INVITATION: DM AT THE LHC

DM@LHC 2017

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3 April 2017

INTRODUCTION

Motivations for new physics

- Gauge hierarchy problem
- Dark matter
- Dark energy
- Baryon asymmetry
- Inflation
- Flavor problem
- Neutrino masses and mixings
- ...

In the last few years, the cosmic questions have risen in importance, and among these, dark matter has become the dominant motivation to expect new particles and forces

DARK MATTER AT THE LHC

1997 2007 2017

- Why has dark matter become so important?

Ancient history ahead!

A BRIEF HISTORY OF DM AT COLLIDERS

- ~1984: LHC Conception

- 1993: SSC Canceled, future hadron colliders = LHC. LHC program:
  - Discover and study the Higgs boson
  - Precisely study SM particles, e.g., the top quark
  - Discover and study new particles that solve the gauge hierarchy problem

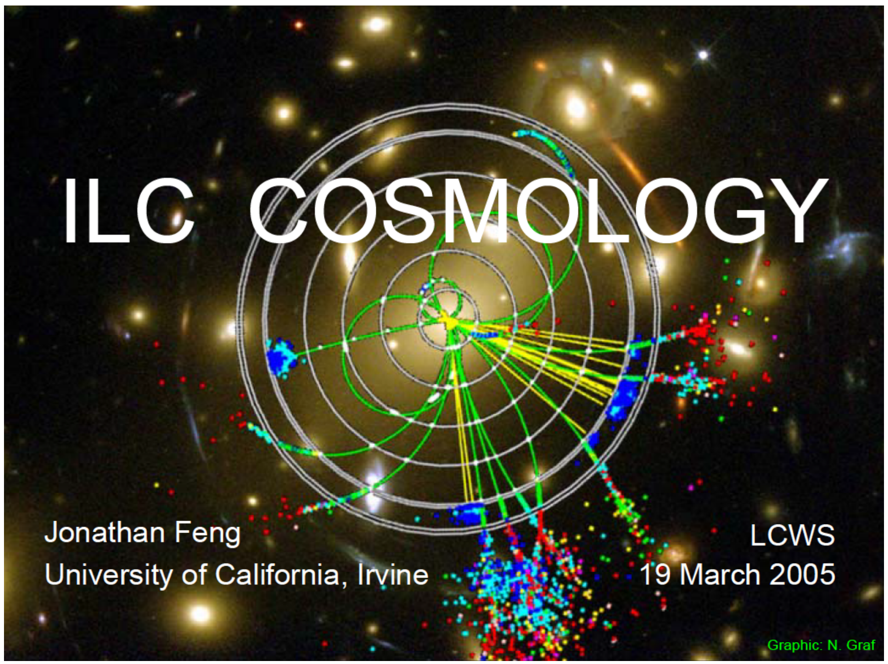
- 1993: SLAC demonstrates highly polarized beams, linear collider efforts in Asia, Europe, and America start becoming the ILC. ILC program:
  - Precisely study the Higgs boson
  - Precisely study SM particles, e.g., the top quark
  - Discover and precisely study new particles that solve the gauge hierarchy problem with mass up to E_{beam}

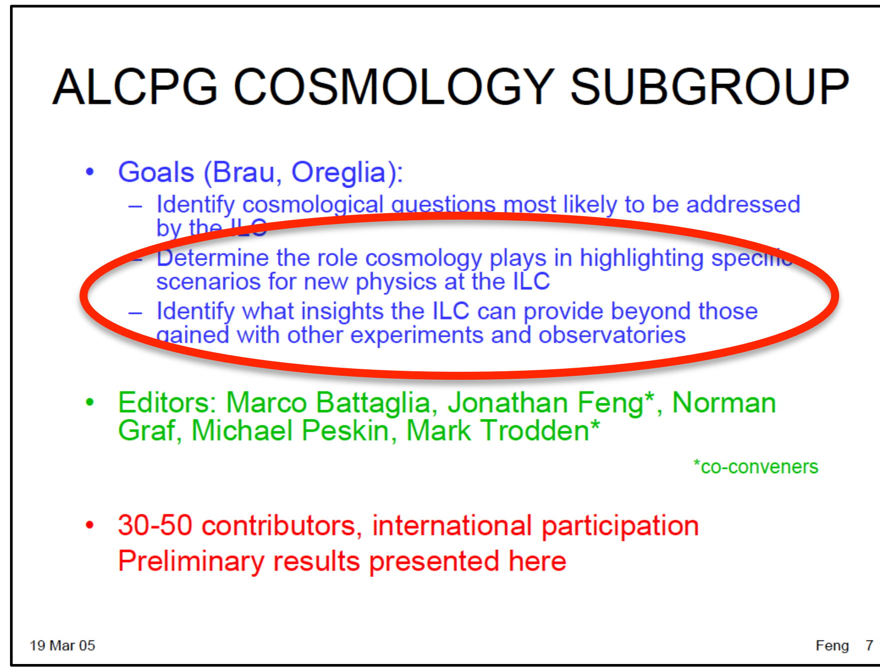
- Why build the ILC? What does precision study of new particles buy you?

THE ANSWER: DARK MATTER

- 1998: Accelerating universe discovered
- 2001-: rapid rise in precision cosmology from CMB experiments, etc.
- Late 1990's-: a new boom in DM candidates begins (Q balls, WIMPzillas, inelastic DM, KK dark matter, T-odd dark matter, superWIMPs, etc.)
- New collider goals
  - What can colliders tell us about cosmology?
  - How well can dark matter properties be determined?
  - For example, how precisely can m_X and Ω_X be determined?
- A shift in thinking
  - old: lightest neutralino = cascade endpoint, missing E_T signature
  - new: lightest neutralino = dark matter, critically importance
- Most LHC physicists were too busy doing real work, and so this largely fell to ILC study groups to investigate

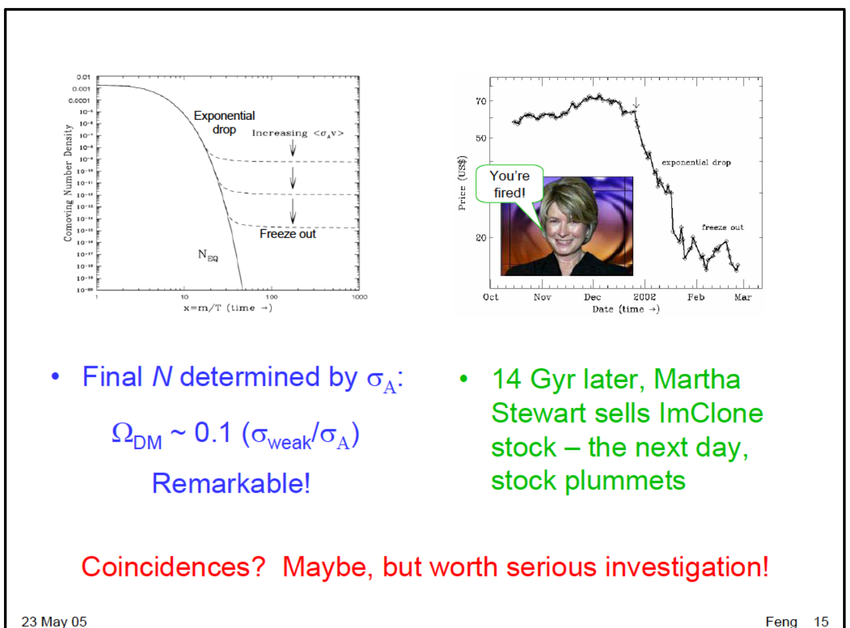
ILC COSMOLOGY GROUP 2004-05

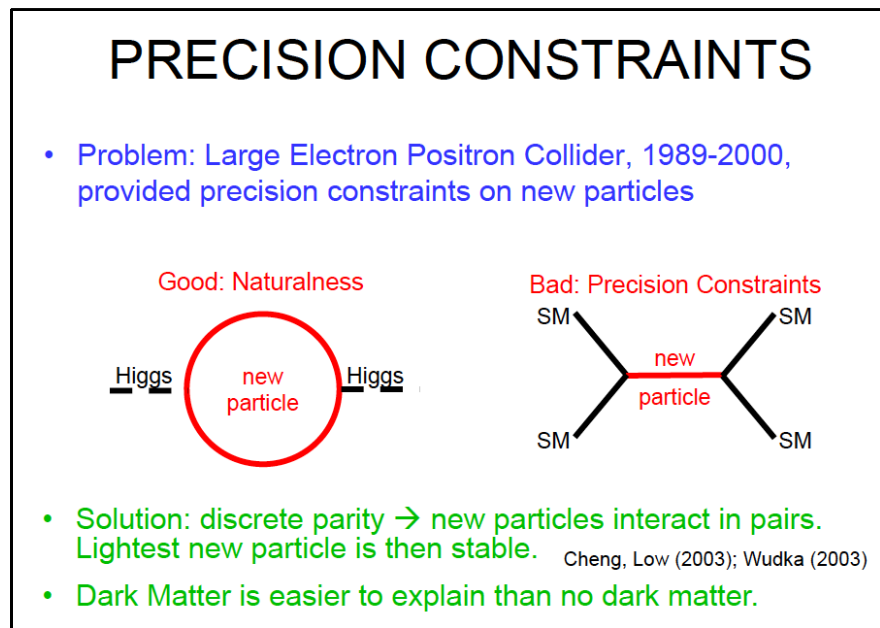




THE WIMP MIRACLE

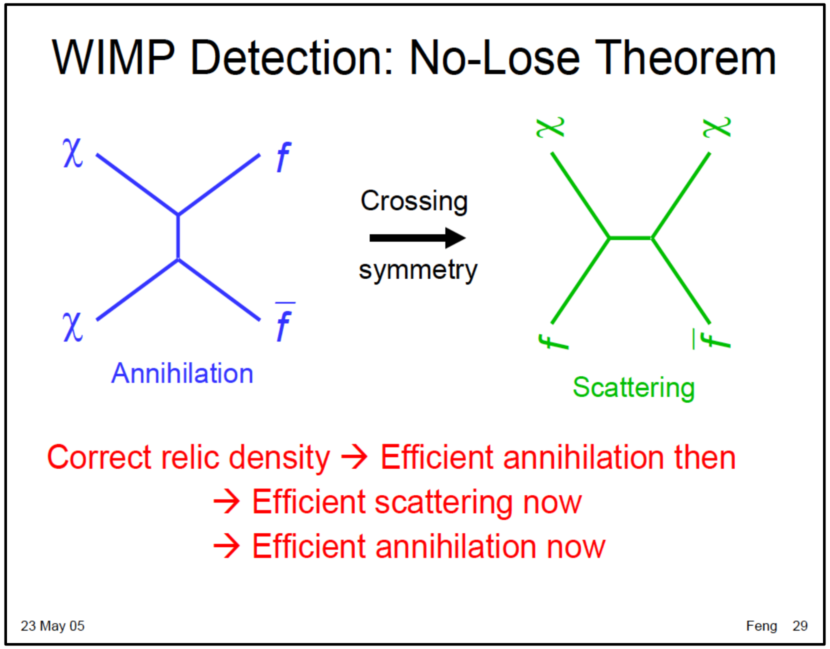
- "Determine the role cosmology plays in highlighting specific scenarios for new physics"
- The WIMP miracle: Continuous (relic density) and Discrete (stability)
- Irrespective of the gauge hierarchy problem, cosmology → weak scale, and the LHC is ideally suited to probing this scale definitively

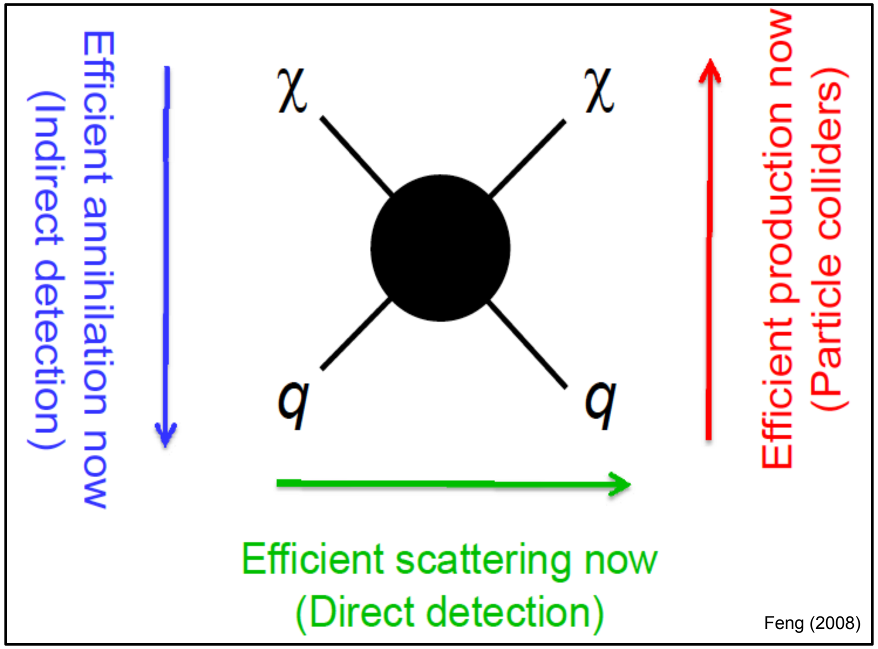




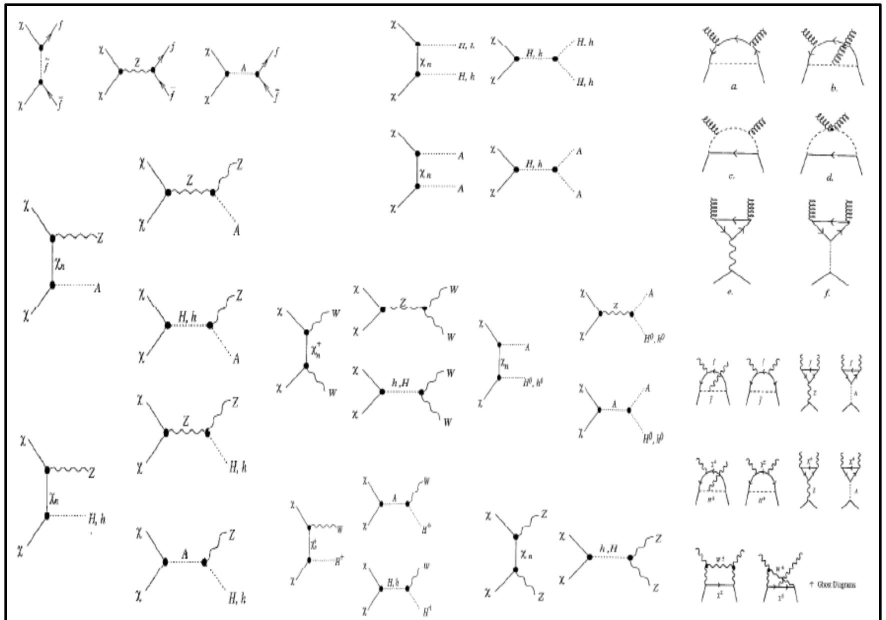
COMPLEMENTARITY

- "Identify what insights the ILC can provide *beyond those gained with other experiments and observations*"
- essentially required understanding what the LHC, direct detection, and indirect detection could do: complementarity
- The LHC is an integral part of any comprehensive program to understand dark matter



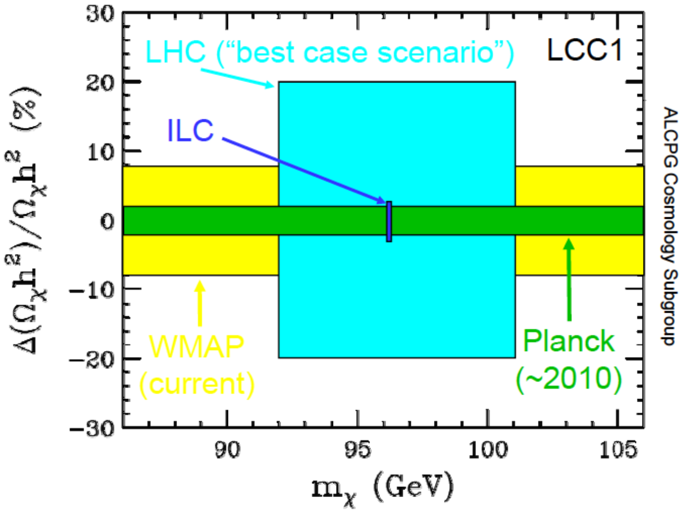


RELIC DENSITY AND COMPLETE MODELS



Jungman, Kamionkowski, Griest (1995)

RELIC DENSITY DETERMINATIONS



% level comparison of predicted $\Omega_{collider}$ with observed Ω_{cosmo}

- A crowning achievement: given a complete model, determine the relic density to % level, compare with cosmological measurements

Baltz, Battaglia, Peskin, Wizansky (2006)

- Addressed many now famous slogans: “colliders can’t discover dark matter”, “dark matter might be multi-component”, “the dark sector could be complicated”

- The LHC can determine if missing particles are all of the DM, probe the Universe’s history back to t ~ 1 ps (cf. BBN and 1 s)

COMPLETE MODELS

- How is the WIMP paradigm doing now?
- “Rumors of its death have been greatly exaggerated.” -- Dark Twain
- Naturalness is highly subjective. Within the considerable variation of what constitutes a good definition of naturalness, there are natural, viable models. For example, in SUSY:
  - Effective SUSY
  - Focus point SUSY
  - Compressed SUSY
  - R-parity violating SUSY
  - Dirac gaugino SUSY
  - ...
- A new personal favorite: 4^{th} generation SUSY

MSSM4G

- Naturalness suggests light stops and sbottoms, m_h = 125 GeV suggests heavy stops and sbottoms

- A resolution: introduce a 4th generation of particles to raise the Higgs mass

Moroi, Okada (1992)

- Chiral 4th generation particles are possible, but highly constrained. Instead, add vector-like 4th generation particles

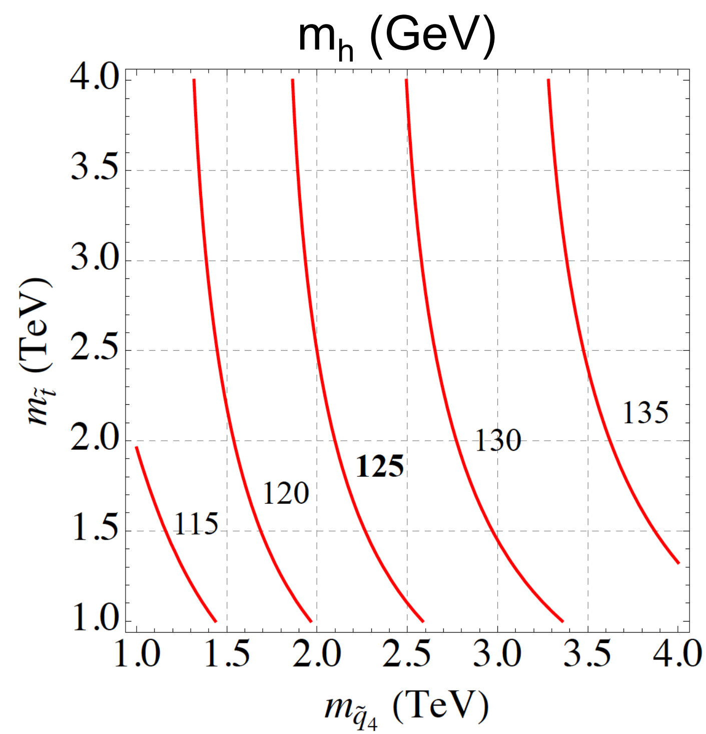
Kribs, Plehn, Spannowsky, Tait (2007)

- Remarkably, requiring gauge coupling unification, there are only two options: the QUE and QDEE models. E.g., QUE:

Dirac fermions: T_4, B_4, t_4, τ_4

Complex scalars: $\tilde{T}_{4L}, \tilde{T}_{4R}, \tilde{B}_{4L}, \tilde{B}_{4R}, \tilde{t}_{4L}, \tilde{t}_{4R}, \tilde{\tau}_{4L}, \tilde{\tau}_{4R}$

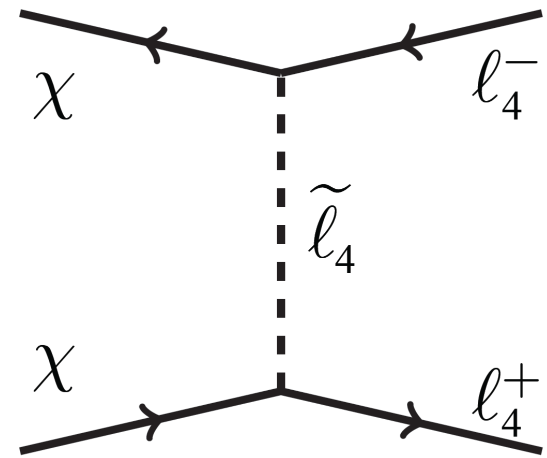
Martin (2010)

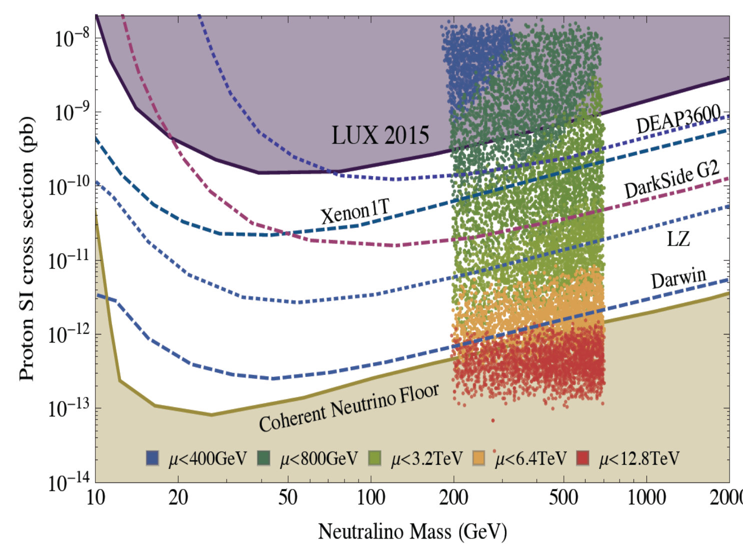


MSSM4G COSMOLOGY

Abdullah, Feng (2015); Abdullah, Feng, Iwamoto, Lillard (2016)

- The introduction of a heavy 4th generation completely changes the cosmology
- The single process $\chi\chi \rightarrow \tau_4\tau_4$ dominates all SM processes combined
- The resulting DM is a Bino-like neutralino, but heavier
- Direct detection cross sections are Higgs-mediated and Higgsino-fraction suppressed, naturally fall between current bounds and the neutrino floor





MSSM4G AT THE LHC

see Mo Abdullah and Ben Lillard's poster

- A broad range of interesting LHC signals. 4^{th} generation particles must decay, but can decay to any of the 1^{st} three generations with a variety of lifetimes

- Quarks and squarks in the 1-2 TeV range

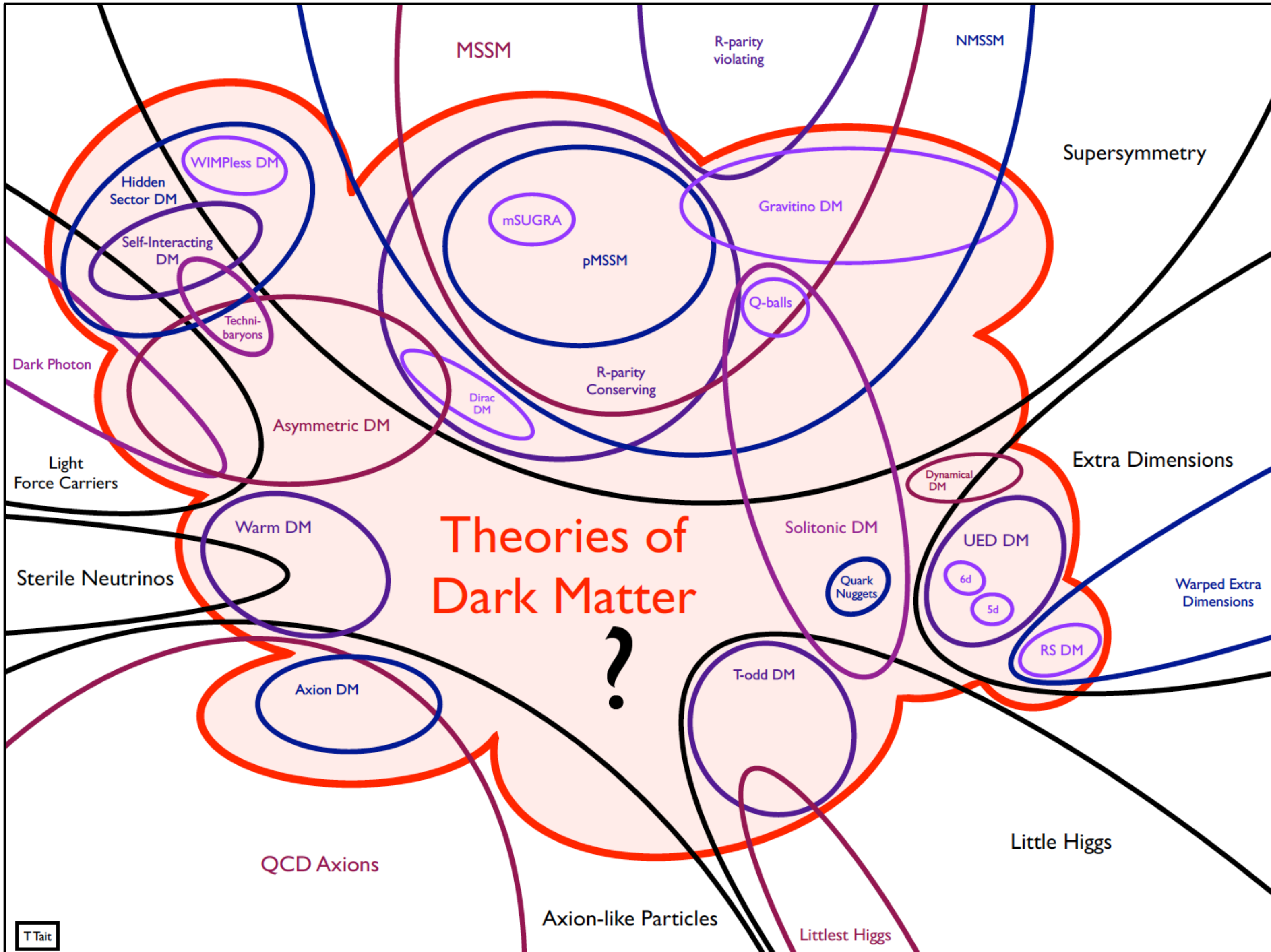
- $\tilde{\tau}_4 \tilde{\tau}_4$ Drell-Yan production, leading to long-lived charged particles, displaced vertices, etc.

- $\tilde{\tau}_4 \tilde{\tau}_4$ Drell-Yan production, followed by decays $\tilde{\tau}_4 \rightarrow e\,\chi, \mu\,\chi, \tau\,\chi$

- $\tau_4 \tau_4$ Drell-Yan production, followed by decays $\tau_4 \rightarrow \tau$ Z, ν W, τ h, etc.

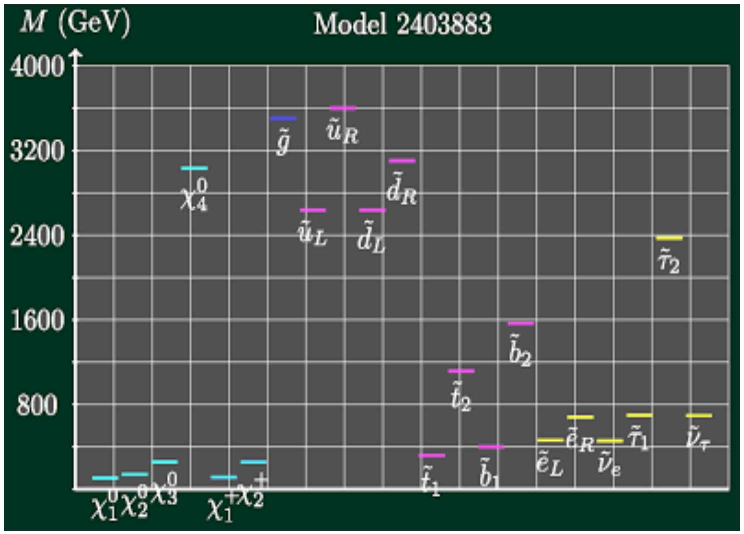
Parameter	QUE (GeV)
$M_{\tilde{B}}$	$200 - 540$
$m_{\tilde{q}_4}$	$1000 - 4000$
$m_{\tilde{\ell}_4}$	$350 - 550$
m_{q_4}	$1000 - 2000$
m_{ℓ_4}	$170 - 450$
$m_{\tilde{t}}$	$1000 - 4000$

OTHER COMPLETE MODELS

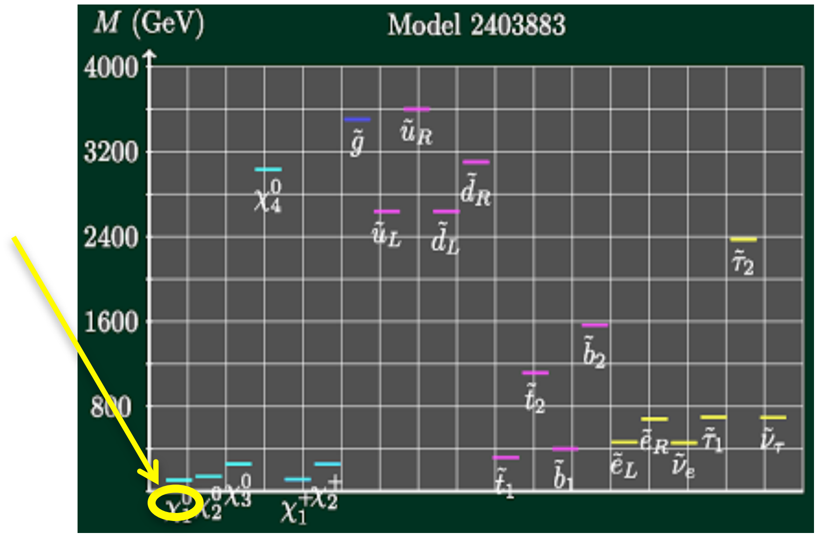


DM EFFECTIVE THEORIES & SIMPLIFIED MODELS

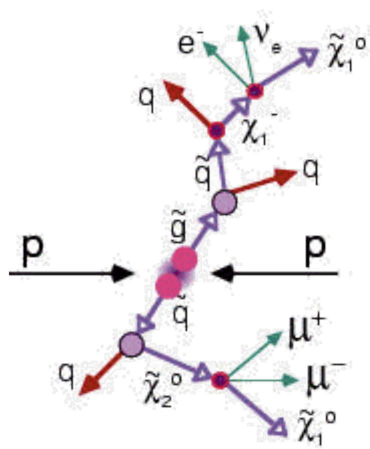
Complete Models



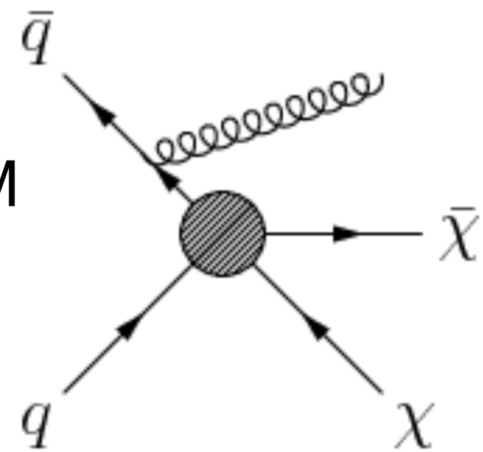
Effective Theories



Produce other particles, which decay to DM



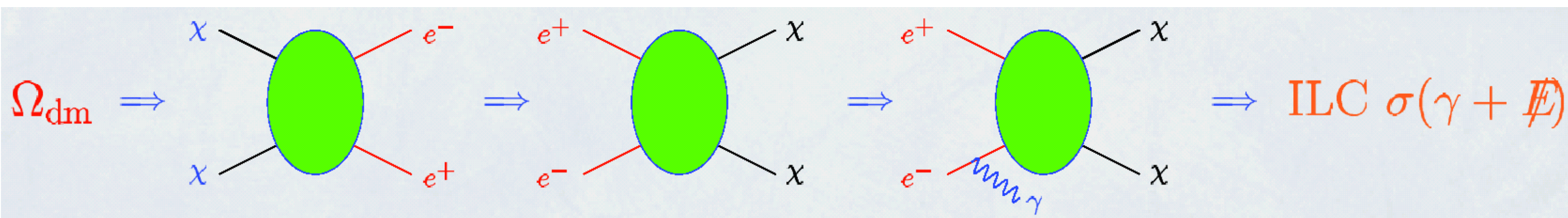
Produce DM directly



PROTO-EFFECTIVE THEORIES AT THE ILC

- Thermal relic WIMPs annihilate to SM particles, and so should be produced directly at colliders

- First considered at the ILC: pair production is invisible, so consider photon radiation



Birkedal, Matchev, Perelstein (2004)

- Also (less successfully) mono-jets and mono-photons at the Tevatron and LHC

Feng, Su, Takayama (2005)

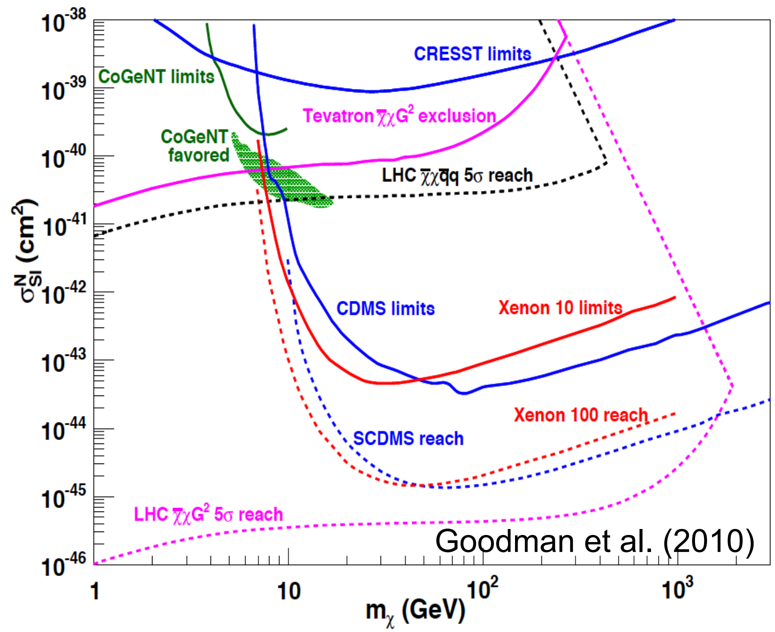
DM EFFECTIVE THEORY

- This approach received a huge boost when hints of light DM motivated a hierarchy between the DM and mediator masses

Beltran, Hooper, Kolb,Krusberg, Tait (2006)
Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu (2010)
Bai, Fox, Harnik (2010)
...

- These have motivated a plethora of mono-γ,j,b,t,W,Z,h searches, probing dark matter at the LHC one operator at a time

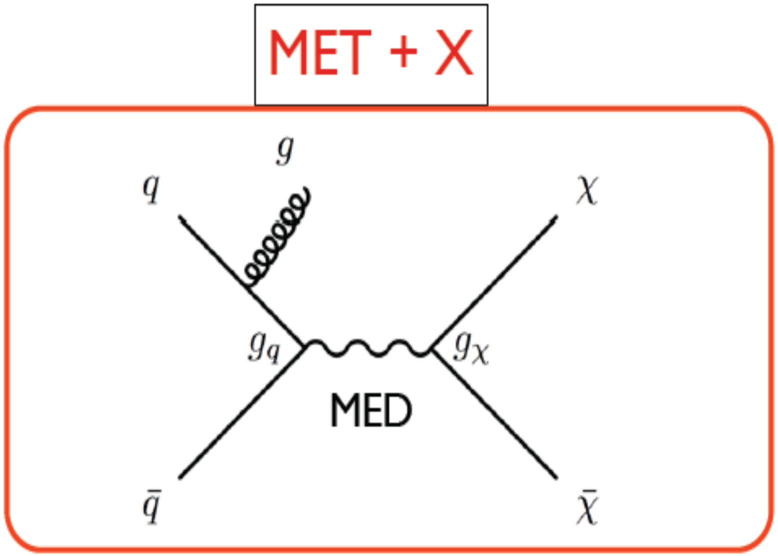
- DM effective theory allows comparison to indirect, direct search results; LHC does very well for some operators, low DM masses

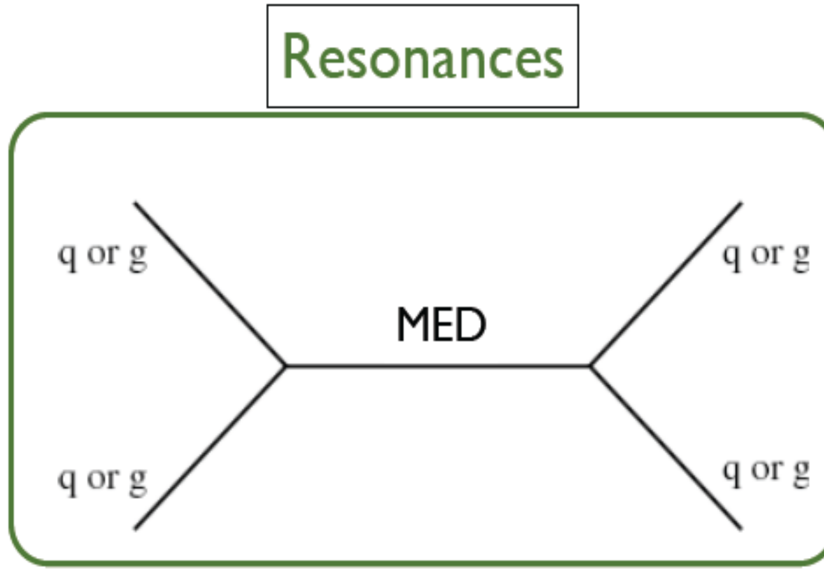


Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$

⋮

DM SIMPLIFIED MODELS





Abercrombie et al. (2015)

- Extends coverage to include explicit dark mediators/forces, signatures include dijets, etc.
- Provides simple framework to interpret searches in terms of
  - Discrete choices of couplings: vector, axial, scalar, pseudoscalar
  - Continuous choices of a small set of parameters: g_q, g_χ, m_χ, m_{MED}

RECENT LHC RESULTS

List of CMS/ATLAS DM searches

K. Hahn Aspen 2017 talk

X	Dataset	Documentation
jet or hadronic V	2016, 12.9 fb-1	EXO-16-037, 1703.01651
photon	2016, 12.9 fb-1	EXO-16-039
Z(ll)	2016, 12.9 fb-1	EXO-16-038
Higgs (γγ)	2015, 2.3 fb-1	EXO-16-011
Higgs (bb), with γγ combo	2015, 2.3 fb-1	EXO-16-012
tt (hadronic, semileptonic)	2015, 2.2 fb-1	EXO-16-005
tt (dileptonic + tt combination)	2016, 2.2 fb-1	EXO-16-028
t hadronic	2016, 12.9 fb-1	EXO-16-040
bb	2015, 2.2 fb-1	B2G-15-007

Not really X	Dataset	Documentation
dijets	2016, 12.9 fb-1	EXO-16-032, 1611.03568
boosted dijets	2016, 2.7 fb-1	EXO-16-030
dijets	2016, 27+36 fb-1	EXO-16-056

S. Schramm 2016 Moriond talk

Summary

ATLAS EXPERIMENT

UNIVERSITÉ DE GENÈVE

Analysis summary table

Analysis	Dataset	Public link	
Production search:			
E_T^{miss}+jet	2015	Paper: EXOT-2015-03	
$E_T^{miss}+\gamma$	2015	Paper: EXOT-2015-05	
E_T^{miss}+Z($\rightarrow \ell\ell$)	2015+2016	Note: ATLAS-CONF-2016-056	new!
E_T^{miss}+W/Z($\rightarrow qq$)	2015	Paper: EXOT-2015-08	new!
E_T^{miss}+H($\rightarrow bb$)	2015	Note: ATLAS-CONF-2016-019	
E_T^{miss}+H($\rightarrow \gamma\gamma$)	2015+2016	Note: ATLAS-CONF-2016-087	new!
E_T^{miss}+H($\rightarrow \ell\ell\ell\ell$)	2015	Note: ATLAS-CONF-2015-059	
E_T^{miss}+b-jets	2015+2016	Note: ATLAS-CONF-2016-086	new!
$E_T^{miss}+t\bar{t}$ (0ℓ)	2015+2016	Note: ATLAS-CONF-2016-077	new!
$E_T^{miss}+t\bar{t}$ (1ℓ)	2015+2016	Note: ATLAS-CONF-2016-050	new!
$E_T^{miss}+t\bar{t}$ (2ℓ)	2015+2016	Note: ATLAS-CONF-2016-076	new!
Mediator search:			
Dijet	2015+2016	Note: ATLAS-CONF-2016-069	new!
Trigger-level dijet	2015	Note: ATLAS-CONF-2016-030	
Dijet+ISR	2015+2016	Note: ATLAS-CONF-2016-070	new!
Summary plots:			
Mediator searches	2015+2016	Plot: Summary plot page	new!
Search combination	2015+2016	Plot: Summary plot page	new!

Trovato, Cosmic Visions talk (2017)

CONCLUSIONS

- Dark matter has long been one of the great scientific problems of our time, but it has become leading evidence for new particles and forces. Much of BSM physics is now also DM physics

- Irrespective of the gauge hierarchy problem, cosmology → weak scale, and the LHC is ideally suited to probing this scale definitively

- The LHC is an integral part of any comprehensive program to understand dark matter and may probe the Universe's history back to t ~ 1 ps (cf. BBN and 1 s)

- Recent progress continues to make the DM/LHC interface an incredibly fertile area for creative ideas connecting theory/experiment and astrophysics/particle physics, with dark matter motivating many interesting scenarios that the LHC is ideally suited to probe. Lots of fascinating work ahead!