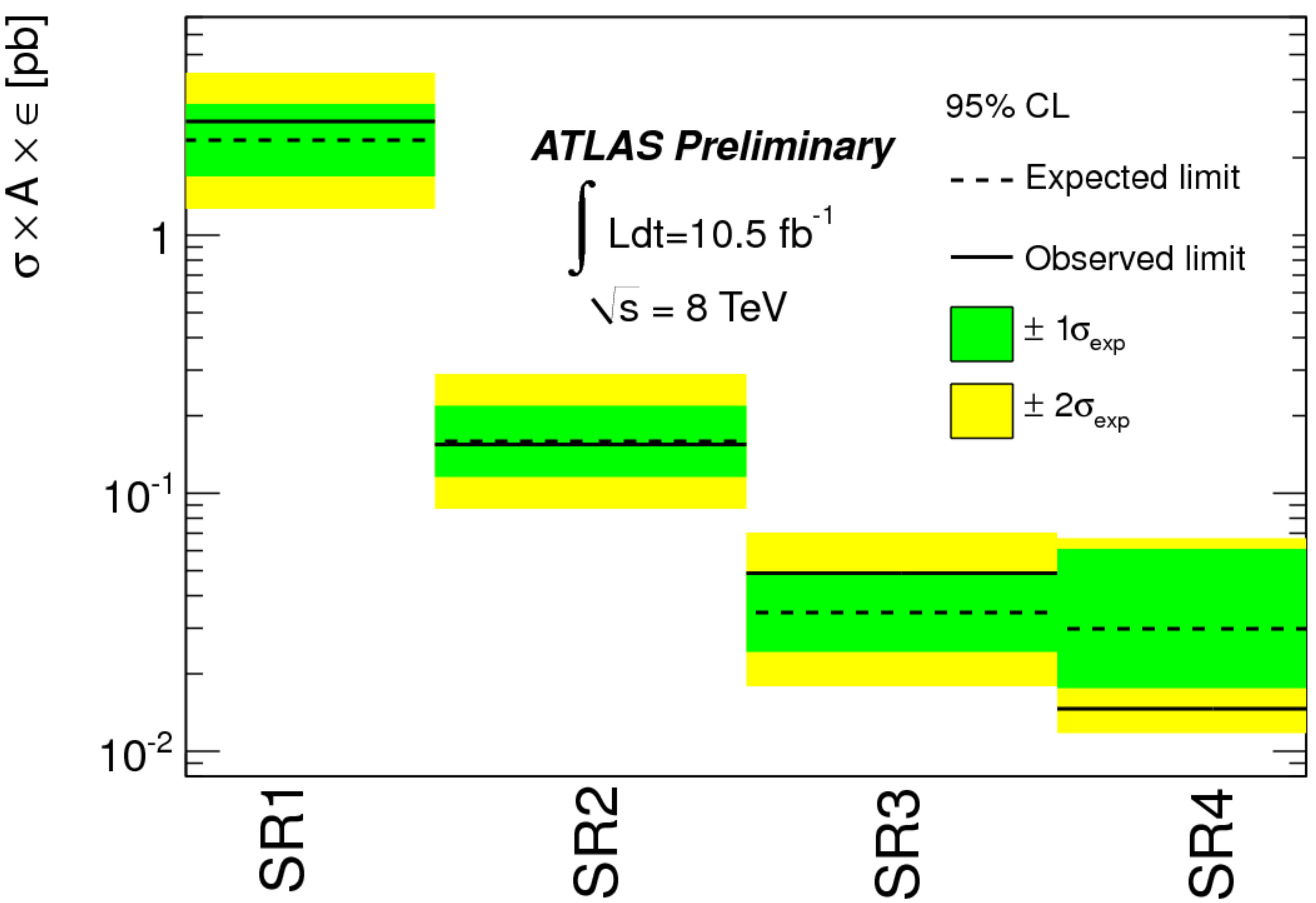
MISSING ENERGY MEASUREMENT

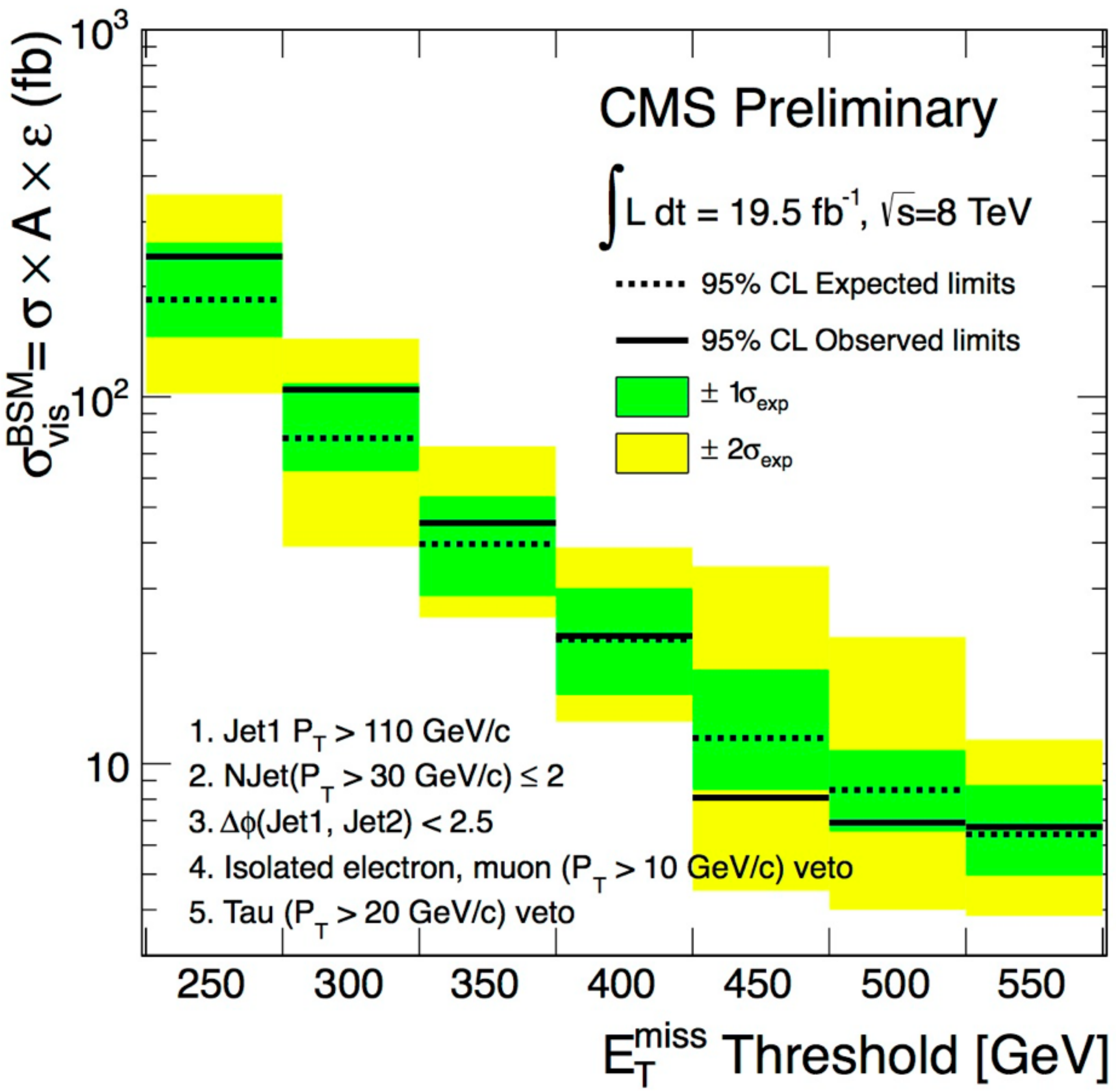






Model-Independent Limits

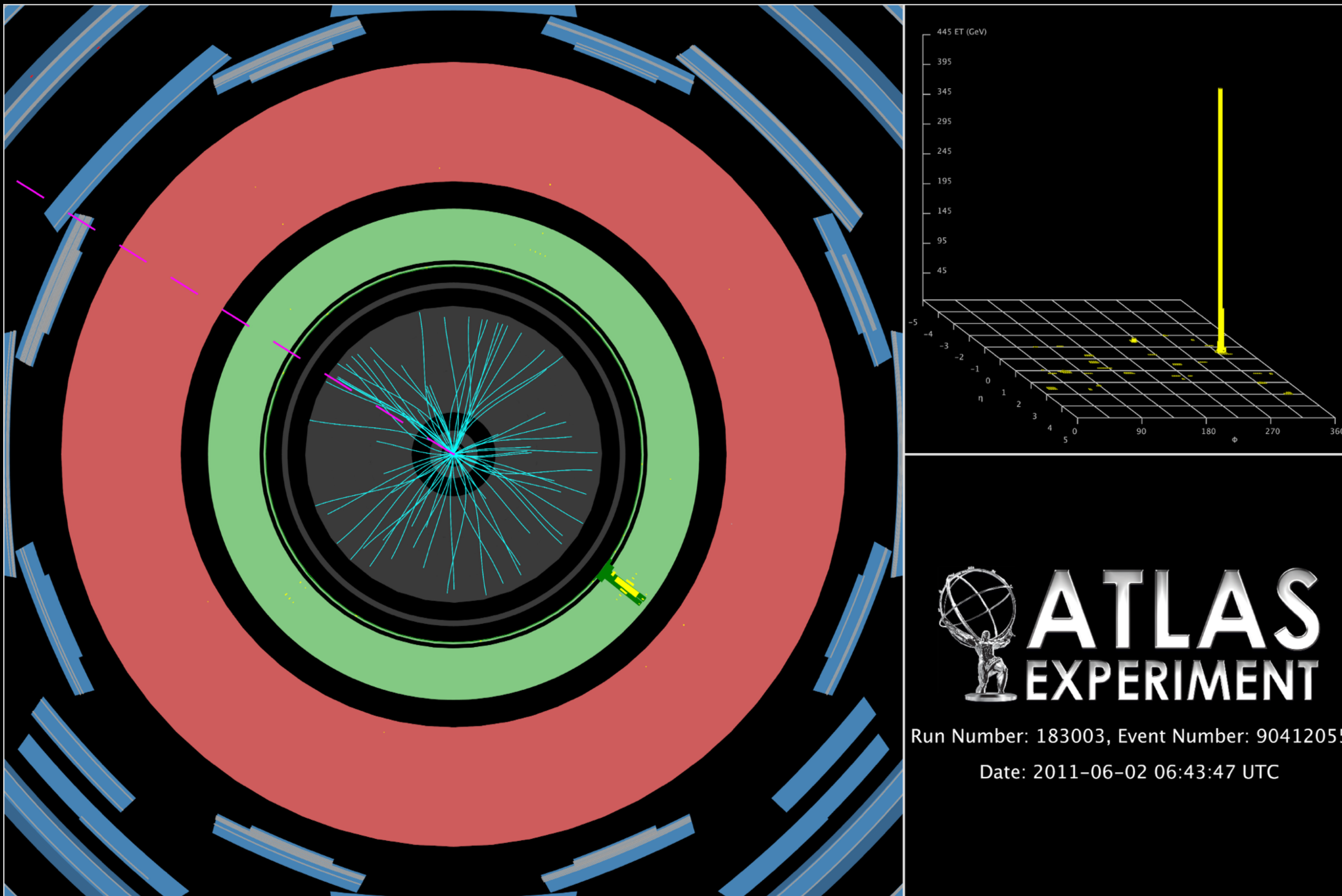




[ATLAS-CONF-12-147, CMS EXO-12-048]

- Both experiments quote model-independent limits for generic applicability to SUSY compressed spectra, invisible Higgs, or any other "monojet" signature

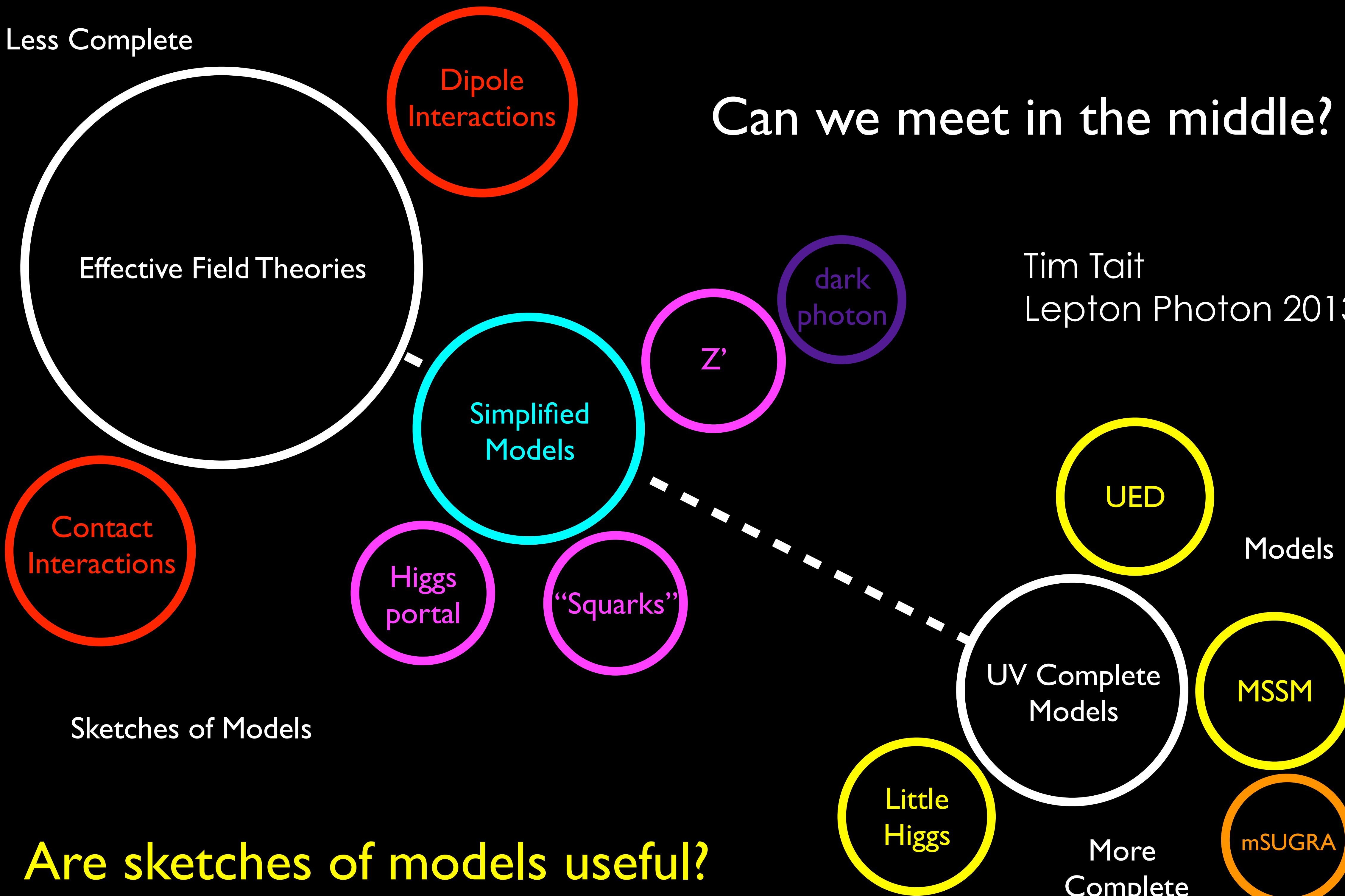
Mono-Photon Candidate



Spectrum of Theory Space

Can we meet in the middle?

Tim Tait
Lepton Photon 2013



Are sketches of models useful?

Modeling the DM Interaction

$$\sigma(pp \to \bar{\chi}\chi + X) \sim \frac{g_q^2 g_\chi^2}{(q^2 - M^2)^2 + \Gamma^2/4} E^2$$

~ $1/\Lambda^4$ E^2 for $M \to$ 40 TeV (EFT)

$$\Lambda \equiv M/\sqrt{g_\chi g_q}$$

- Pair-production of χ can be characterized by a contact interaction with operators

$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}$$

vector --> spin independent (SI)

$$\mathcal{O}_{AV} = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2}$$

axial-vector --> spin-dependent (SD)

- Cross section depends on the mass (m_χ) and the scale Λ (for couplings g_χ, g_q)

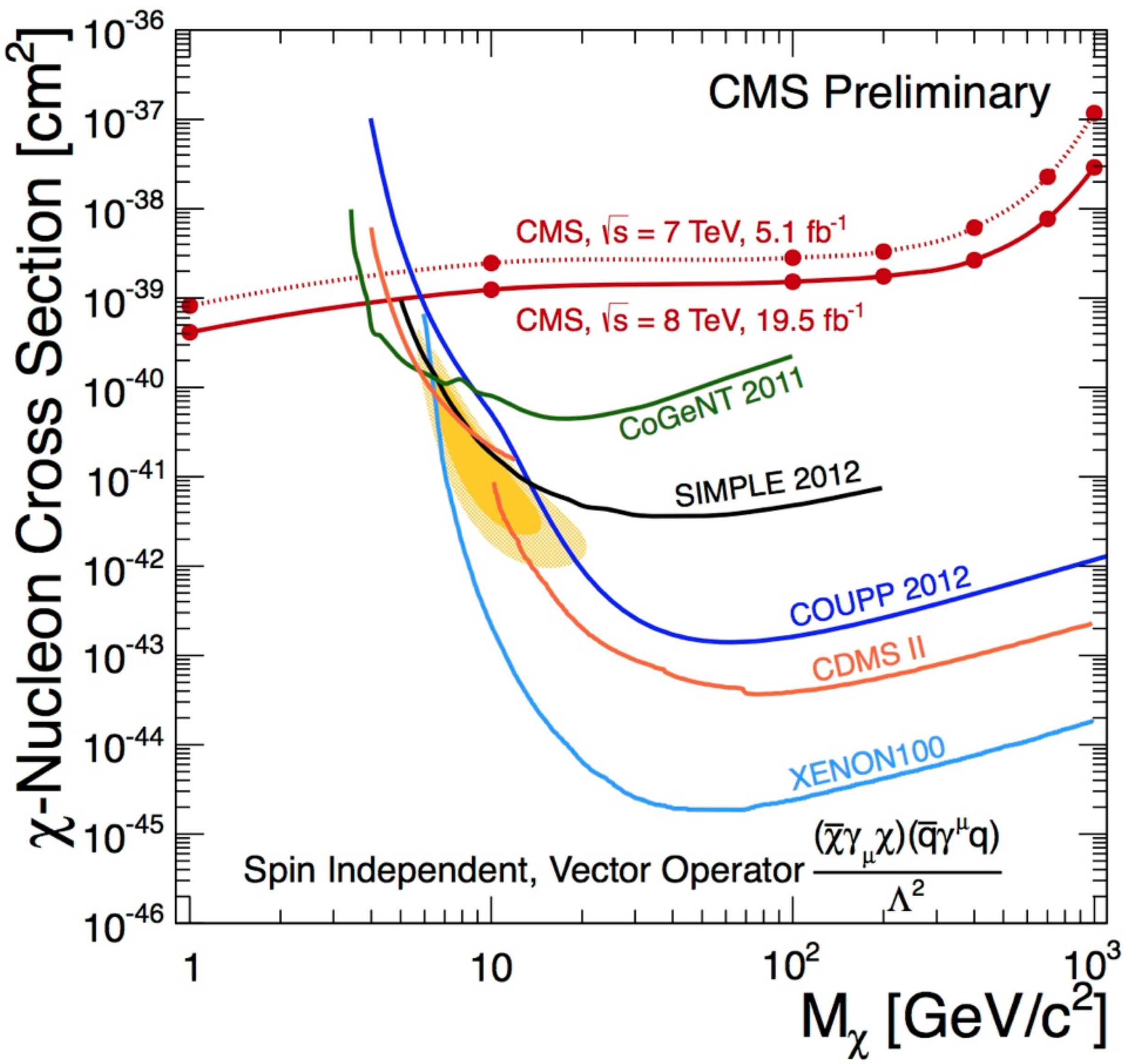
spin-independent and spin-dependent cross sections

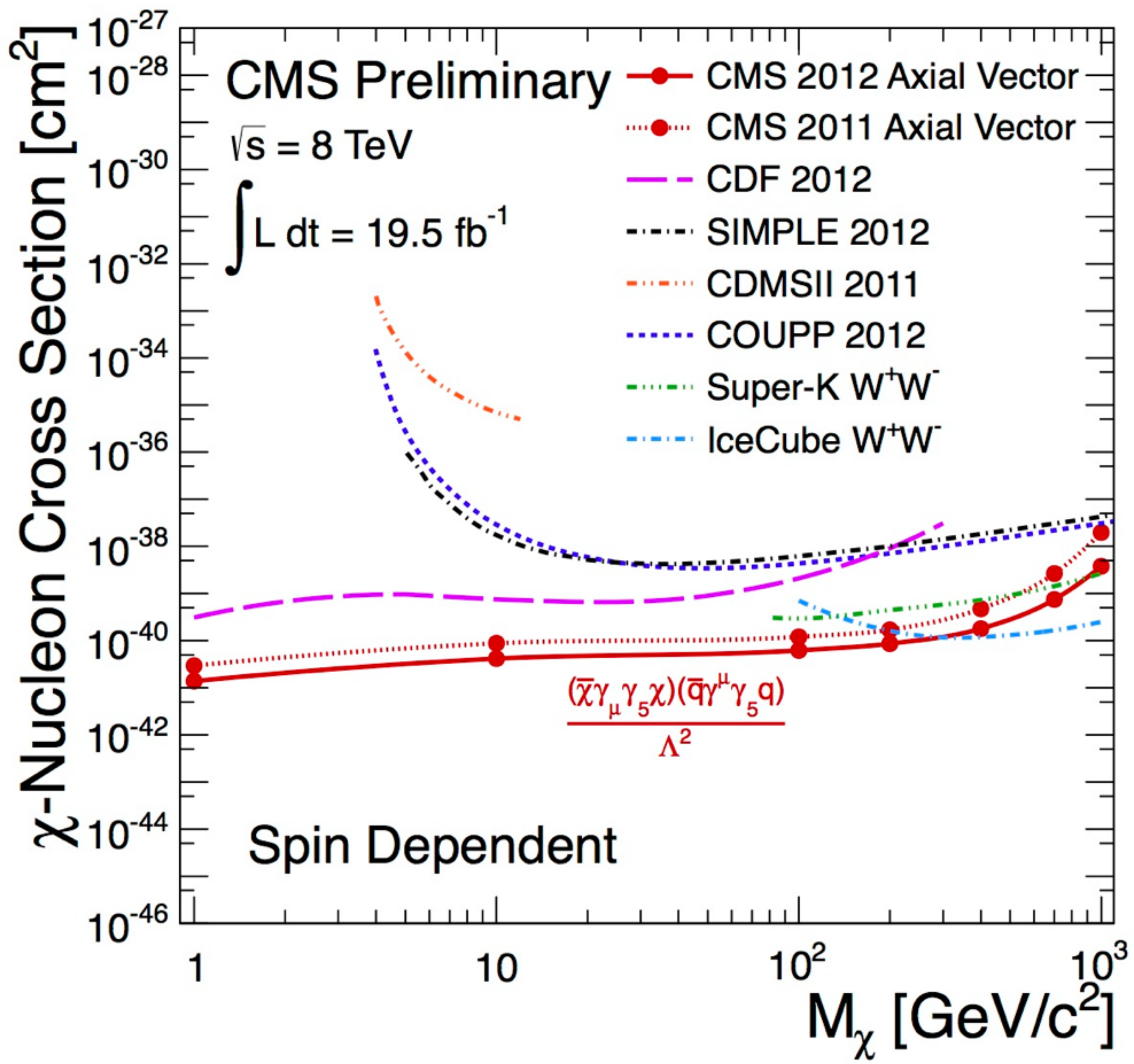
$$\sigma_{SI} = 9\frac{\mu^2}{\pi\Lambda^4} \qquad \Lambda = M/\sqrt{g_\chi g_q}$$

$$\sigma_{SD} = 0.33\frac{\mu^2}{\pi\Lambda^4} \qquad \mu = \frac{m_\chi m_p}{m_\chi + m_p}$$

[Bai, Fox and Harnik, JHEP 1012:048 (2010)]
[Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu, Phys.Rev.D82:116010 (2010)]
[Beltran, Hooper, Kolb, Krusberg, Tait, JHEP 1009:037 (2010)]

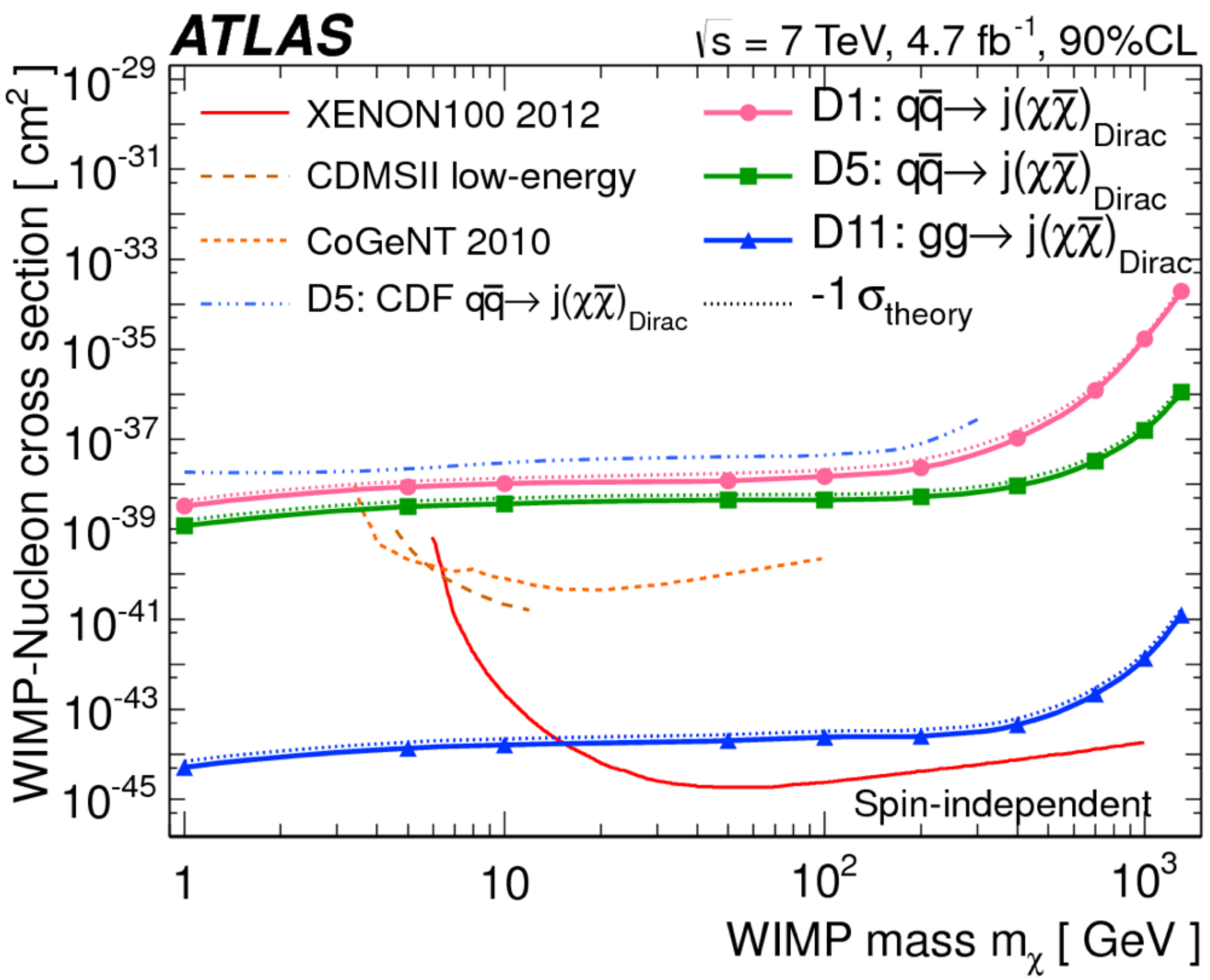
LIMIT ON CROSS SECTION

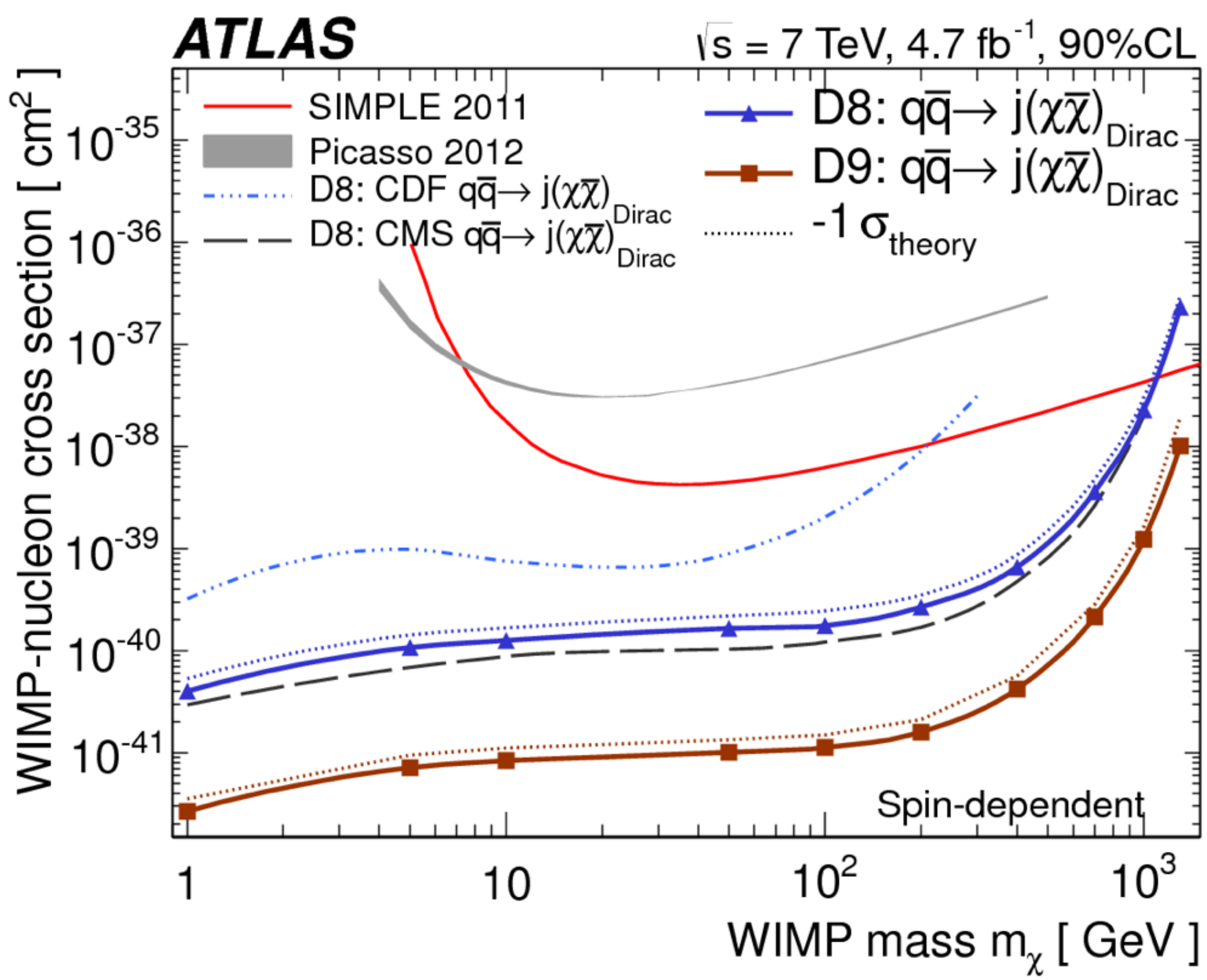




- Limits depend on assumption on operator nature in Effective Theory
  - Varies significantly for different operators
  - Validity of assumption depends on mass of mediator
  - At low mediator mass, assumptions might not hold at high center of mass energy

Cross Section and Operators





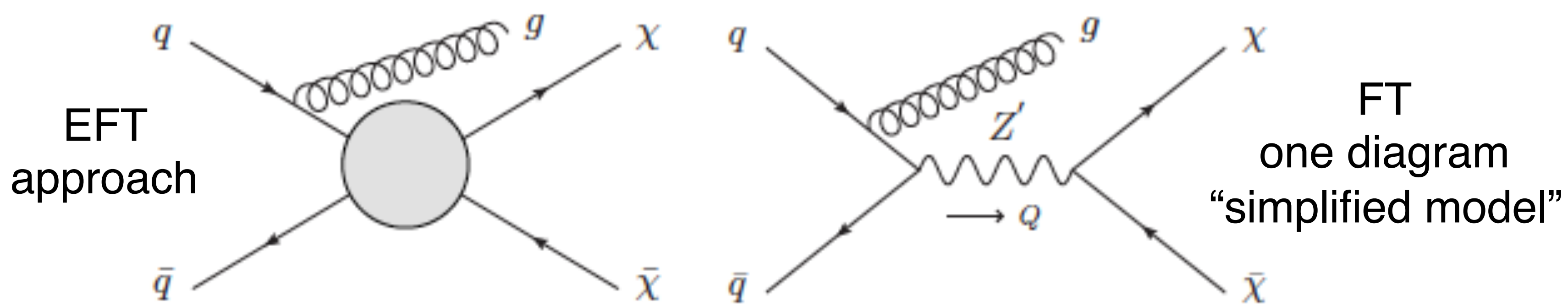
Name	Initial state	Type	Operator
D1	qq	scalar	$\frac{m_q}{M_\star^3}\bar{\chi}\chi\bar{q}q$
D5	qq	vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D8	qq	axial-vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
D9	qq	tensor	$\frac{1}{M_\star^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$
D11	gg	scalar	$\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$

in the loop

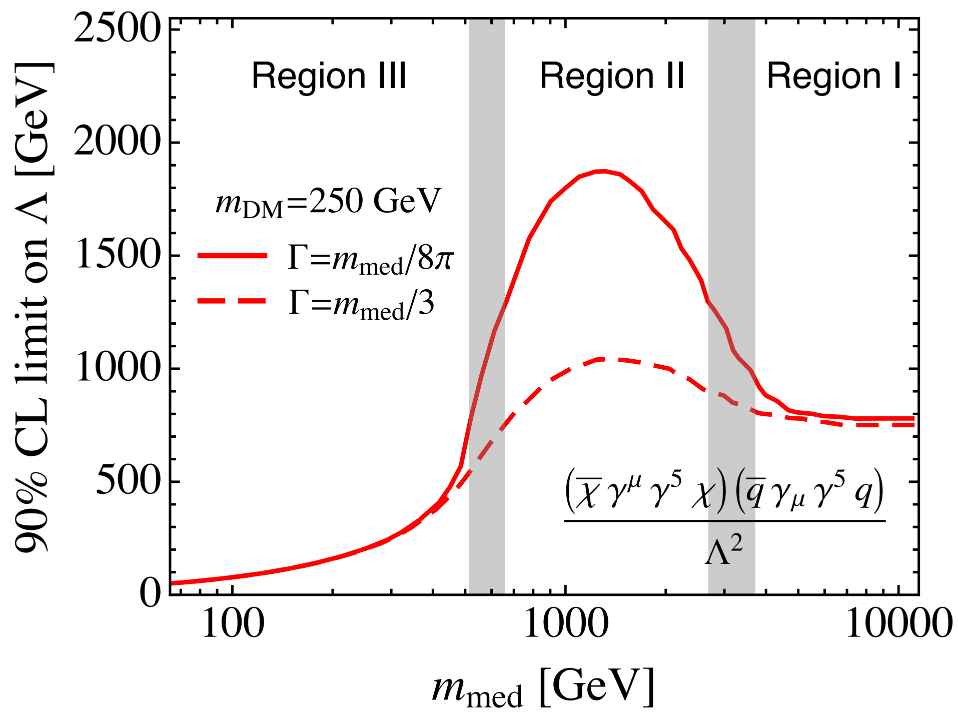
Validity of EFT Limits

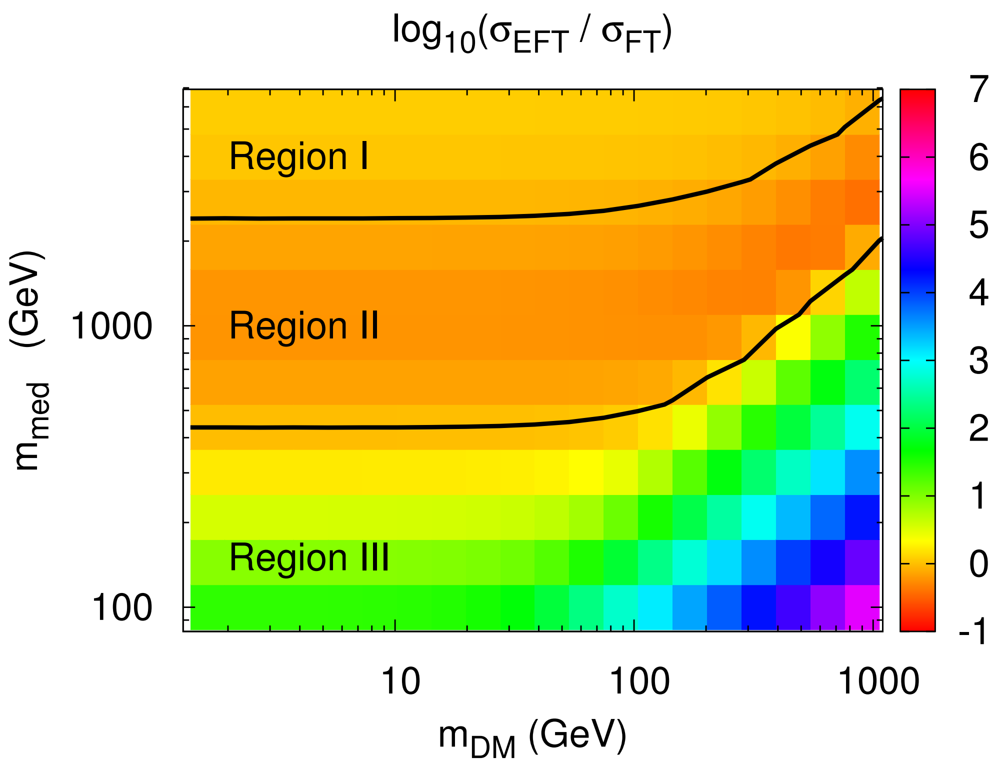
Recent work from OB, M.Dolan,C.McCabe: arXiv:1308.6799

- Compare Effective Field Theory (EFT) with Full Theory (FT)



Use vector and axial-vector mediators (e.g. Z') as example - scalar are similar in conclusion!





Region I: Heavy m_{med}
- EFT is valid!

Region II: Medium m_{med} – Resonant enhancement
- EFT limits are too conservative!

Region III: Low m_{med}
- EFT limits are too aggressive!

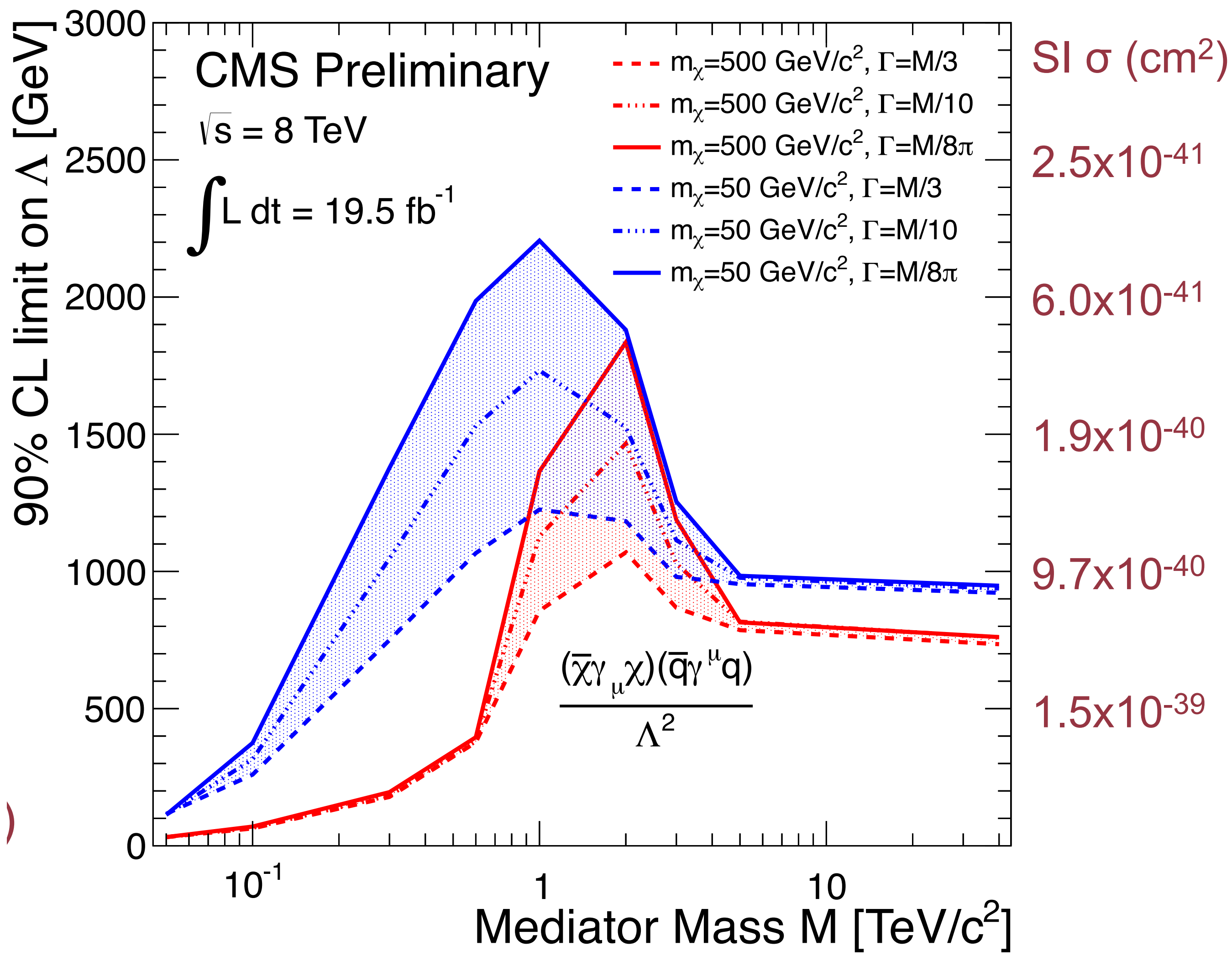
Region I: EFT and FT agree better then 20%
- EFT is valid!

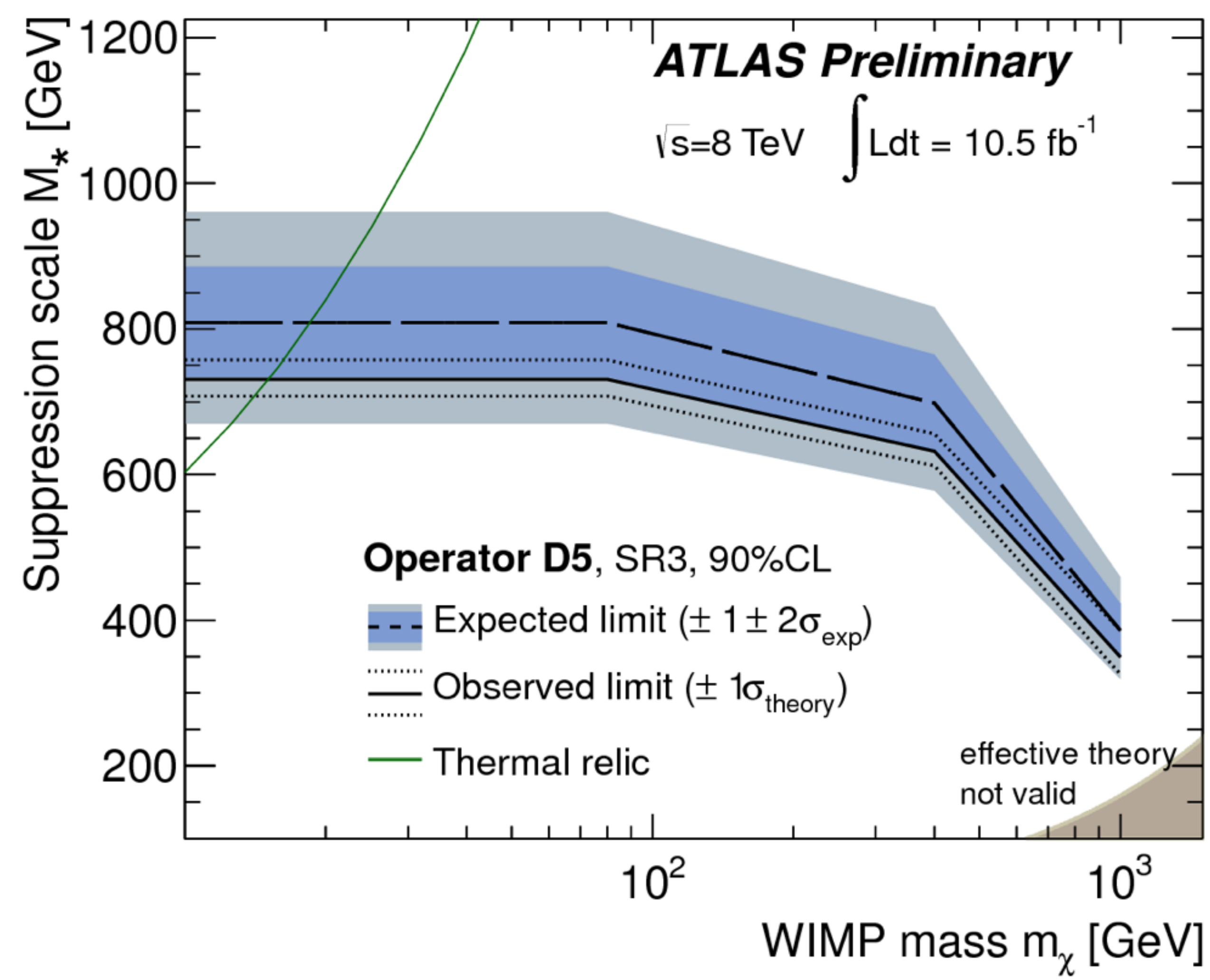
Region II: EFT yields significant weaker limits then FT
- EFT limits are too conservative!

Region III: EFT yields significant stronger limits then FT
- EFT limits are too aggressive!

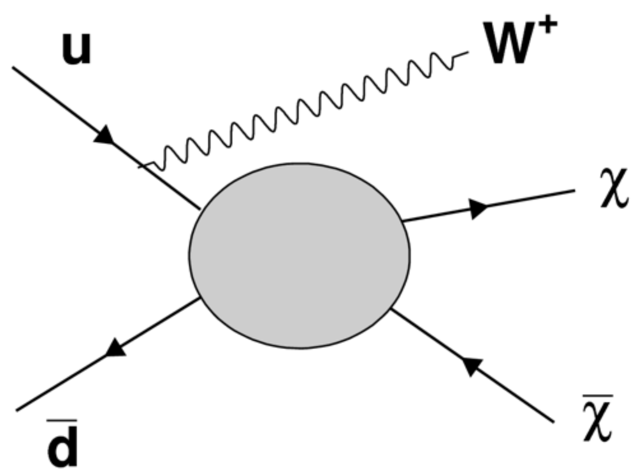
from Oliver Buchmüller

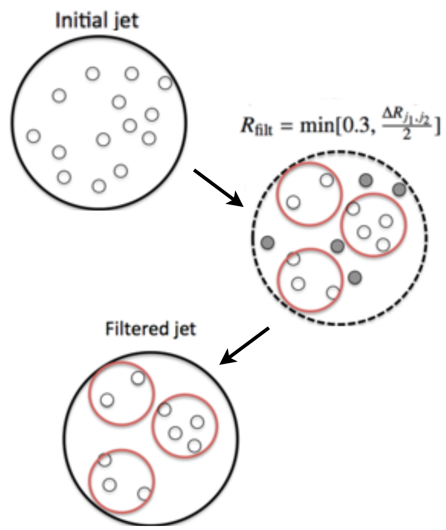
Constraints on Mediator and Scale

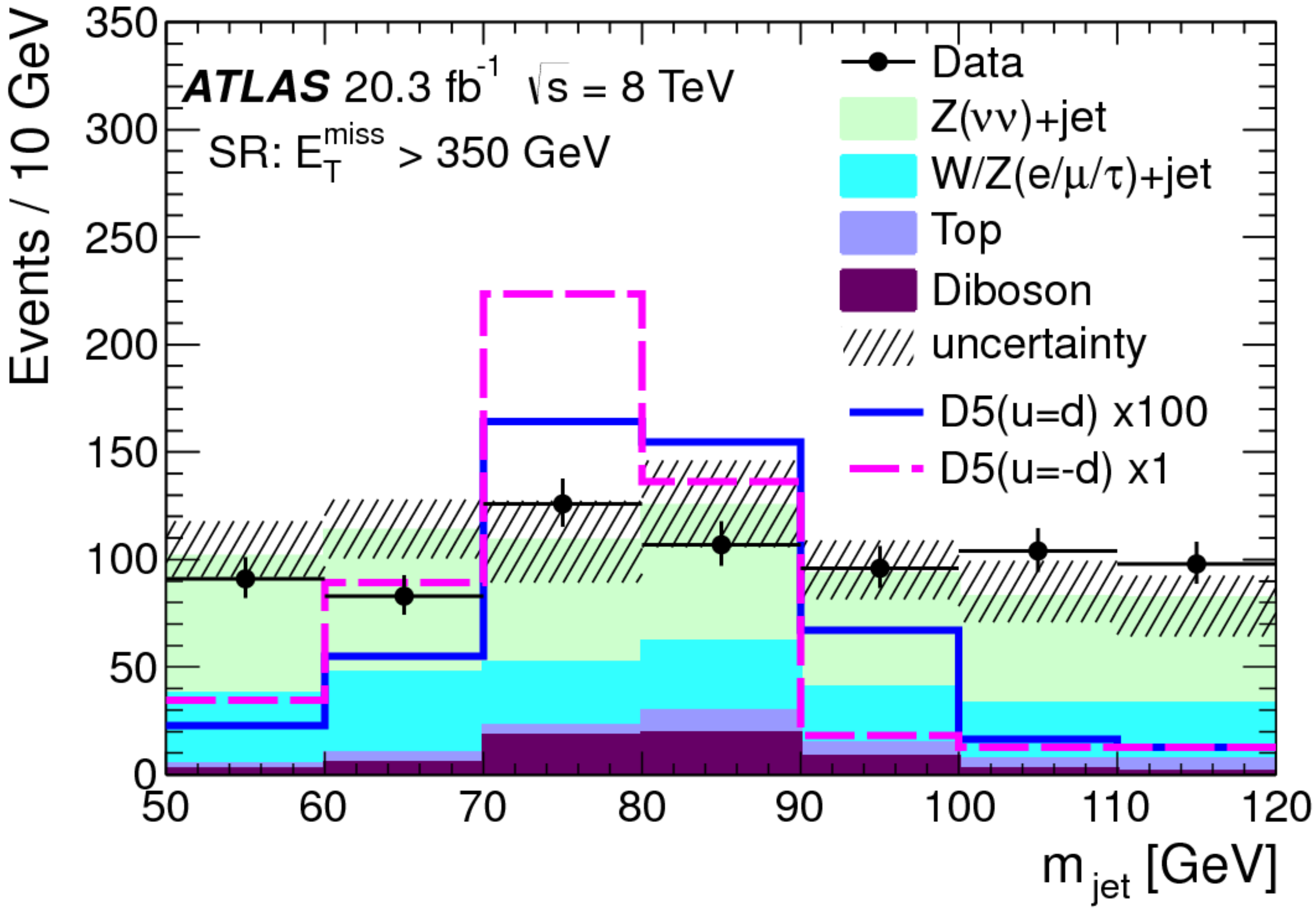




Hadronic Mono-W

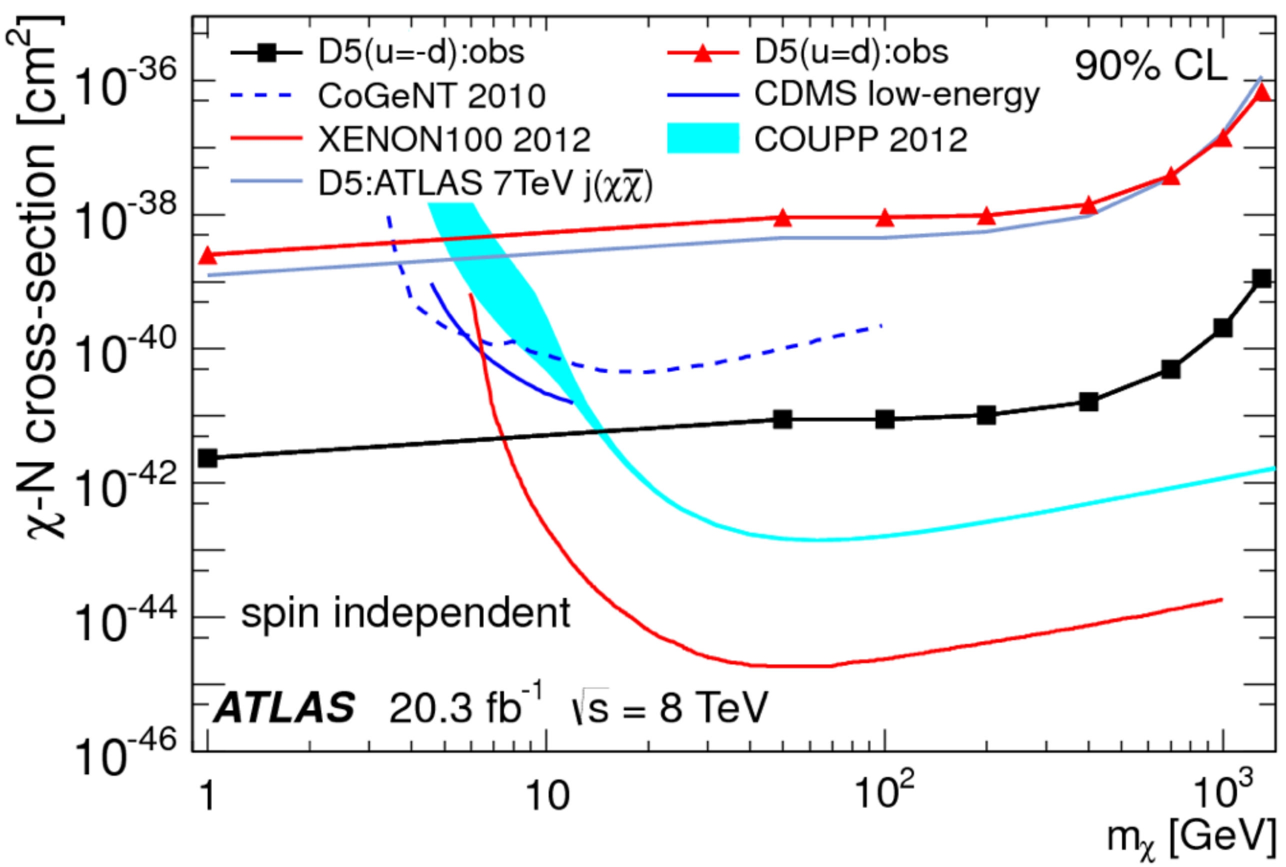




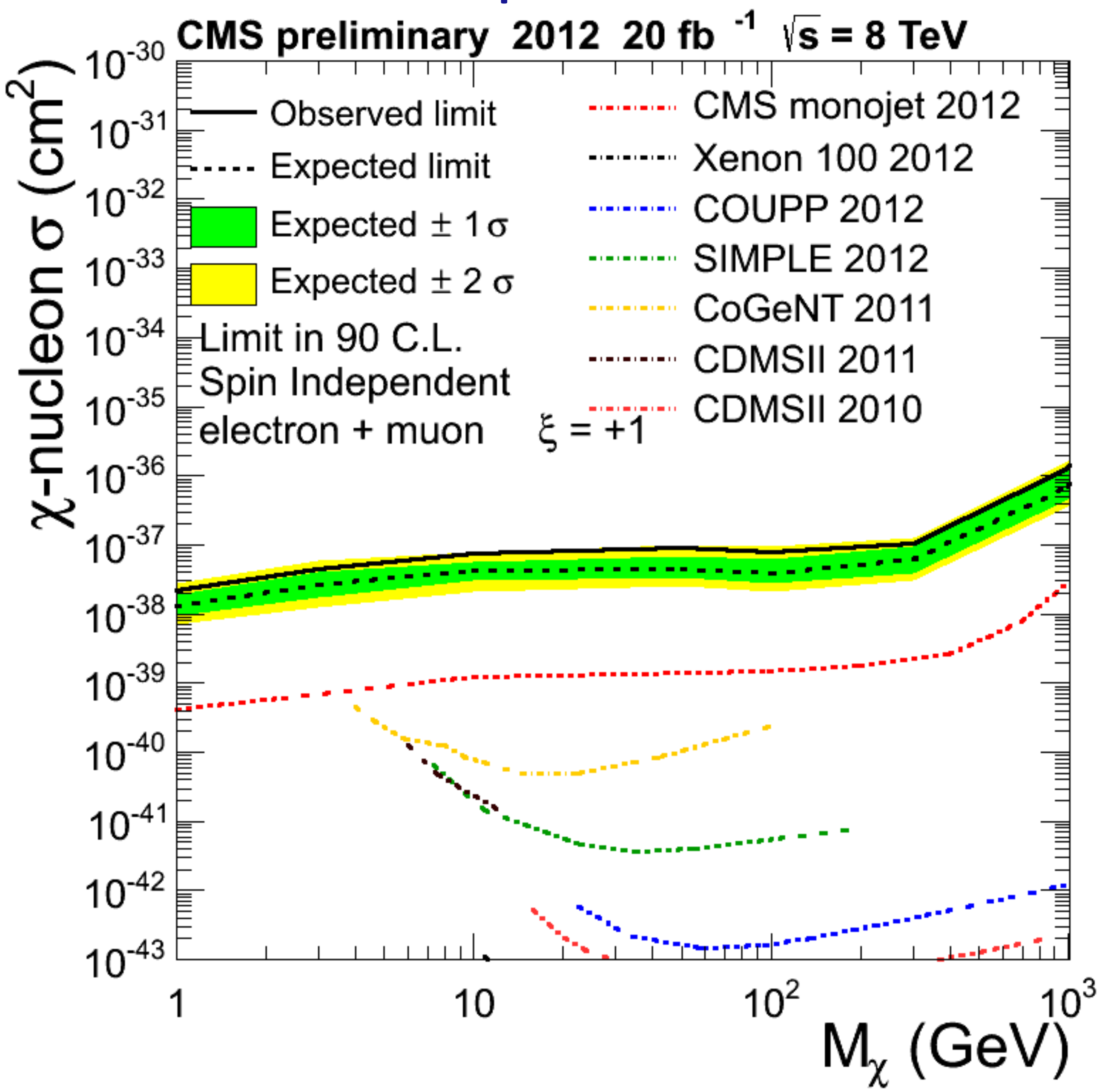


MONO-W CONSTRAINTS

Hadronic W



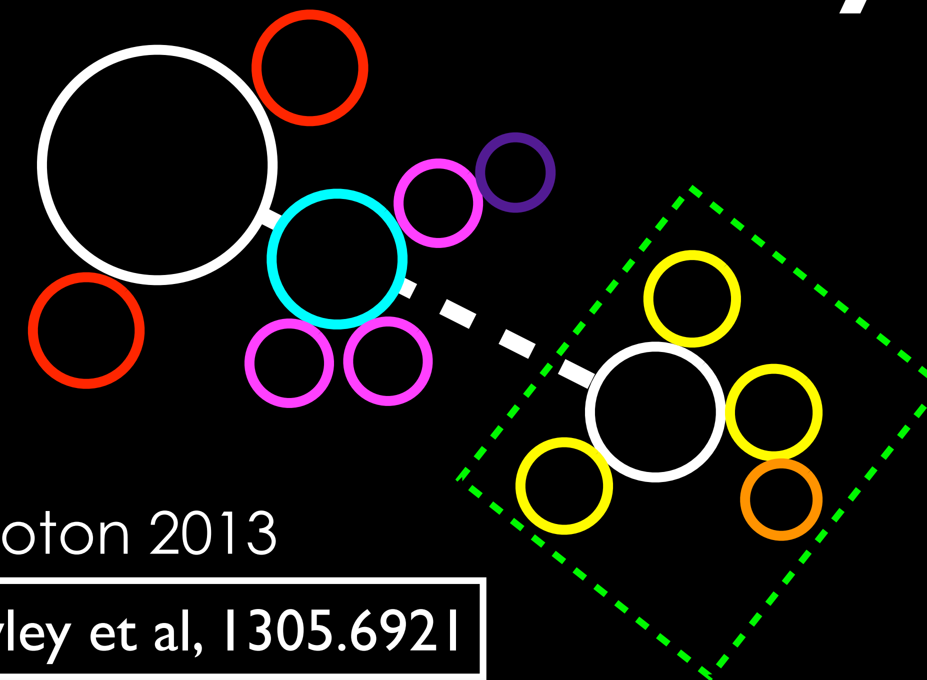
Leptonic W



- Constraints depend strongly on interference of up and down quark amplitudes

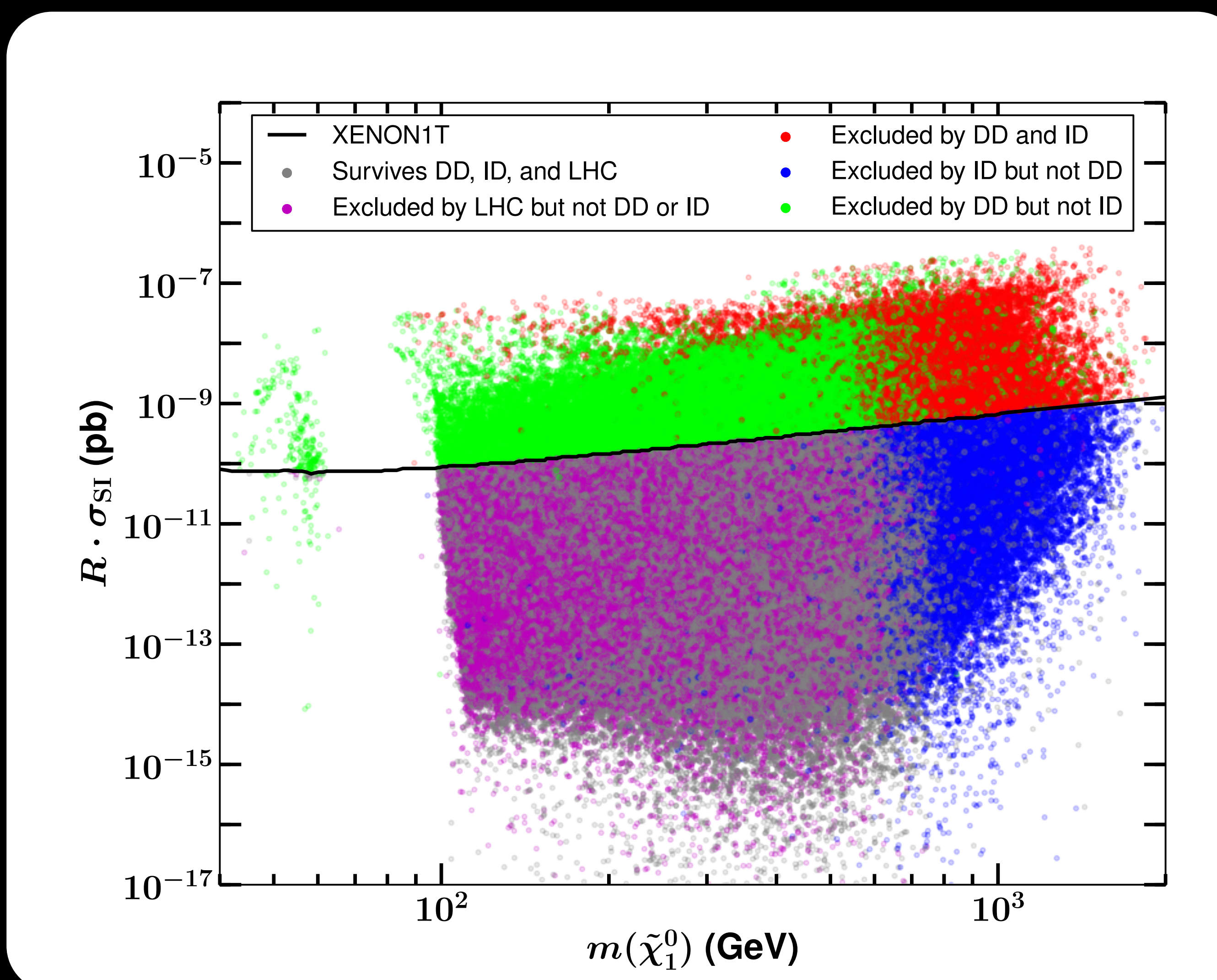
The Most Complete Theory

- On the "complete" end of the spectrum is our favorite theory: the MSSM.
- Reasonable phenomenological models have ~20 parameters, leading to rich and varied visions for dark matter.
- This plot shows a scan of the `pMSSM' parameter space by the SLAC group, in the plane of the WIMP mass versus the SI cross section.
- There are clear trends as to which experiments work best in different regions of this parameter space!

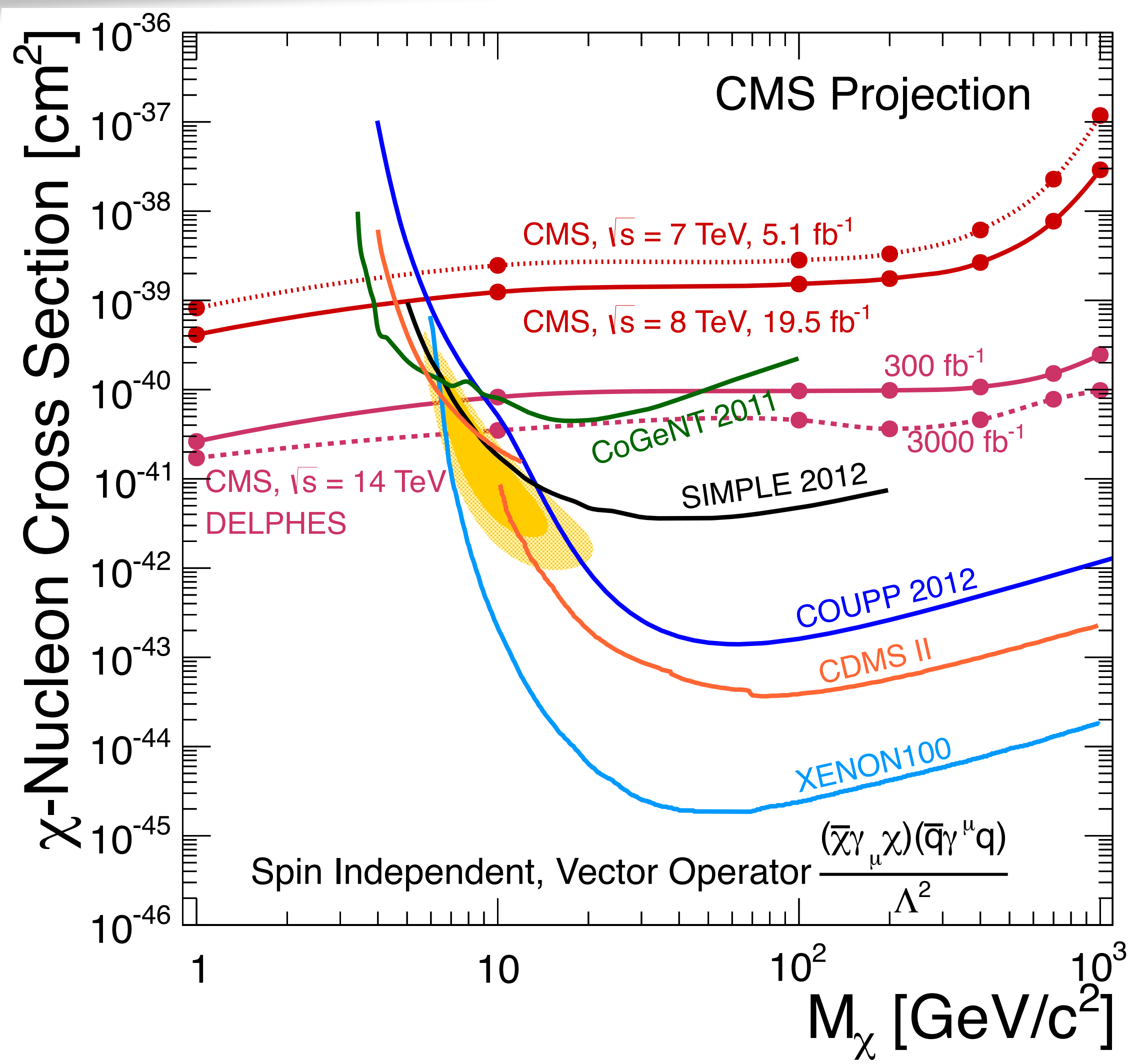


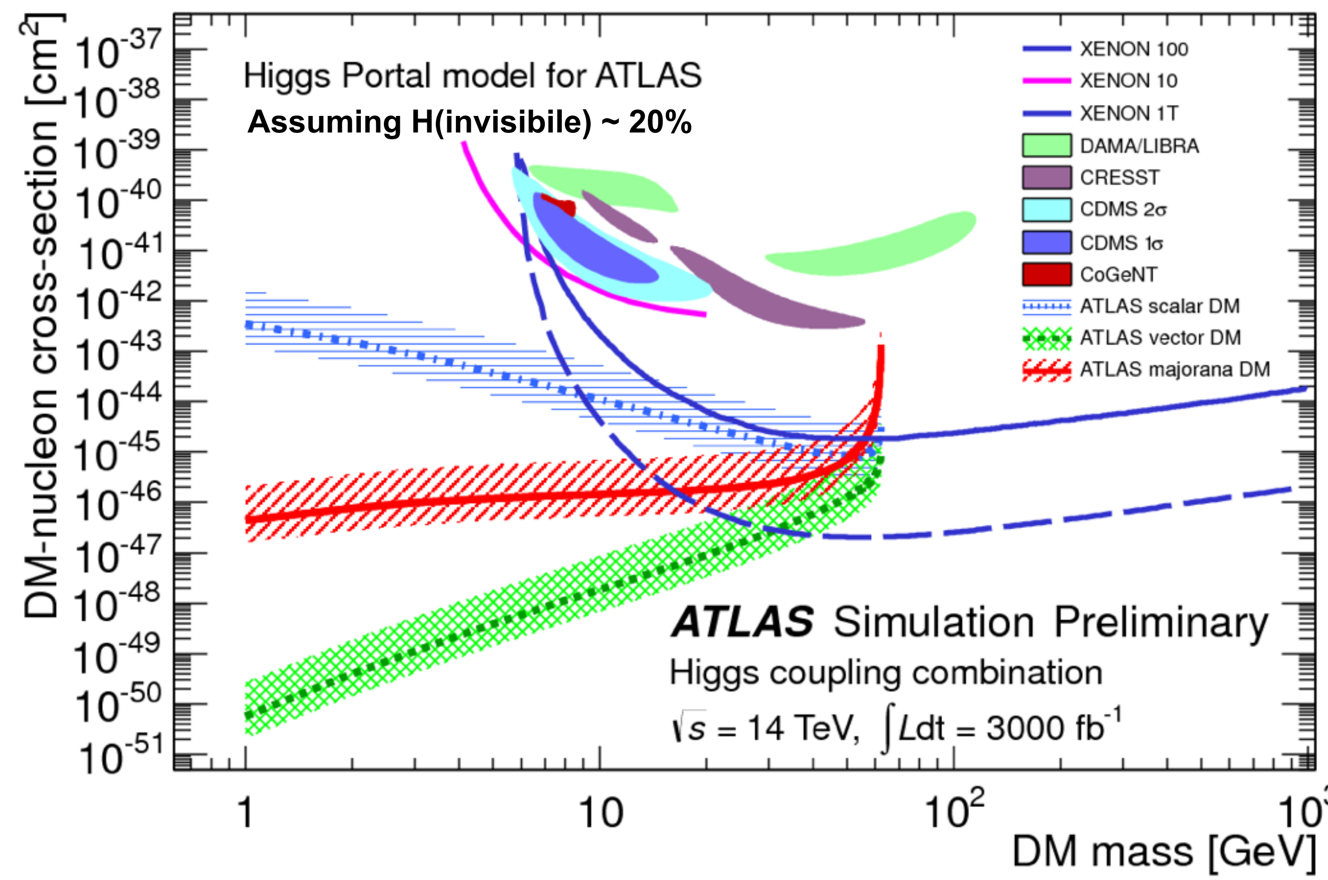
Tim Tait
Lepton Photon 2013

Cahill-Rowley et al, 1305.6921

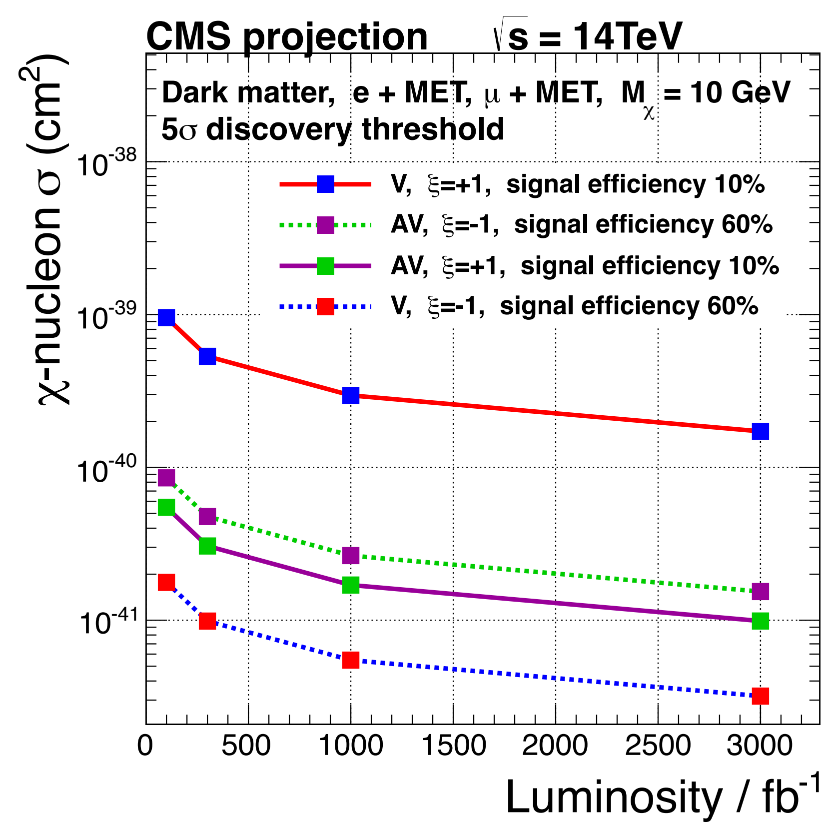


HIGH ENERGY AND LUMINOSITY LHC





- Increased LHC energy in 2015 critical for searches in Run II
- High-Luminosity LHC provides an opportunity for Higgs to play a crucial role for dark matter (if not found yet!)



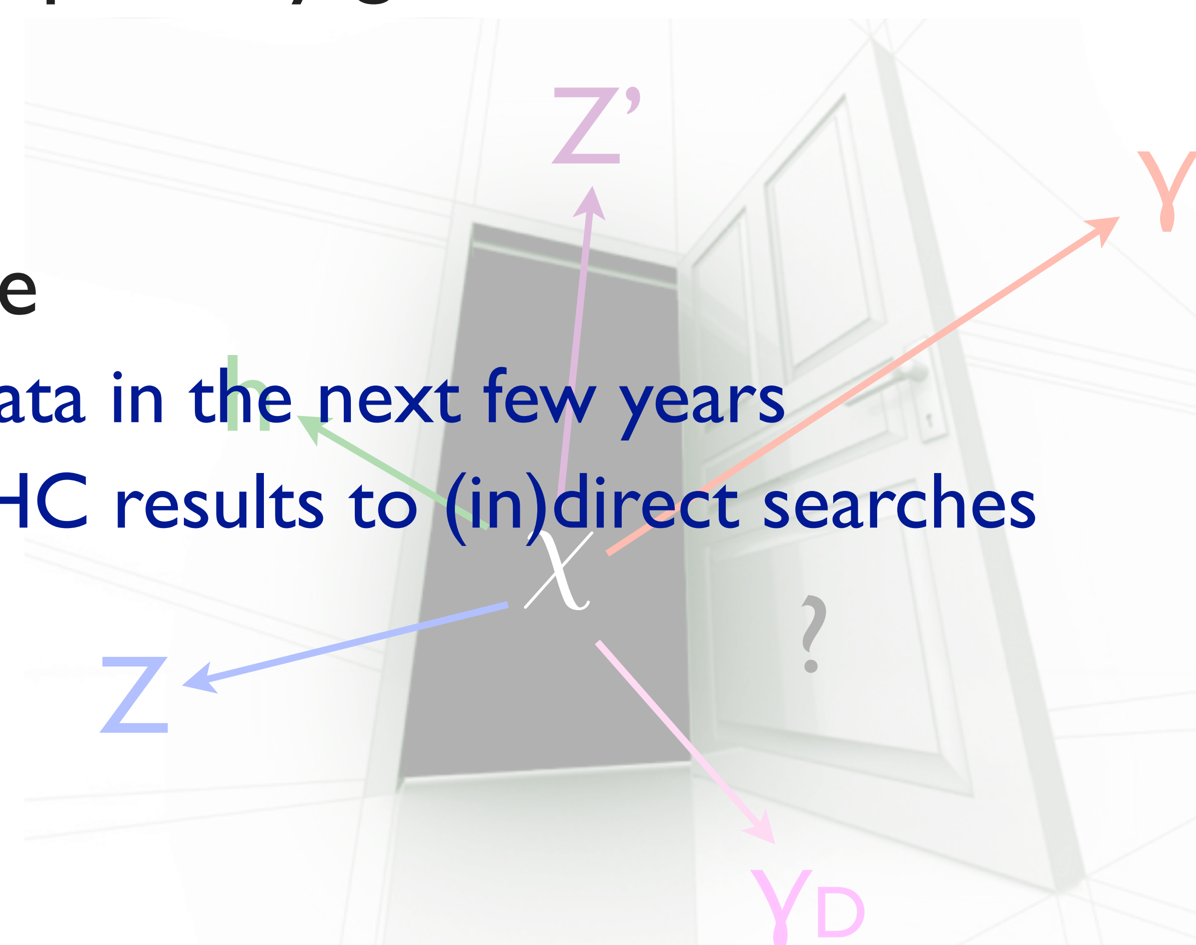
OUTLOOK

- Rich and complementary program at LHC to search for Dark Matter

- Rather than competition, LHC offers a power alternative to probe low-mass candidates

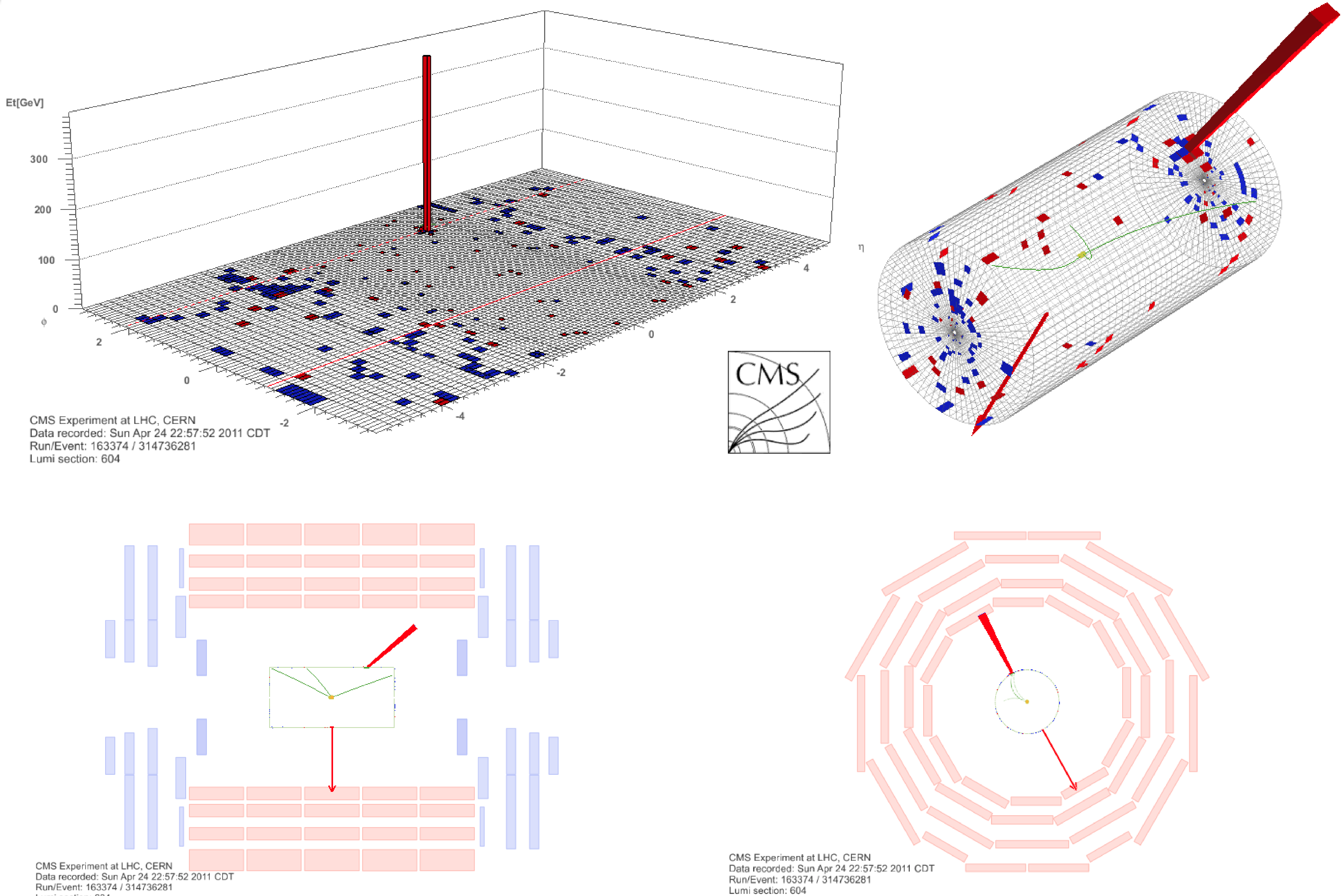
- Dark Matter program will one of the primary goals of Run II

- Intense theoretical activity to provide
  - new ideas and models to probe with data in the next few years
  - proper and optimal way to connect LHC results to (in)direct searches

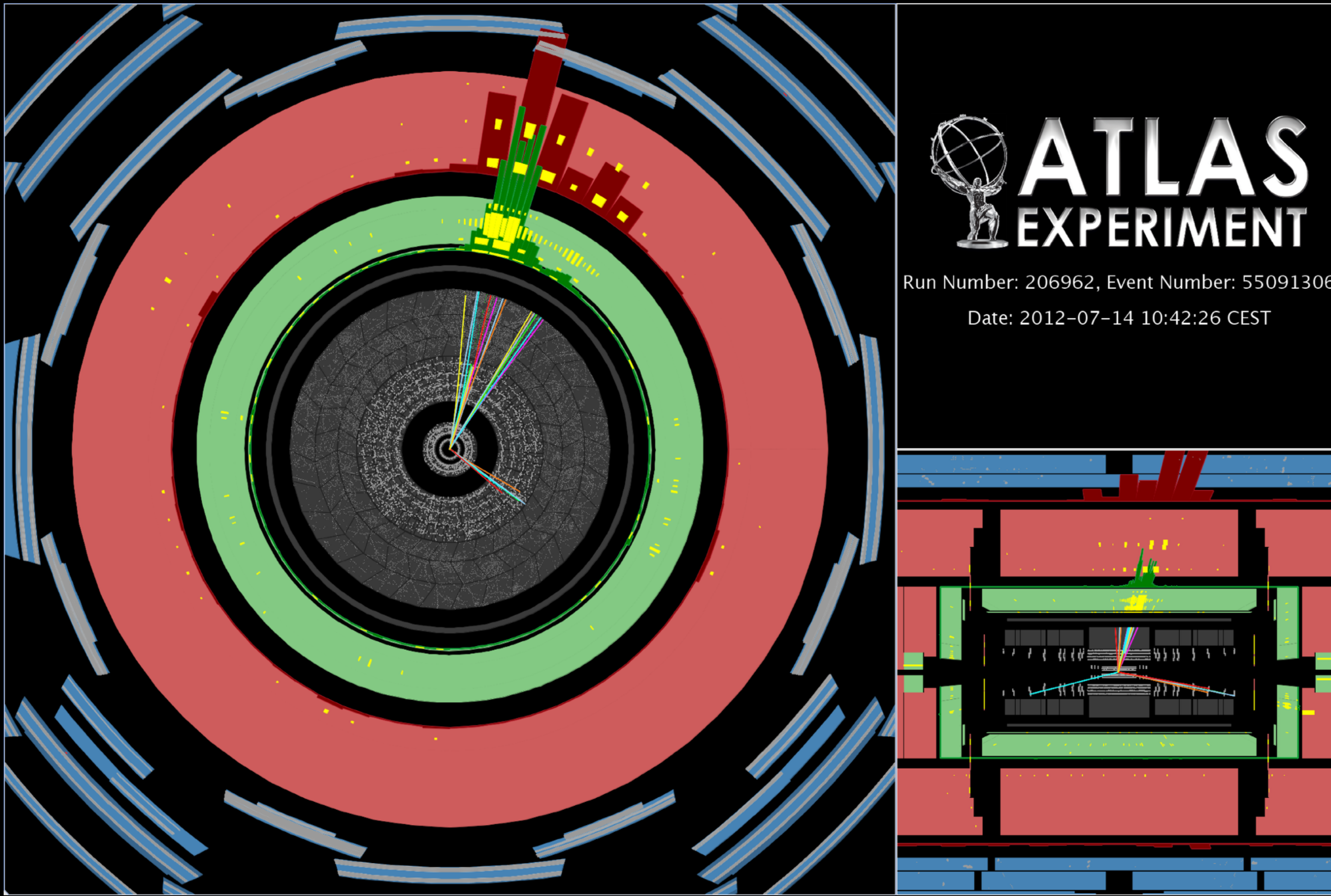


Backup

MONOPHOTON CANDIDATE



MonoJet Candidate



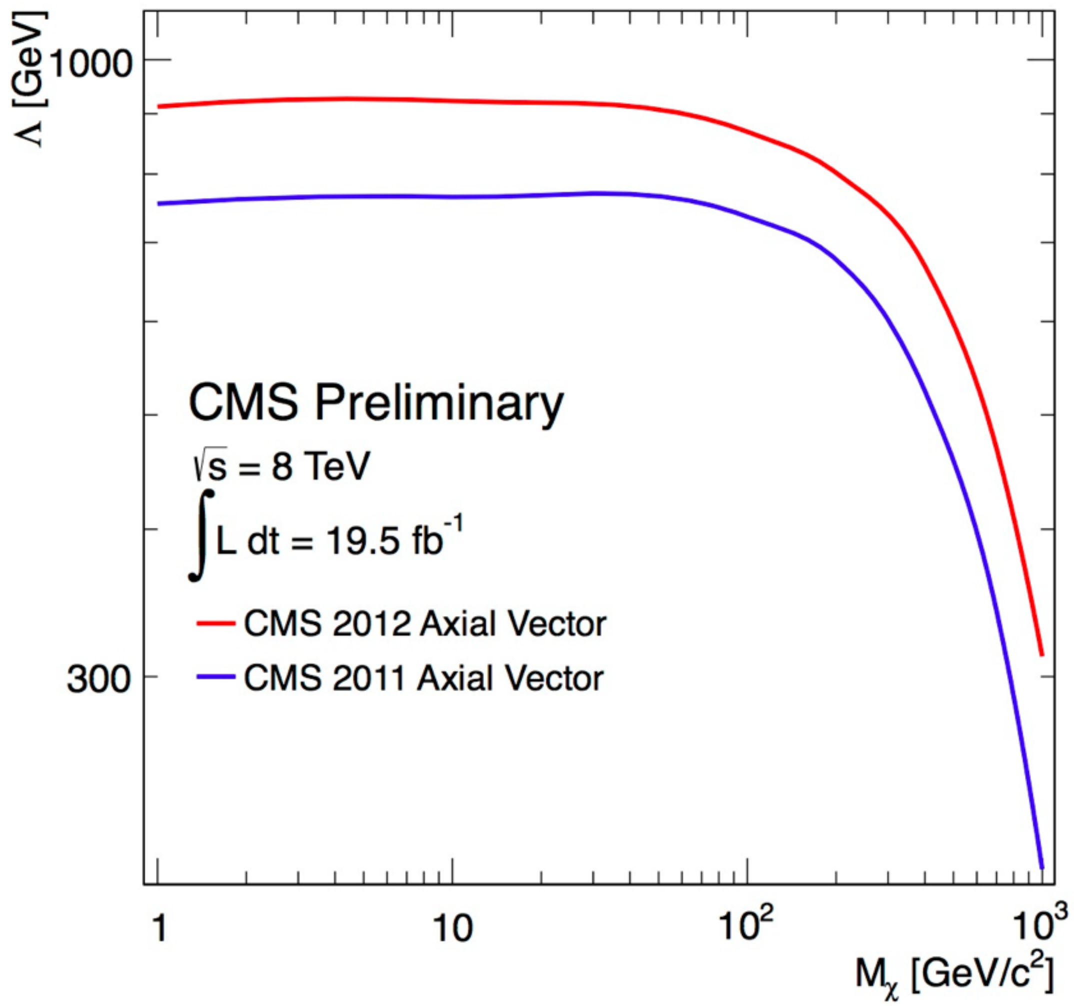
- invisible higgs BR from CMS and ATLAS
- typical mono-X efficiency and trigger efficiency

TRIGGER

- A few hghlights but most likely not enough time

CONSTRAINTS ON INTERACTION SCALE

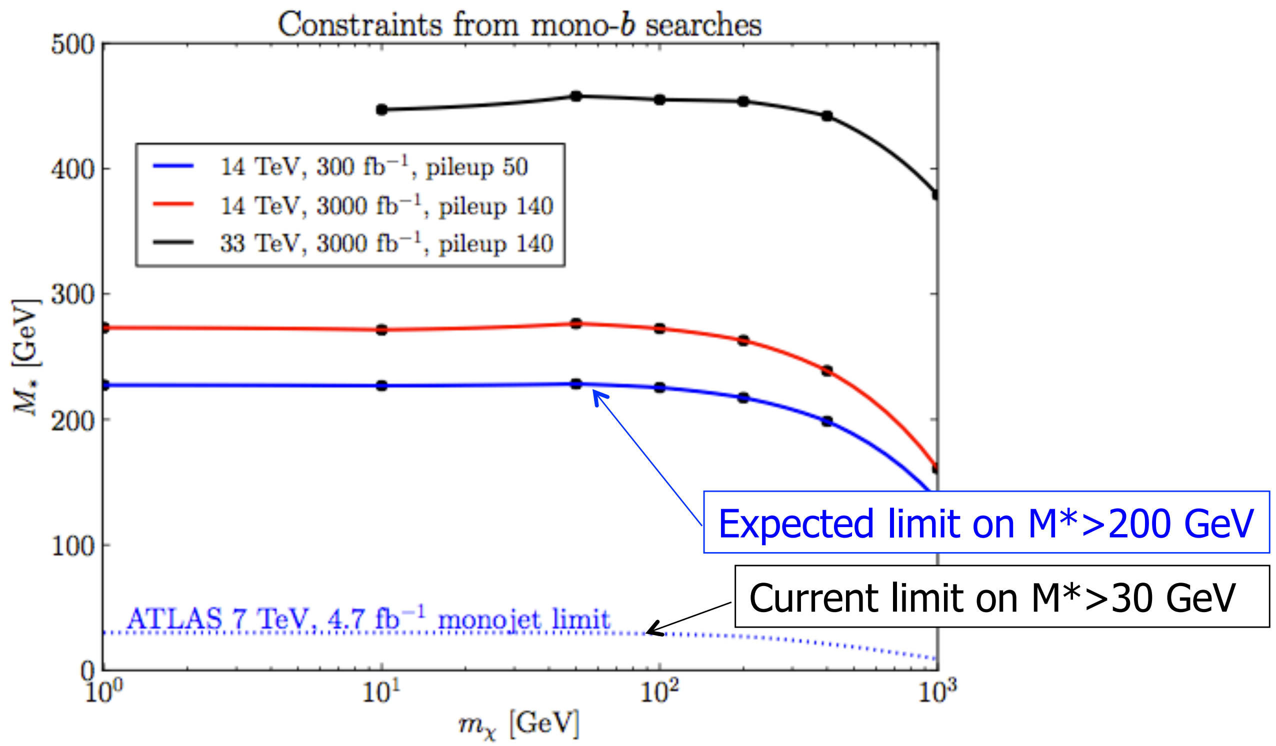
Vector Operator
MET > 350 GeV



Mono-Photon Strategy

- Both ATLAS and CMS results are old - 7 TeV
- Not enough time

MONO-QUARK



90% CL limits on the scalar operator from DM plus heavy jet, including couplings to tops and bottoms