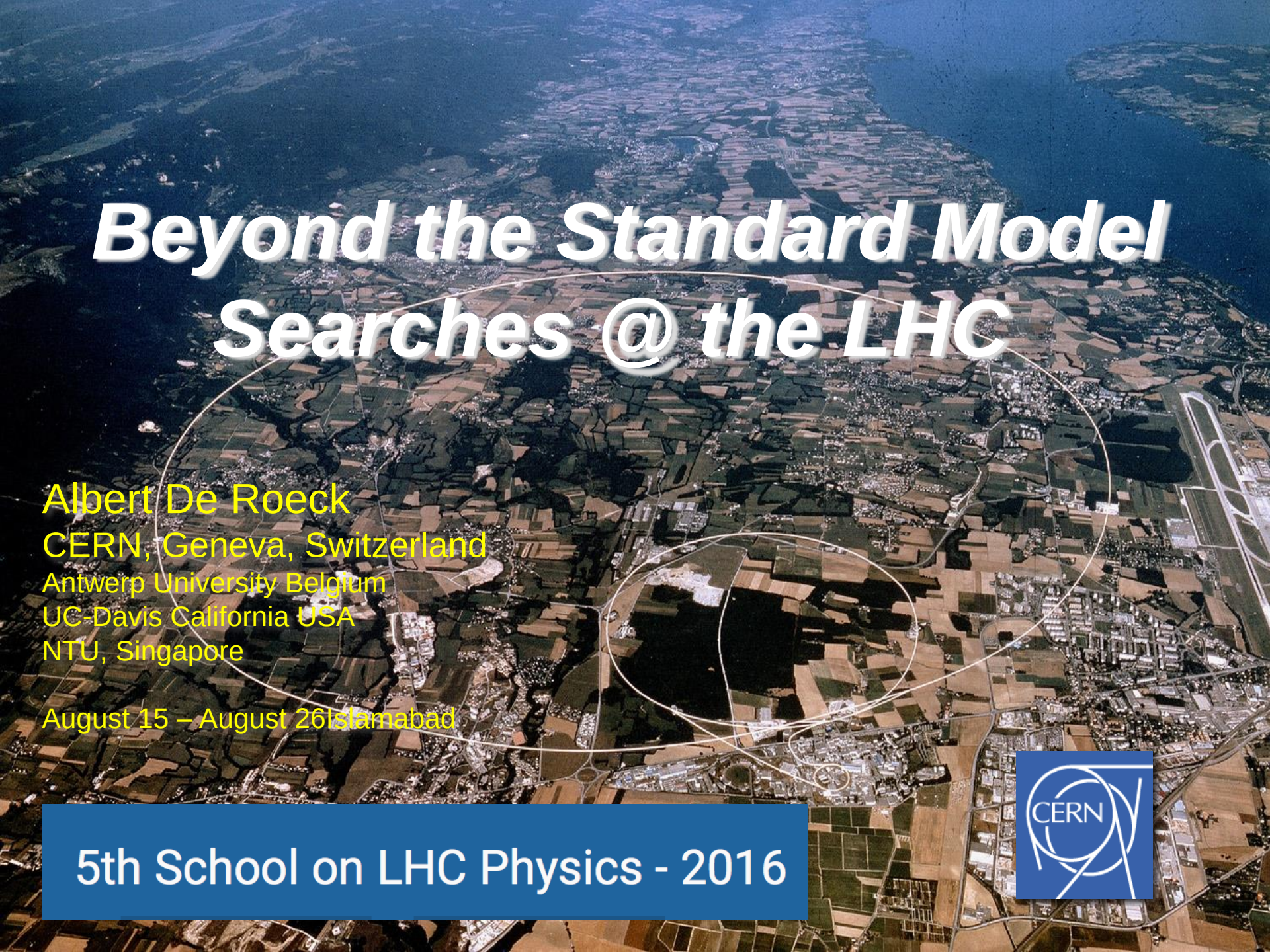


Beyond the Standard Model Searches @ the LHC

Albert De Roeck
CERN, Geneva, Switzerland
Antwerp University Belgium
UC-Davis California USA
NTU, Singapore

August 15 – August 26Islamabad

5th School on LHC Physics - 2016

Lecture Plan

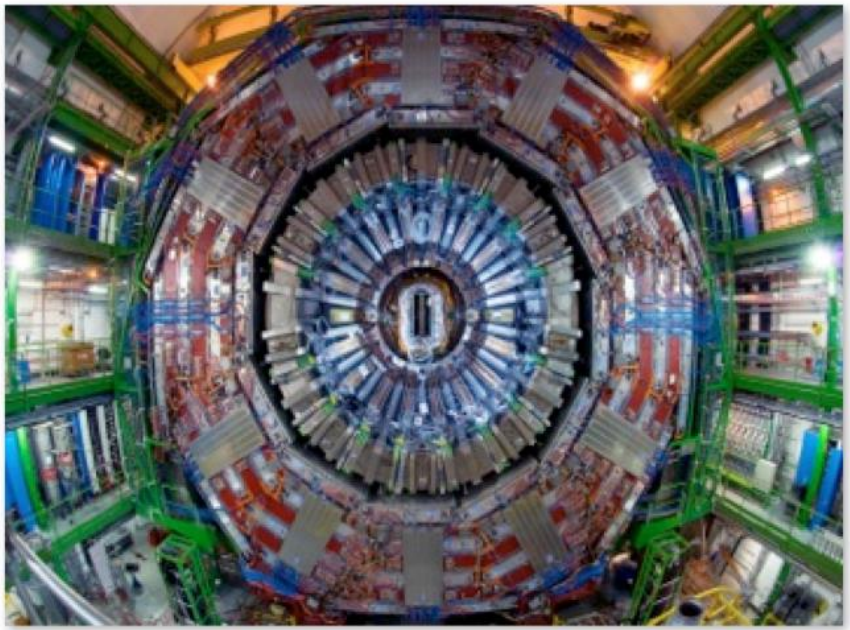
Overview of the 3 lectures in the next days

- Lecture 1:
  - Introduction to searches for new physics
  - Searches for exotica and new phenomena
- Lecture 2:
  - Searches for supersymmetry
  - Searches for real exotic particles
- Lecture 3:
  - The hunt for dark matter
  - Outlook for the LHC and for the Future

Dark Matter: Complementary Searches?

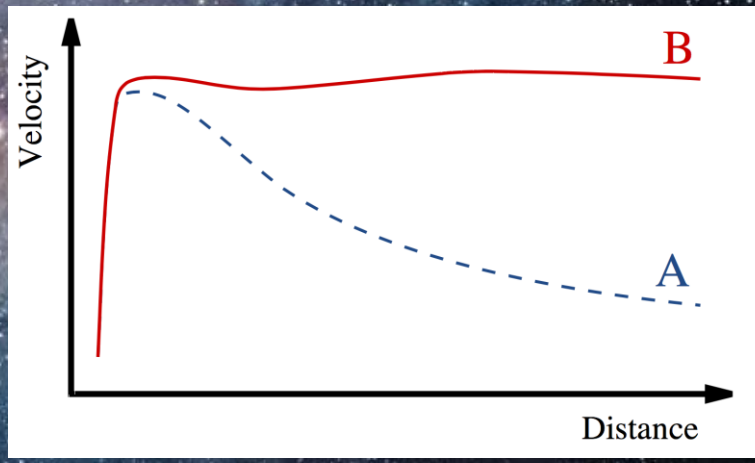
After the discovery of the Higgs particle @ the LHC:
Dark matter is the next important physics problems to tackle for the LHC

The search is complementary to other experimental techniques used.



Dark Matter: The Next Challenge !?!

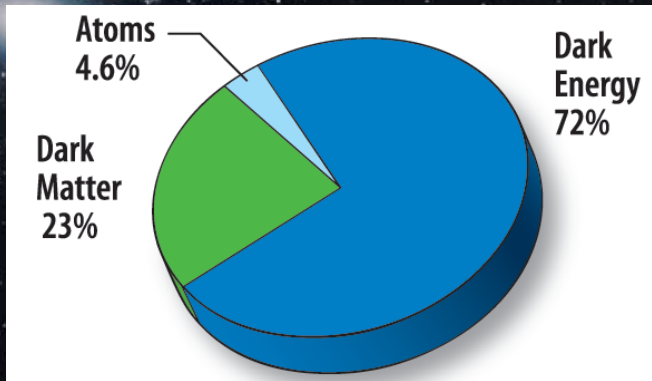
Astronomers found that most of the matter in the Universe must be invisible Dark Matter



'Supersymmetric' particles ?


F. Zwicky 1898-1974


Vera Rubin ~ 1970

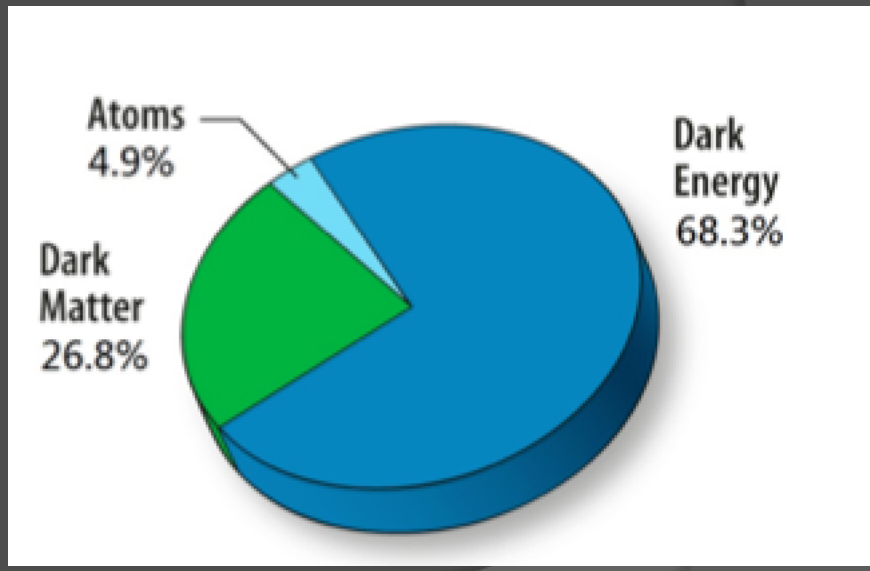


Particle Dark Matter?

The Dark Matter Candidate Zoo

From D. Hooper

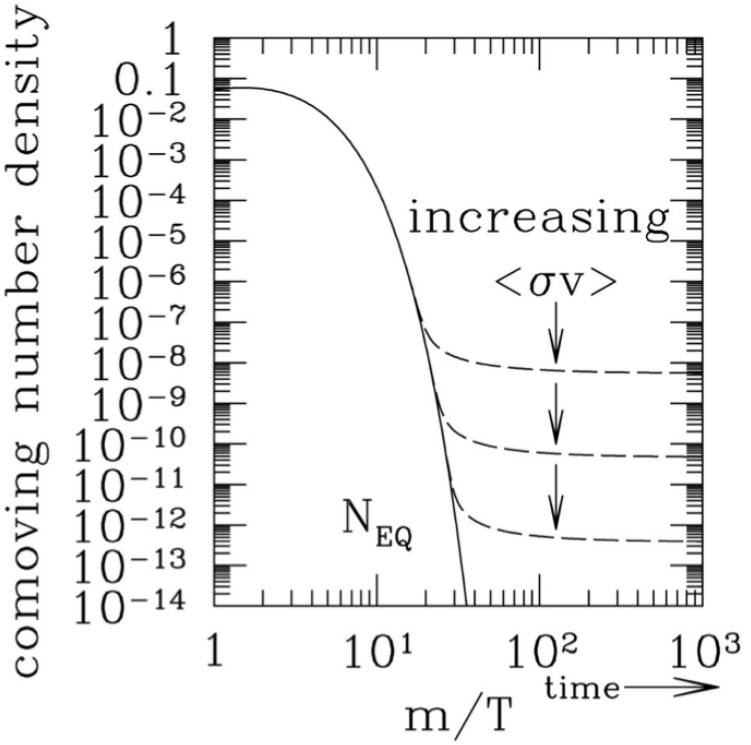
- Neutralinos (higgsino, bins, winos, singlinos)
- Axinos
- Gravitinos
- Sneutrinos
- Axions
- Sterile neutrinos
- 4th generation neutrinos
- Kaluza-Klein photons
- Kaluza-Klein gravitons
- Brane world dark matter/D-matter
- Little higgs dark matter
- Light scalars
- Superheavy states (*ie*. "WIMPzillas")
- Self-interacting dark matter
- Super-WIMPs
- Asymmetric dark matter
- Q-balls (and other topological states)
- CHAMPs (charged massive particles)
- Cryptons, mirror matter, and many, many, many others…



WIMPs

- Perhaps Dark Matter is a particle with weak-scale mass?
  - *Weakly Interacting Massive Particles (WIMPs)*
  - Produced in the Big Bang, interact via $\chi + \chi \rightarrow q + q$

- As the universe expands and the temperature drops...
  - WIMPs become diluted, interact less often and 'freeze out'.
  - Higher cross-section (<σv>) yields lower relic density



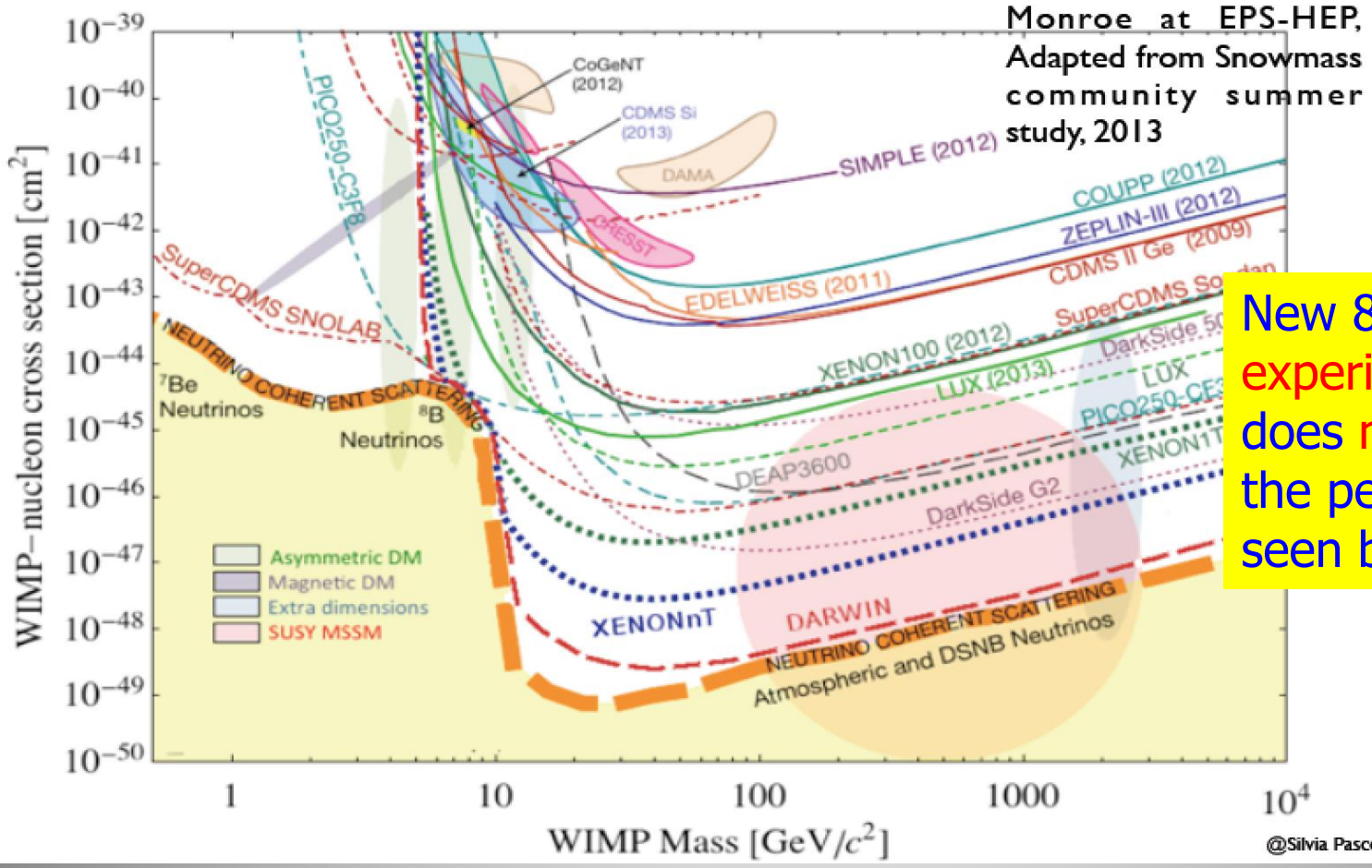
Weakly-interacting massive particles naturally provide the right relic abundance - "WIMP miracle"

Direct Searches for Dark Matter

Underground low noise experiments

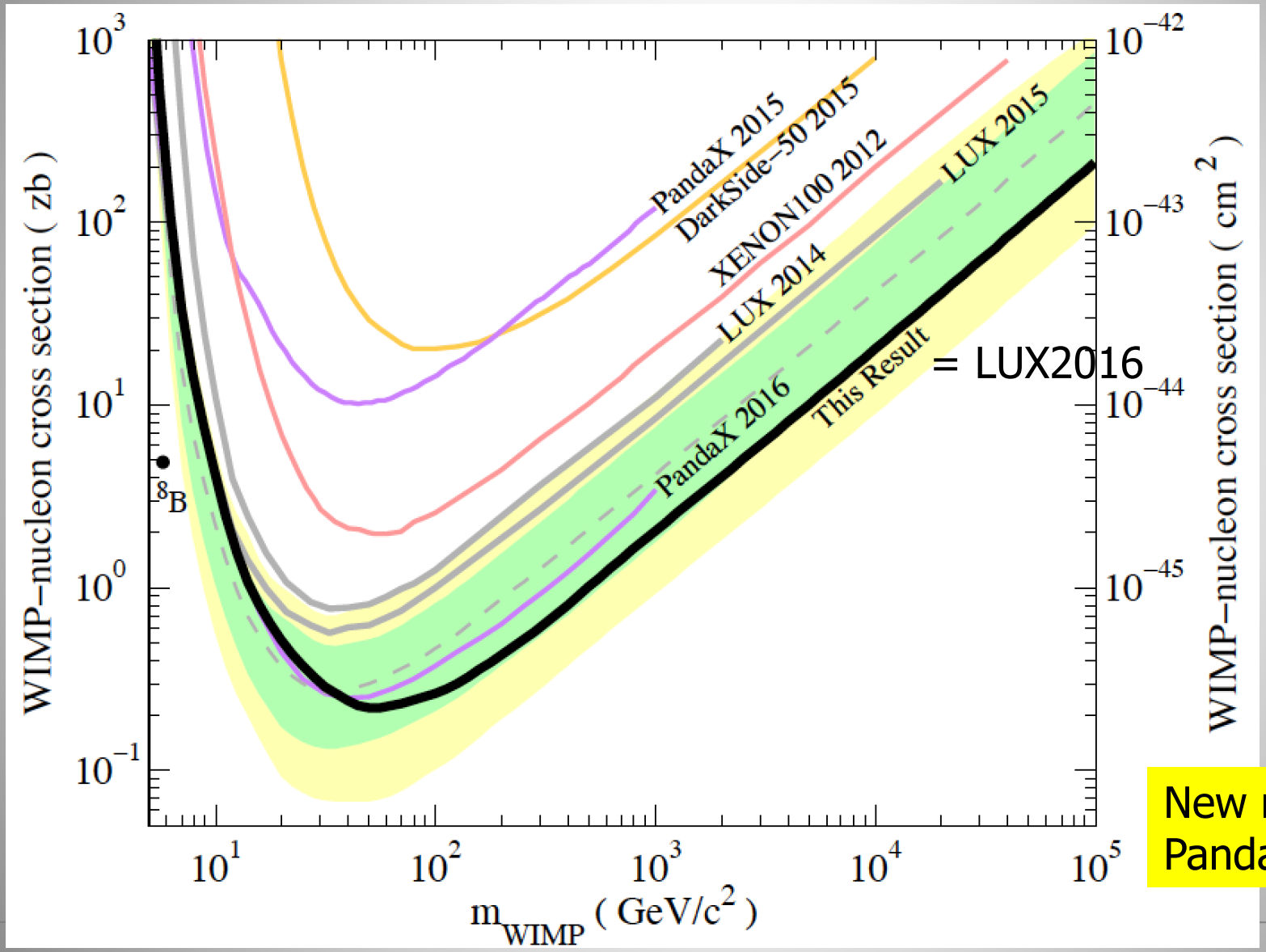
No non-ambiguous signal yet!!

There is a very large number of projects which are under construction or being planned for the future.



New 8/9/15: XMASS experiment (Japan) does not confirm the periodical effect seen by DAMA/LIBRA

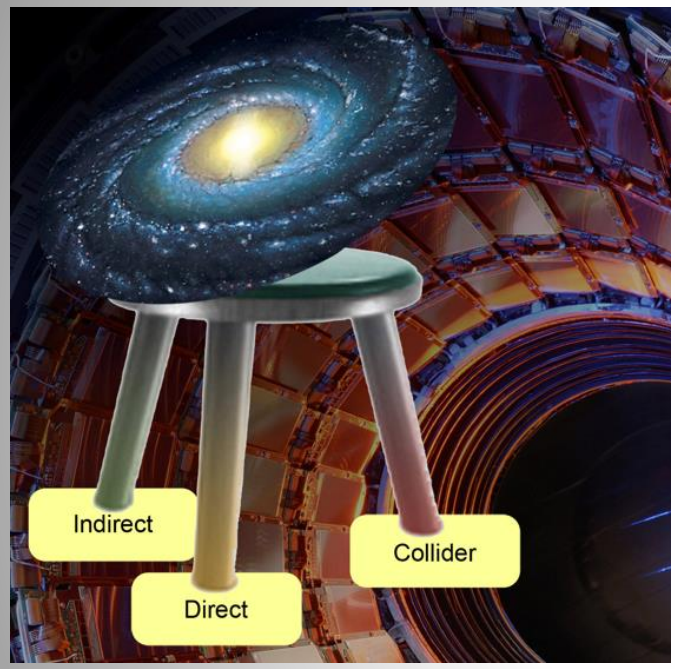
Direct Searches for Dark Matter

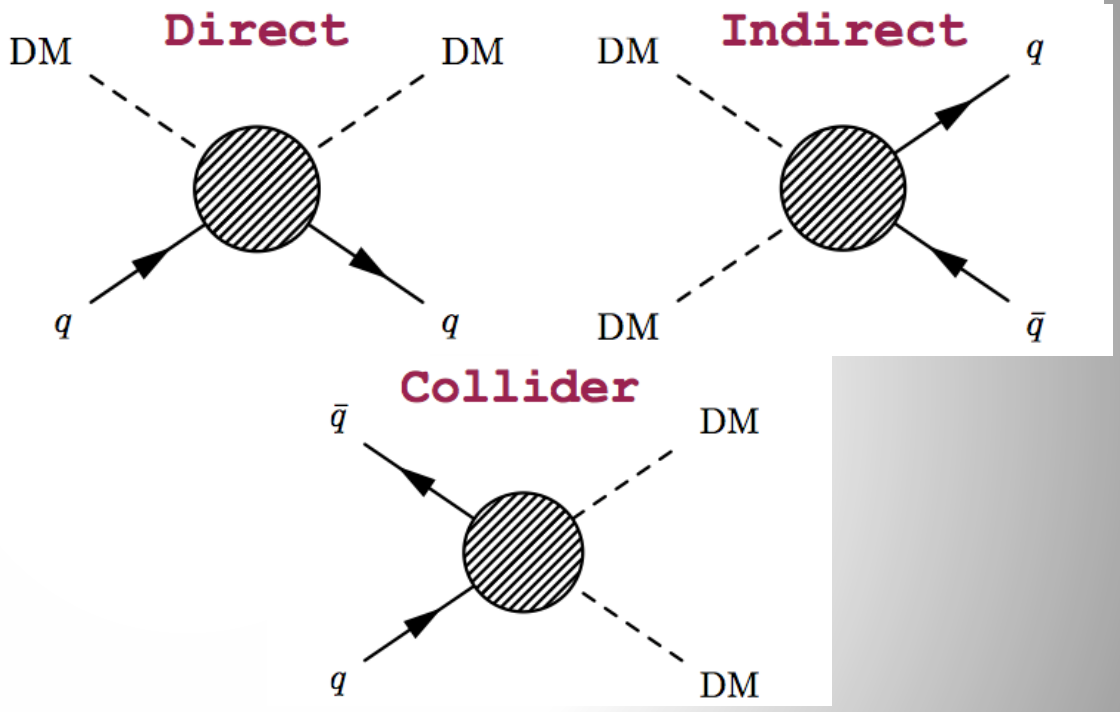


New results from PandaX and LUX

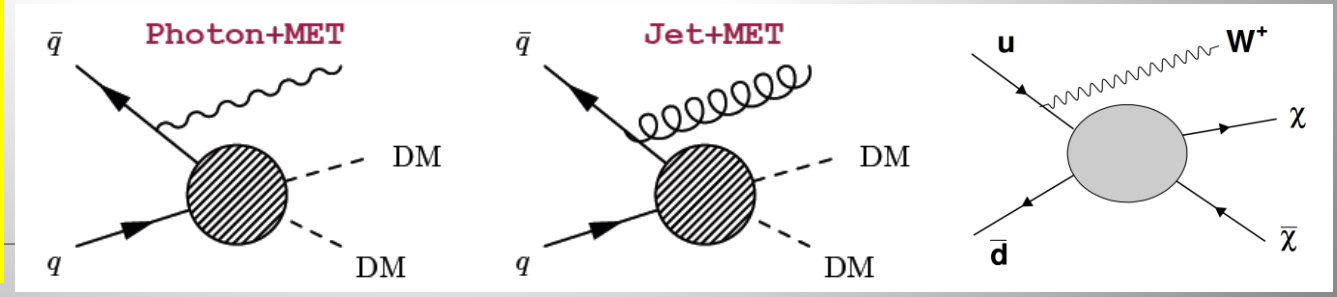
The Generic Dark Matter Connection

Searches for mono-jets and mono-photons etc. can be used to search for Dark Matter (DM)



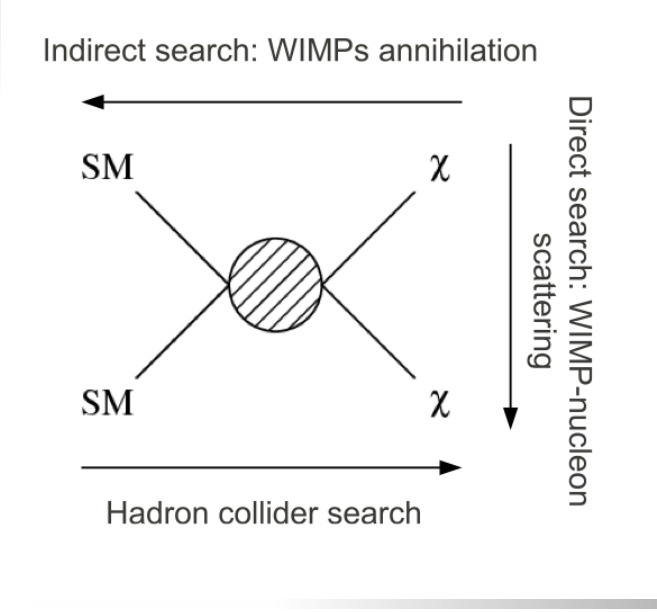


Use effective theory or better simplified models to relate measurements to Dark Matter studies



Dark Matter Searches

Convert collider search results into limits on DM quantities
Two ways:



- Effective field theory (EFT):
  - Mediator too heavy to be generated directly
  - Contact interation with suppression scale $M_\star \sim \frac{M}{\sqrt{g_\chi g_{SM}}}$, with g_χ and g_{SM} the couplings to Standard Model (SM) and DM, and M the mediator mass
- Simplified models: Popular in SUSY
  - Specified massive mediator
  - UV-complete (no validity issue)

Types of interactions chosen in the early studies

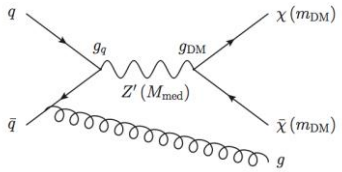
Name	Initial state	Type	Operator
D1	qq	scalar	$\frac{m_q}{M_\star^3}\bar{\chi}\chi\bar{q}q$
D5	qq	vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D8	qq	axial-vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
D9	qq	tensor	$\frac{1}{M_\star^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$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

Discussions on the region of validity became a major issue…

Mono-object Searches @ LHC

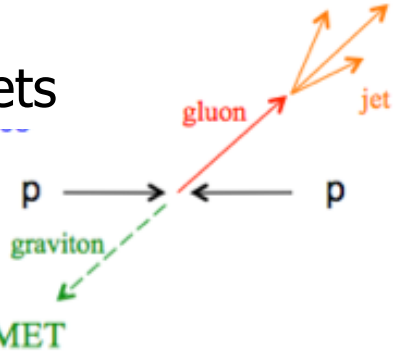
- Mono-jets: Generally the most powerful
- Mono-photons: First used for dark matter Searches
- Mono-Ws: Distinguish dark matter couplings to u- and d-type of quarks
- Mono-Zs: Clean signature
- Mono-Tops: Couplings to tops
- Mono-Higgs: Higgs-portals
- Higgs Decays?

Effective Field Theories for DM interpretation has been riticised!
Alternative SMS now more popular…

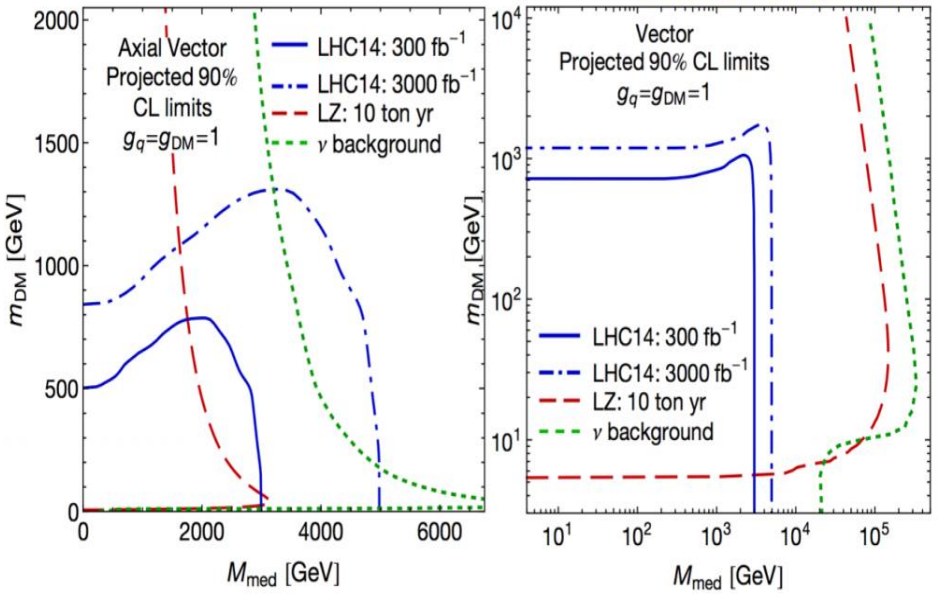


arXiv:1407.8257
arXiv:1411.0535

Example Monojets



Dark Matter?



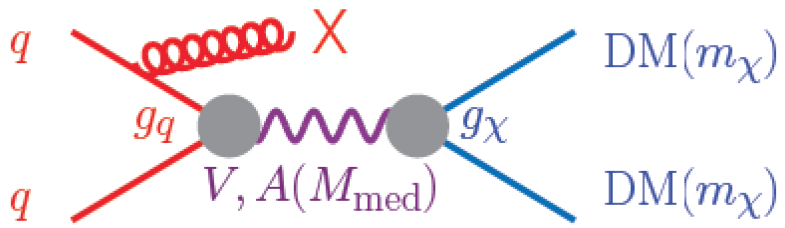
Collider Dark Matter Signatures

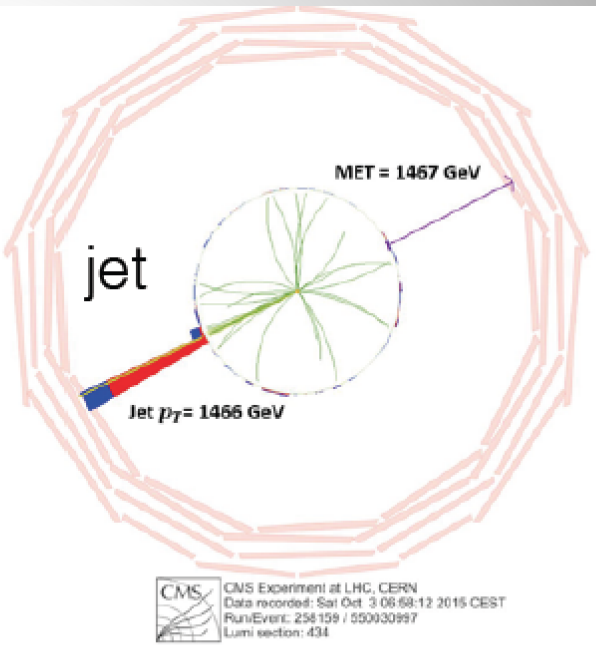
EG: Monojet events

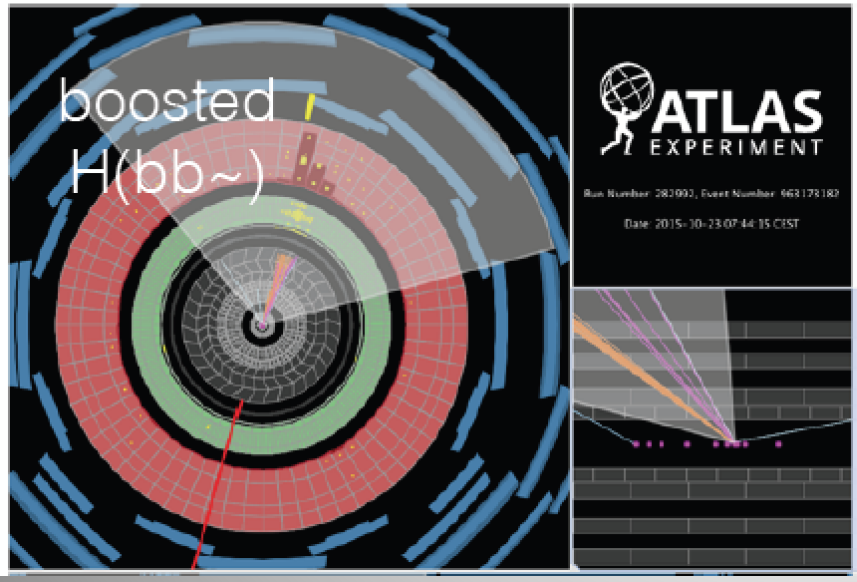
S.C. Shu

ET^{miss}+X a.k.a. Mono-X

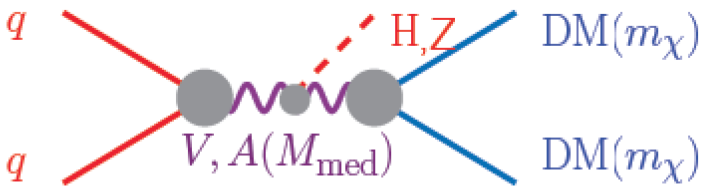
- X from ISR jet, b, t, γ, W, Z







- X from mixing with mediator



- X from paired $t\bar{t}$, $b\bar{b}$

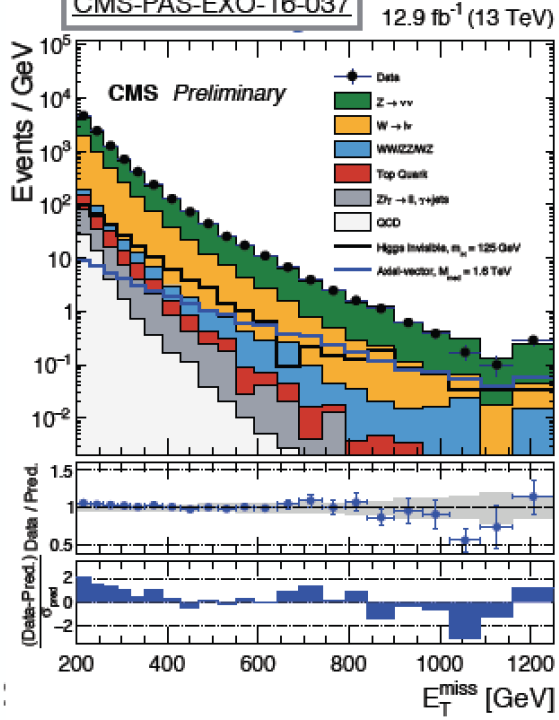
Monojets/top/bb/tt Searches

- Key observables - imbalanced transverse momentum ET^{miss}
- Irreducible background: Z(vv)+jets
  - jets might be mis-reconstructed as b-jets, γ, W, Z

S.C. Shu

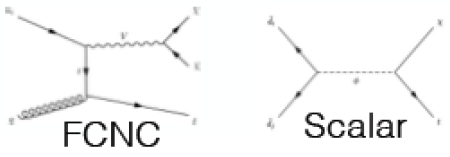
ET^{miss}+jet

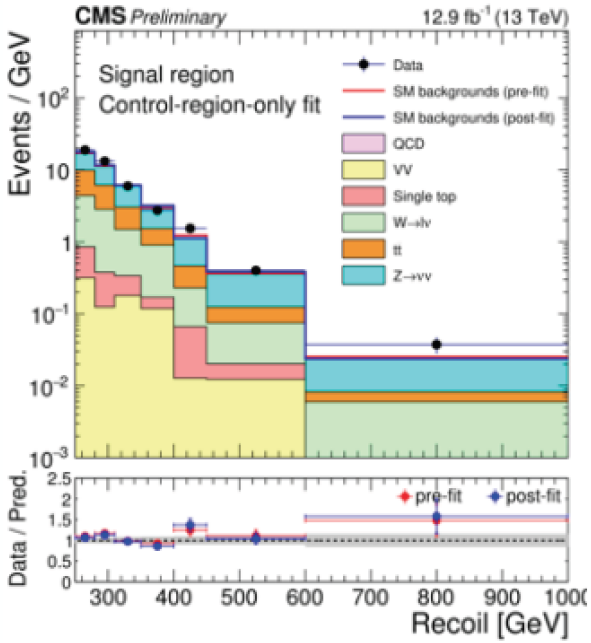
CMS-PAS-EXO-16-037



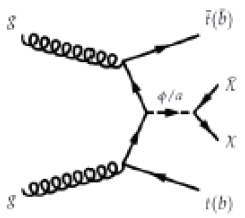
ET^{miss}+t

CMS-PAS-EXO-16-040





ET^{miss}+$b\bar{b}$/$t\bar{t}$



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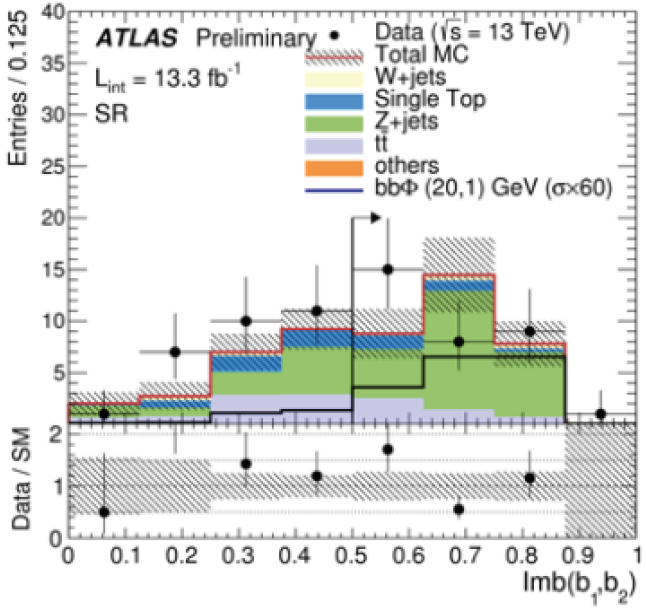
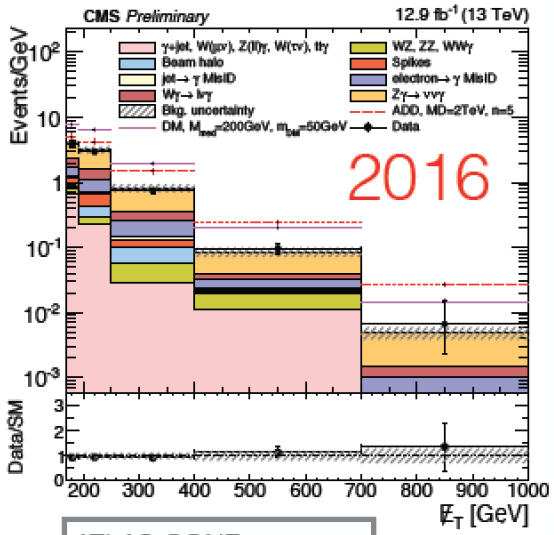
ATLAS-CONF-2016-077

ATLAS-CONF-2016-086



Monophoton/W/Z/H Searches

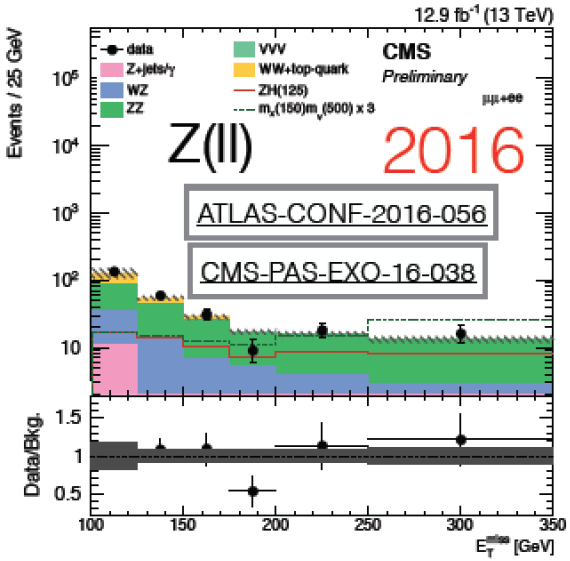
E_T^{miss}+γ



ATLAS-CONF-2015-080

CMS-PAS-EXO-16-039

E_T^{miss} + W/Z



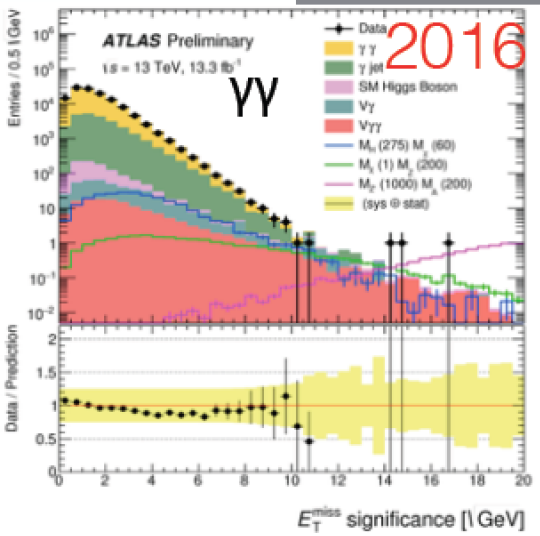
ATLAS-CONF-2016-056

CMS-PAS-EXO-16-038

E_T^{miss}+H

CMS-PAS-EXO-16-011

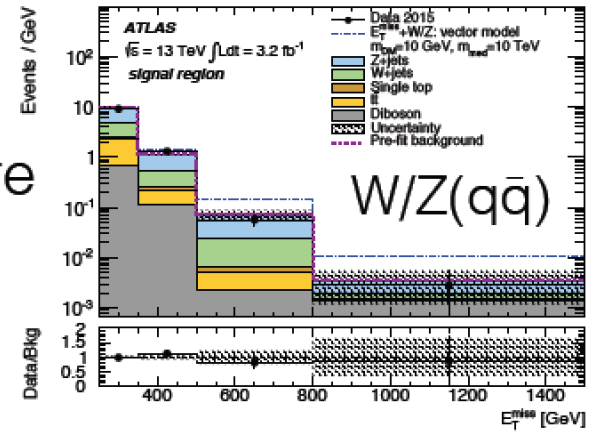
ATLAS-CONF-2016-087



EXOT-2015-08

CMS-PAS-EXO-16-037

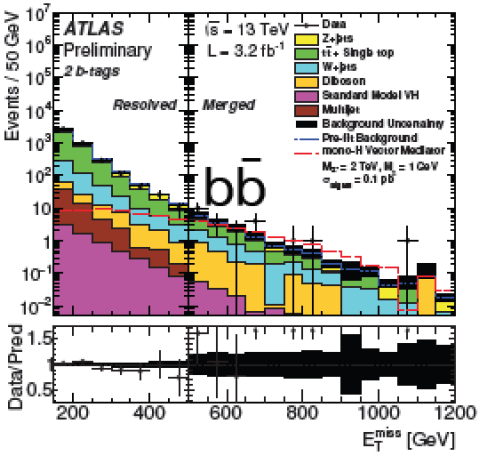
2015



ATLAS-CONF-2016-019

CMS-PAS-EXO-16-012

2015



S.C. Shu

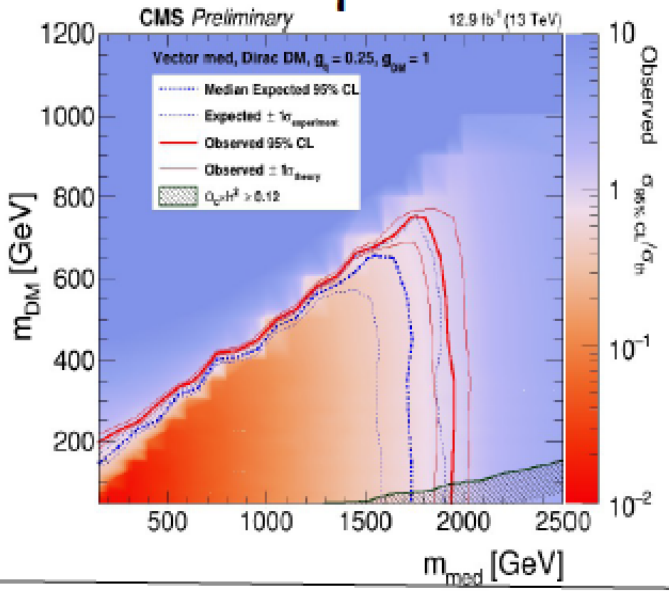
Boosted jet substructure technique is used in hadronic W/Z/H

Monojet Analysis

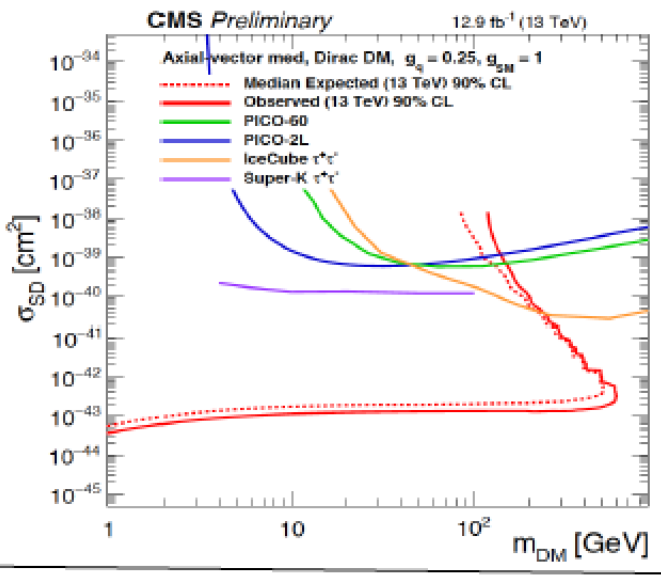
Monojet or V->qq+MET

Spin 1

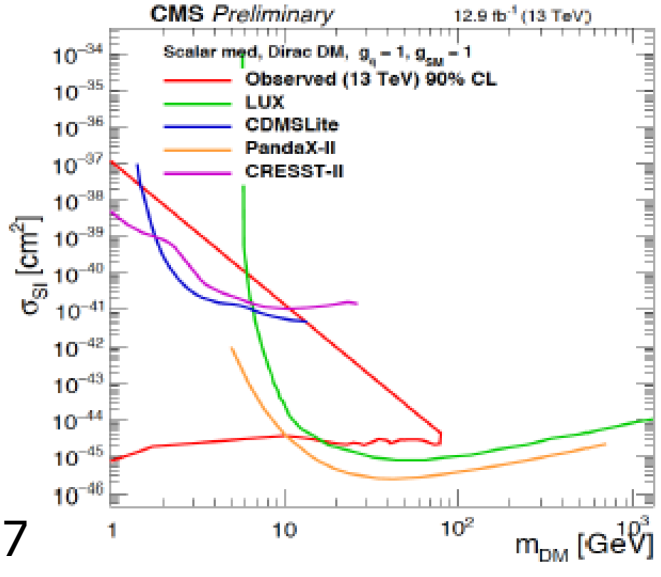
$u\gamma^{\mu}u$

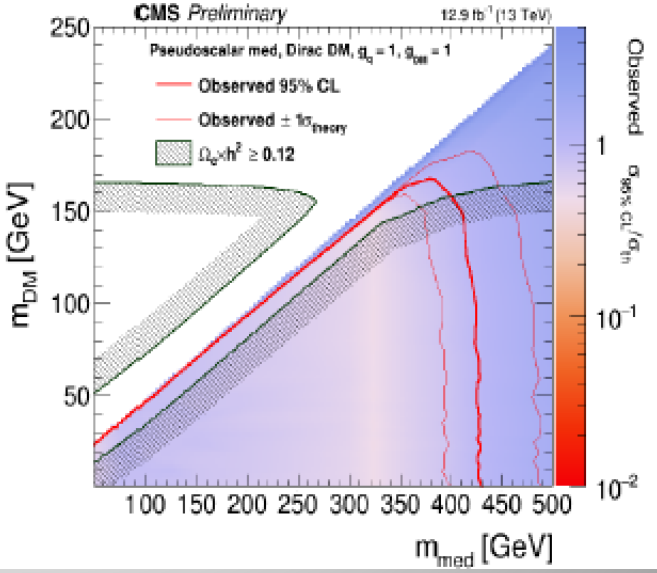


$u\gamma^{5}u$



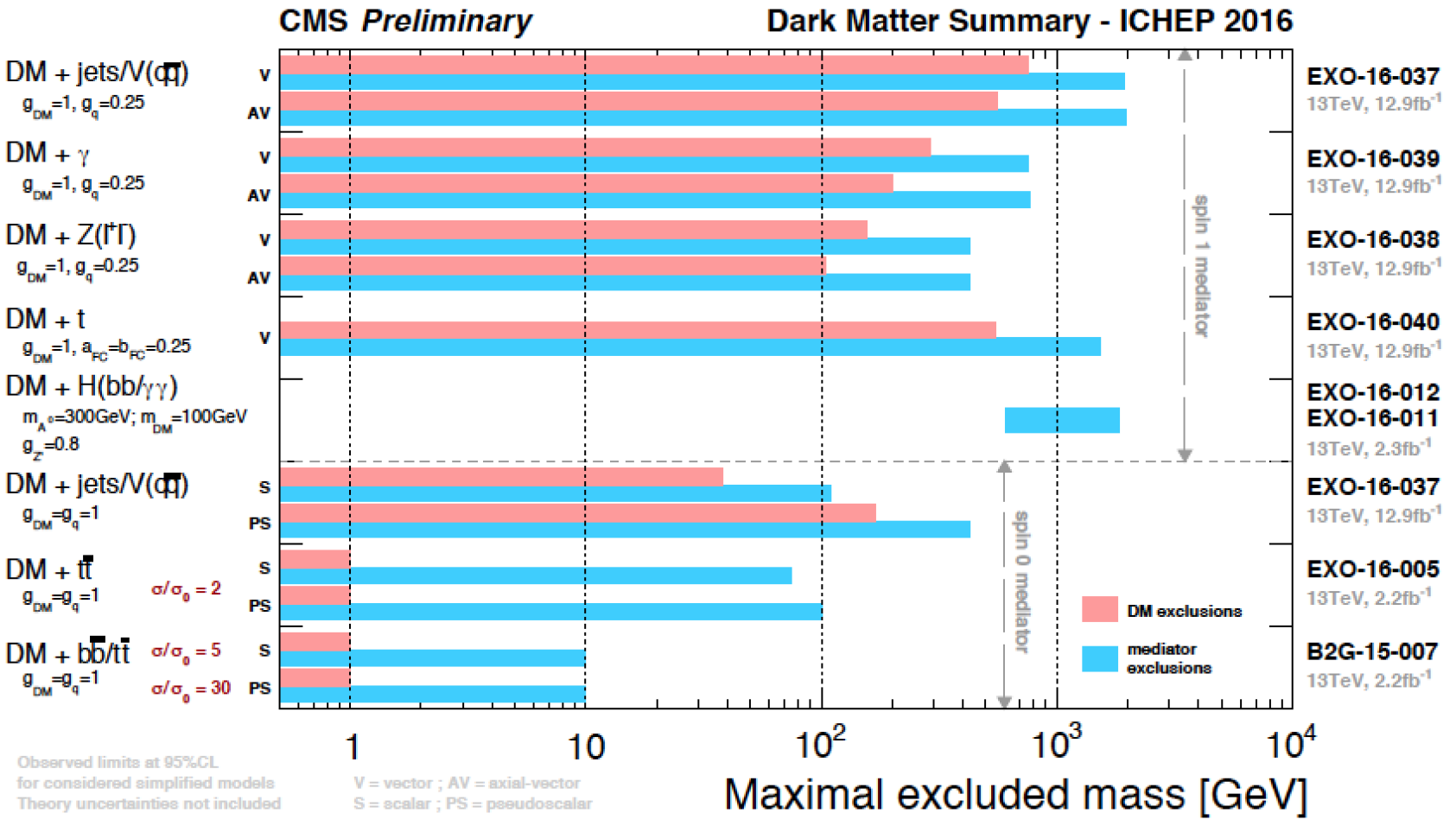
Spin 0





EXO-16-037

Dark Matter / Mediator Exclusion

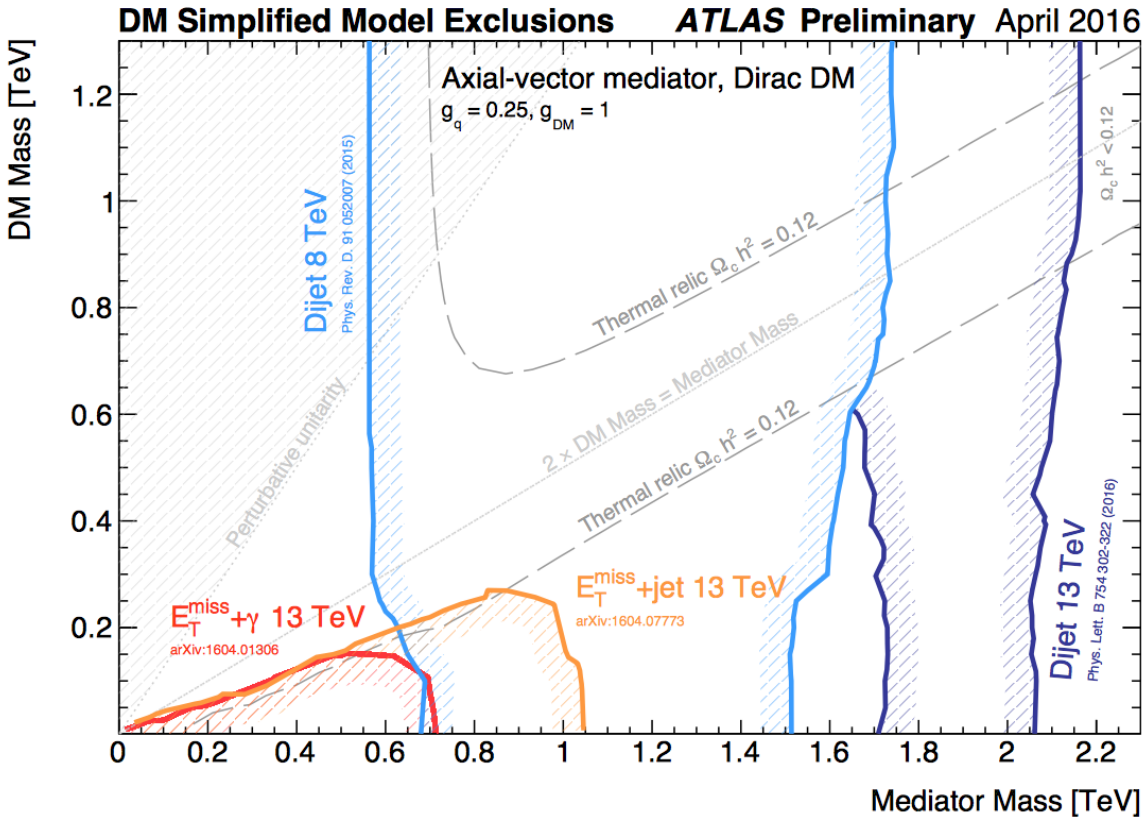


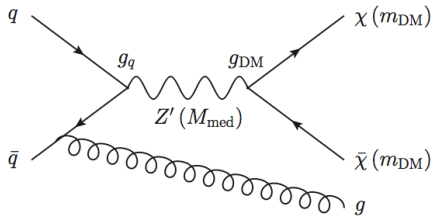
Spin-0 mediator exclusion is at the 100-200 GeV level
Spin-1 mediator exclusion is at the 1-2 TeV level

Dark Matter Searches: Evolution

Dark Matter hunt is one of the new main physics goals for the LHC!

- Mono-object searches are not yet giving better sensitivity compared to 8 TeV
- But new developments with Simplified Models, allow including many more search channels such as dijets (aka "In Search for the Mediator")

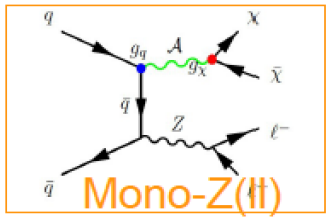


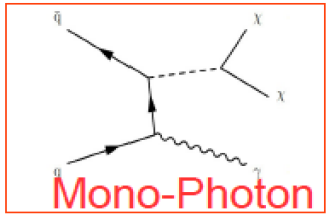


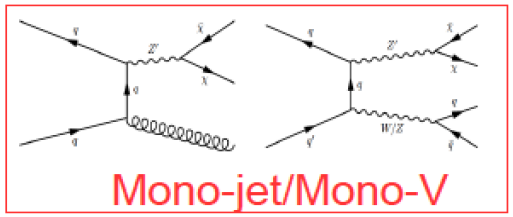
arXiv:1507.00966

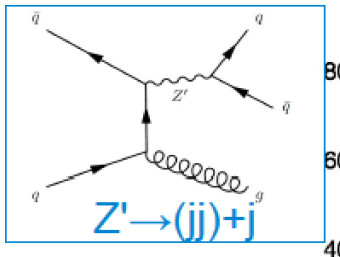
A promise for future studies

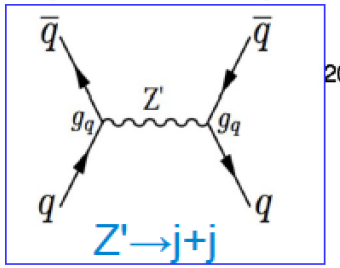
Dark Matter Searches: Evolution

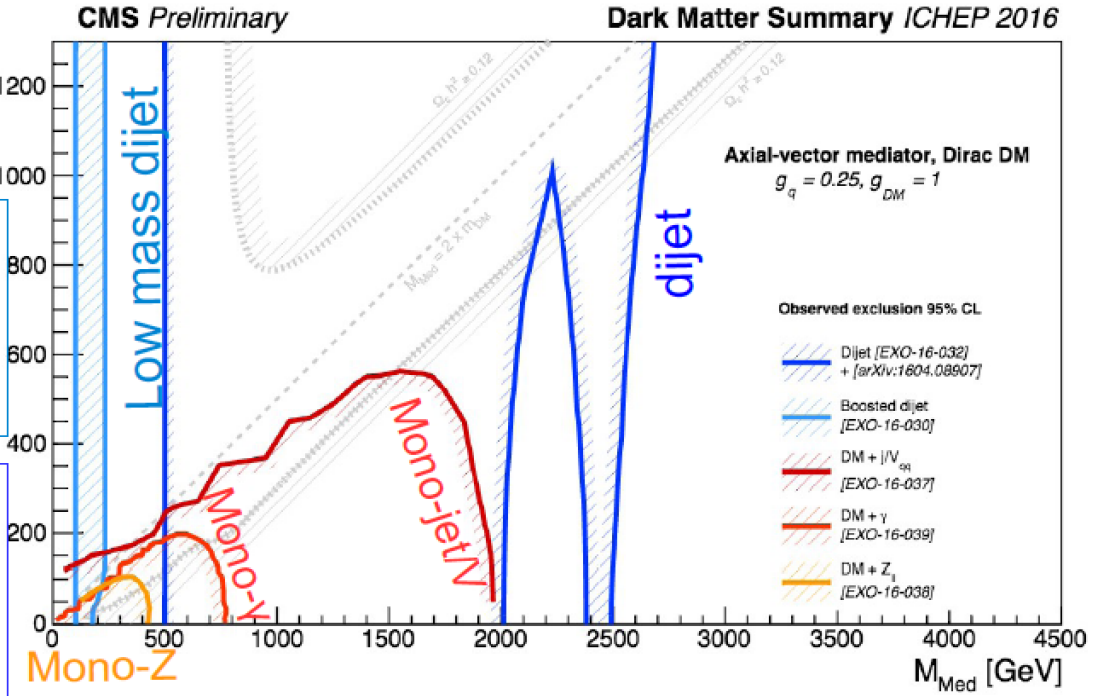


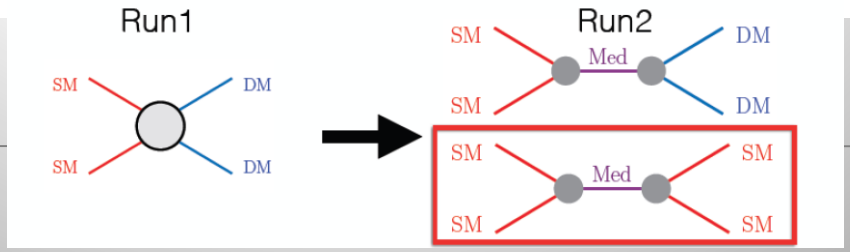




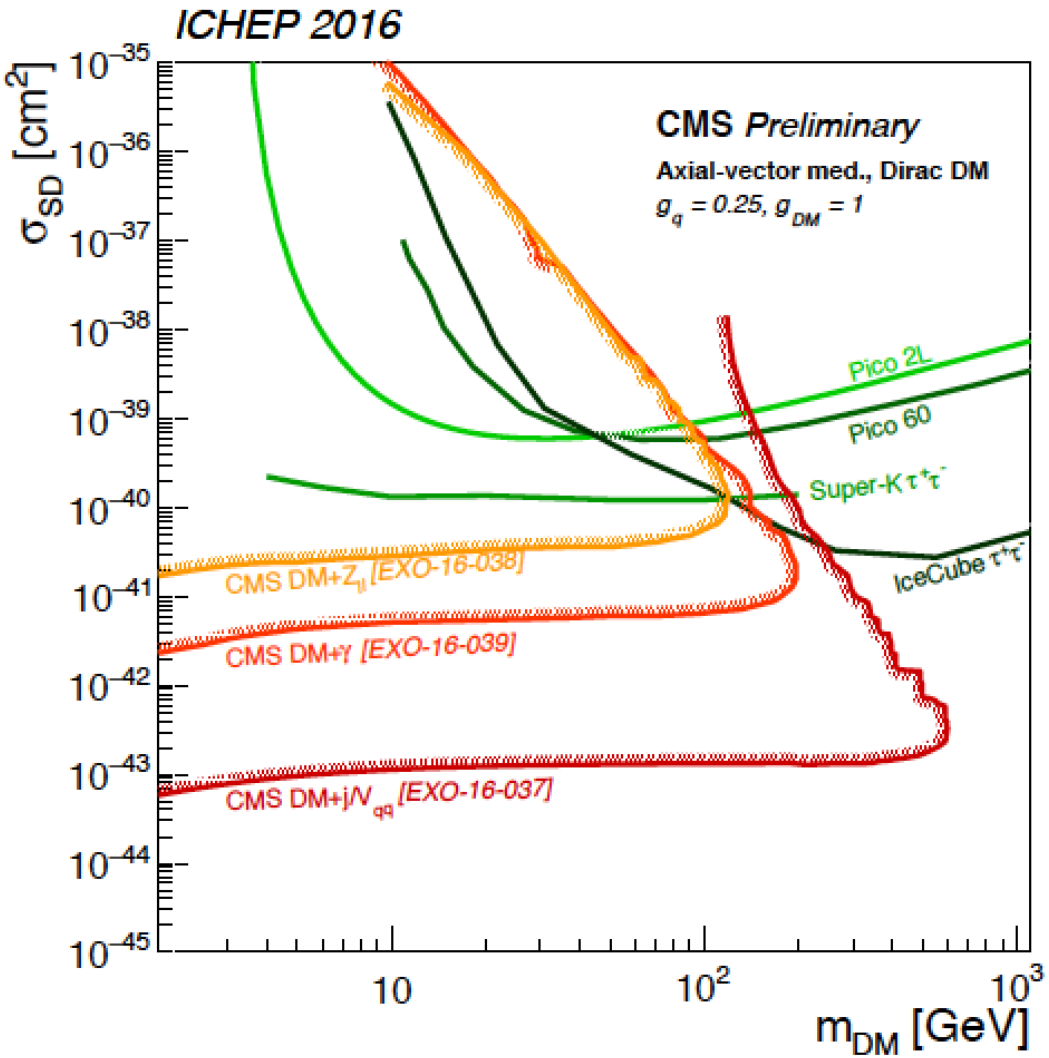






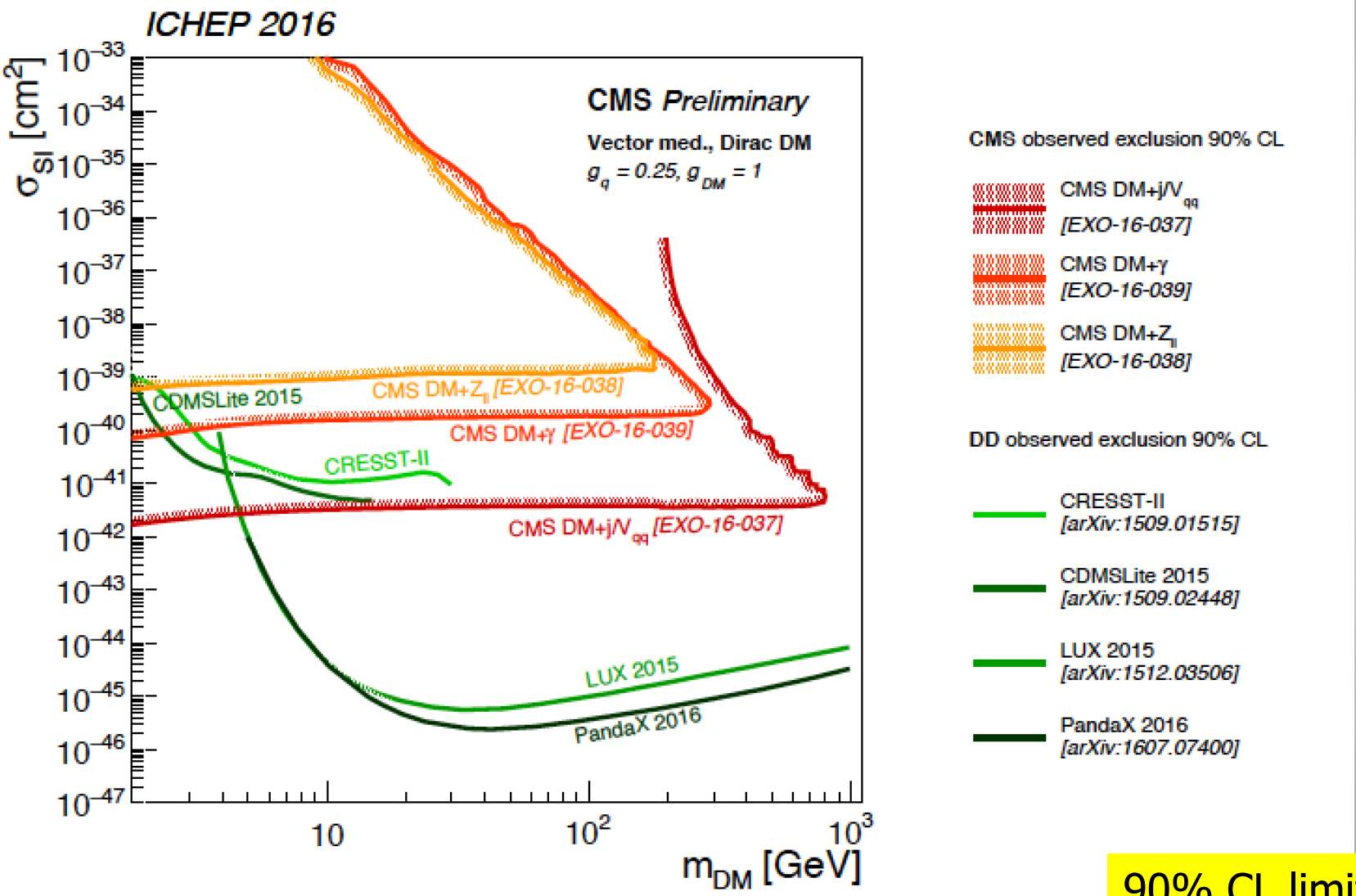


Comparison with Direct Detection



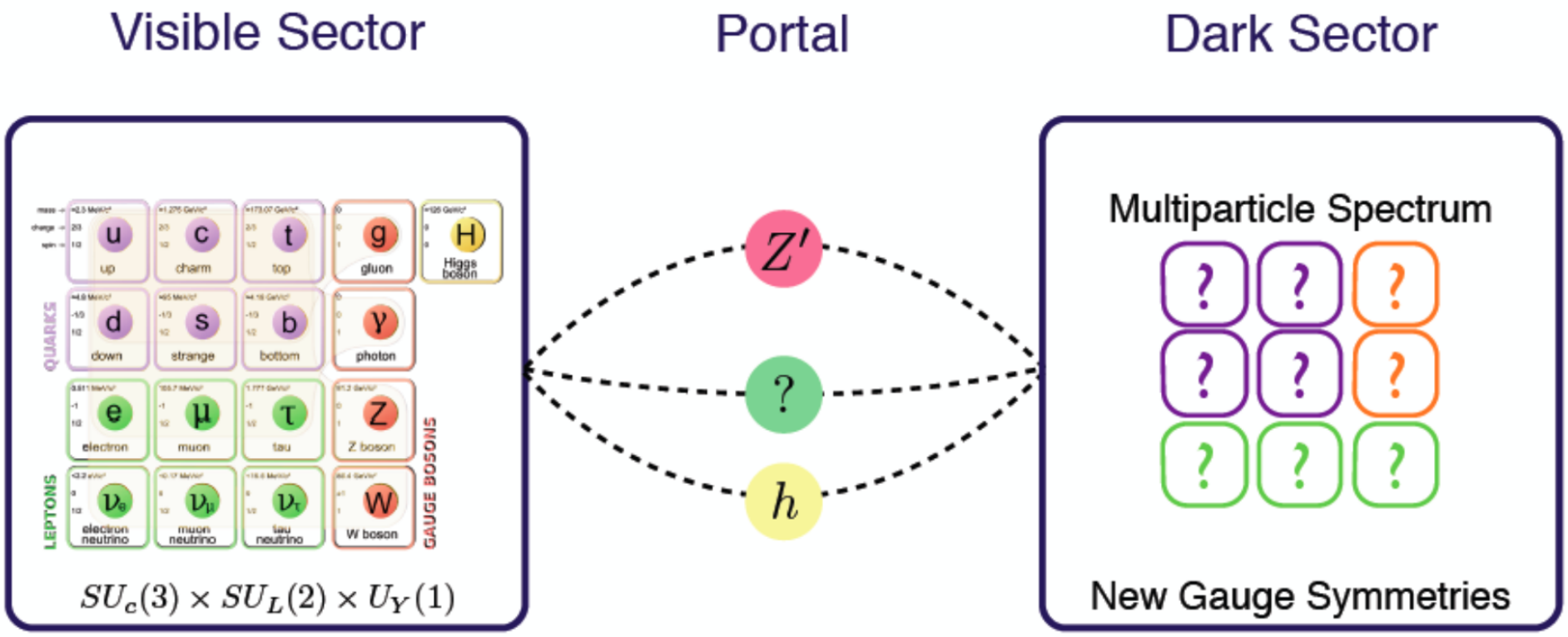
90% CL limits

Comparison with Direct Detection



90% CL limits

Cite: “Why should 5% of the mass density have all the fun?”

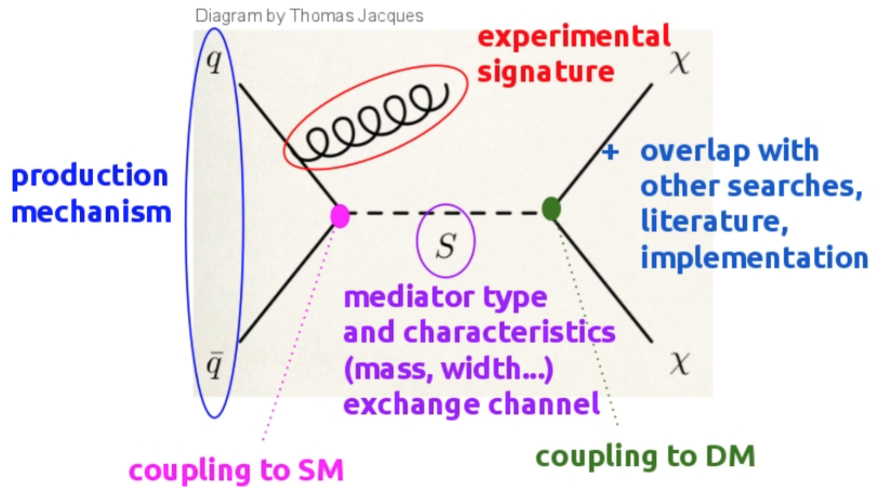


Can motivate alternative searches to MET + X from dark sector

Discussions on Dark Matter Interpretation

ATLAS/CMS Dark Matter Forum:
experiment/theory discussion towards Run-2 DM searches

Many possibilities to be used as building blocks:



https://twiki.cern.ch/twiki/bin/view/LHCDMF/WebHome
Mailing list: lhc-dmf@cern.ch

This Forum agreed upon

- Prioritized **set of simplified models**
- Common **model implementation and details** (e.g. matching, scales) towards MC generation of benchmarks
- **EFT validity** assessment procedure

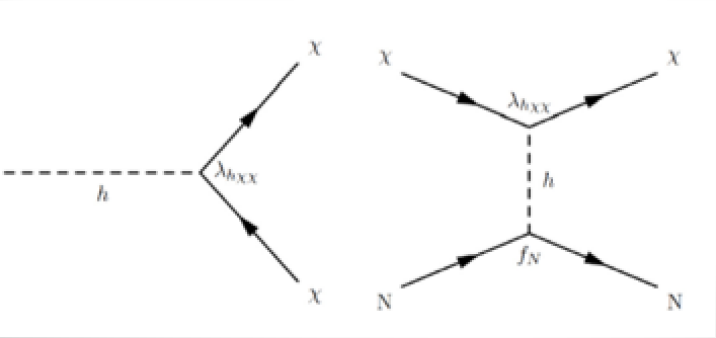
This Forum will document:

models and choices

arXiv:1506.03116

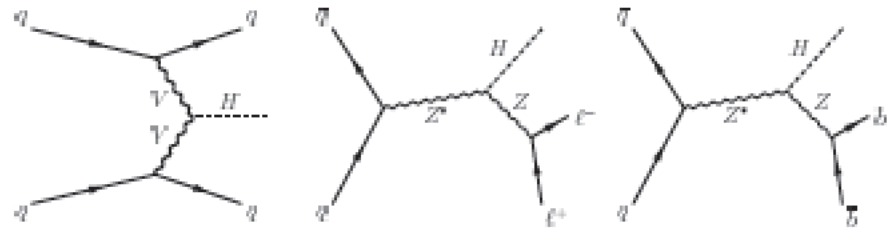
=> Now an ATLAS/CMS +TH working group: arXiv:1603.04156

Dark Matter and the Higgs



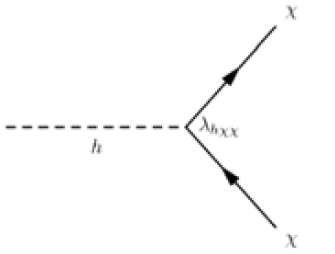
"higgs portal models"
Eg: arXiv:1205.3169

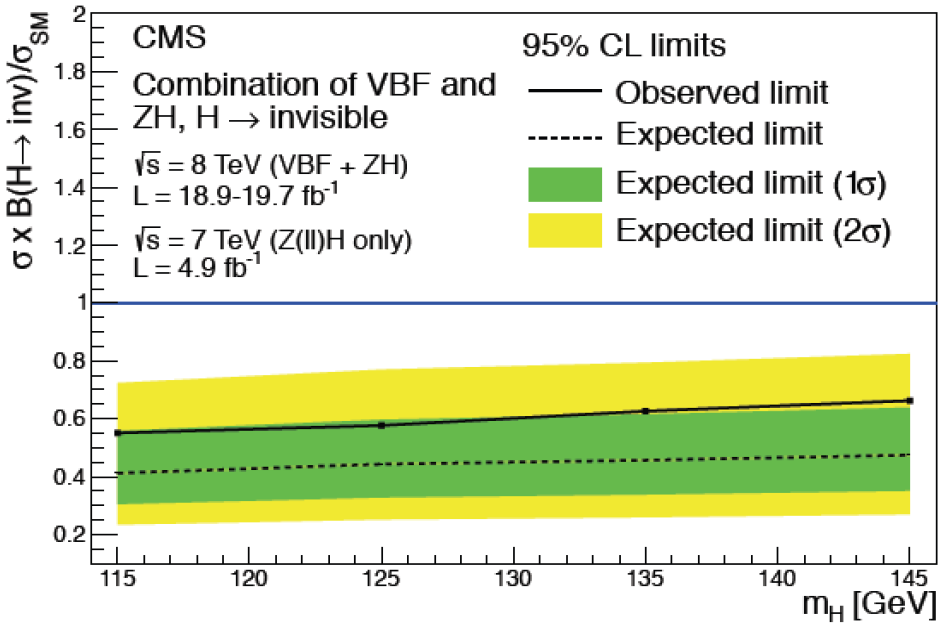
Invisible Higgs Decay Channel



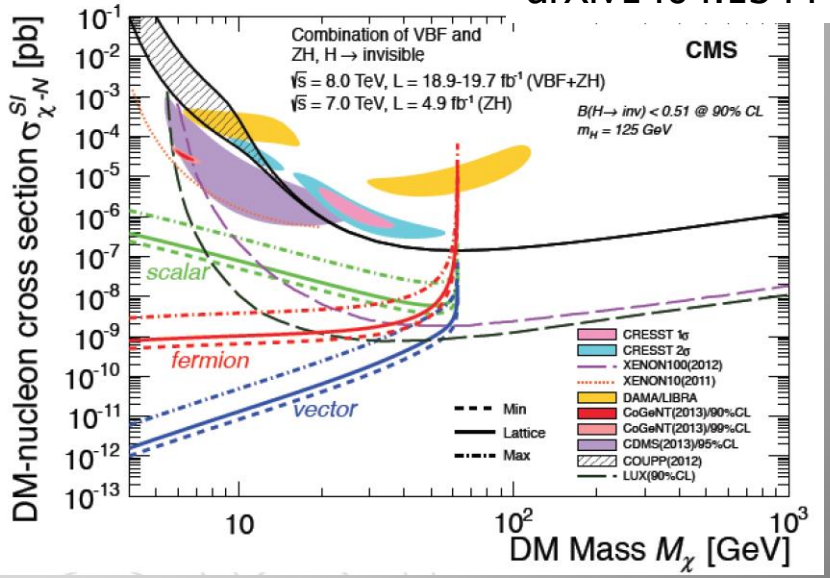
Search for invisible Higgs decays using
Z+H → 2 leptons + missing E_T
VBF H → 2 jets + missing E_T
Possible decay in Dark Matter particles
(if $M<M_H/2$): Higgs Portal Models

Combined result from the three channels
BR(H→invisible)<58%(44% exp) at 95% CL.
for a Higgs with a mass of 125 GeV



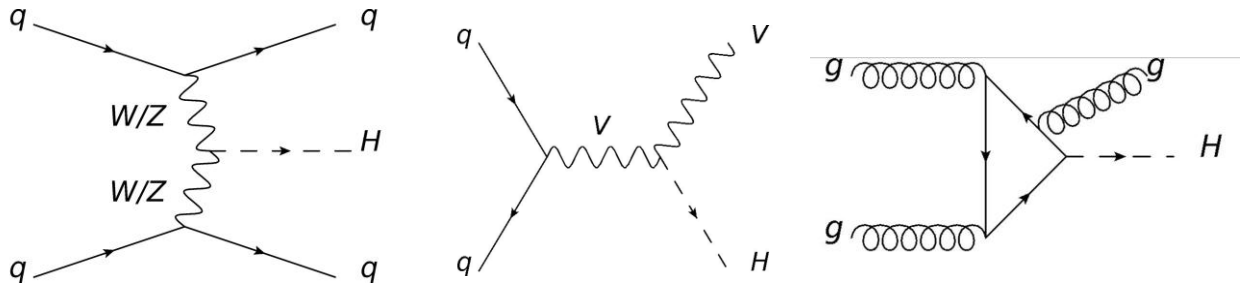


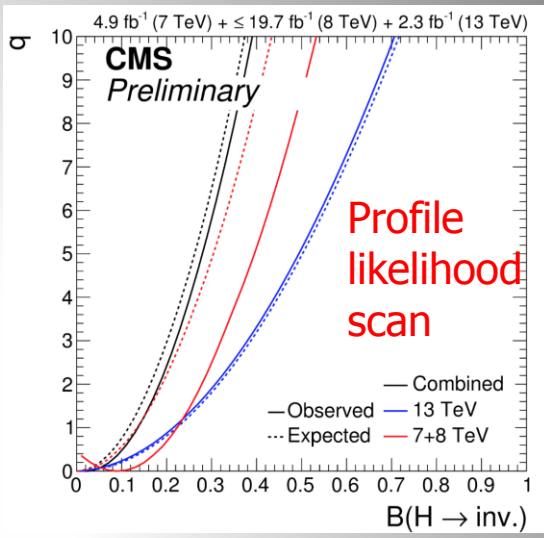
arXiv1404.1344

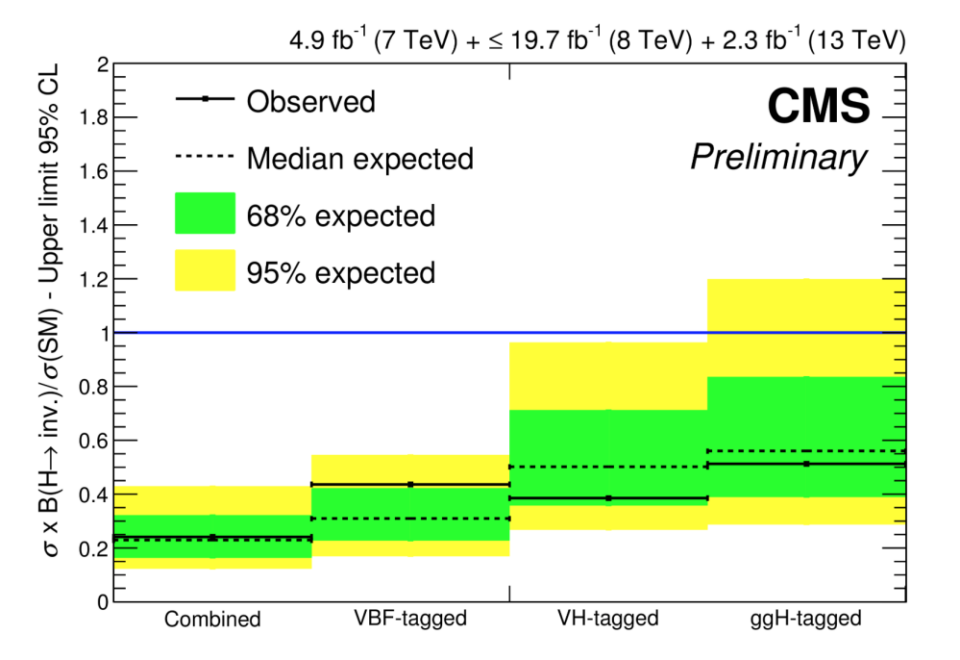


Invisible Channels Combination

Combination of all channels including also the mono-jet channel gives for a 125 GeV Higgs a limit of 24% (23% expected) at 95% CL





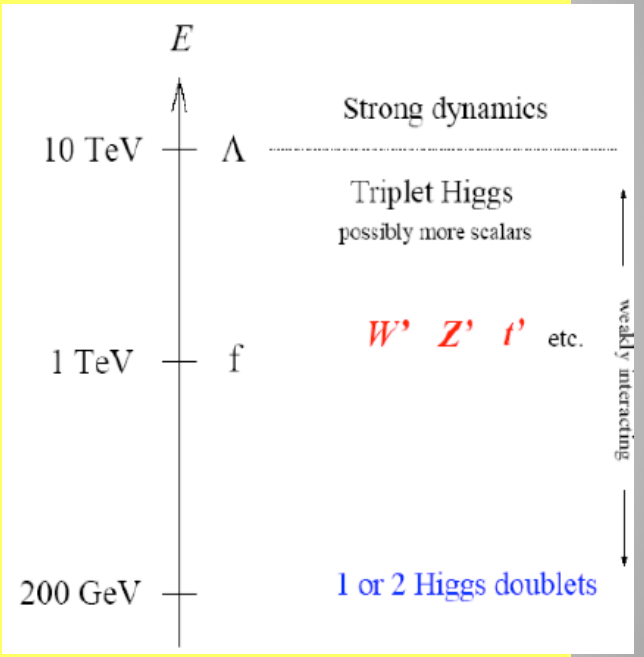


CMS-SUS-16-016

Looking Forward @ the LHC

Other New Physics Ideas…

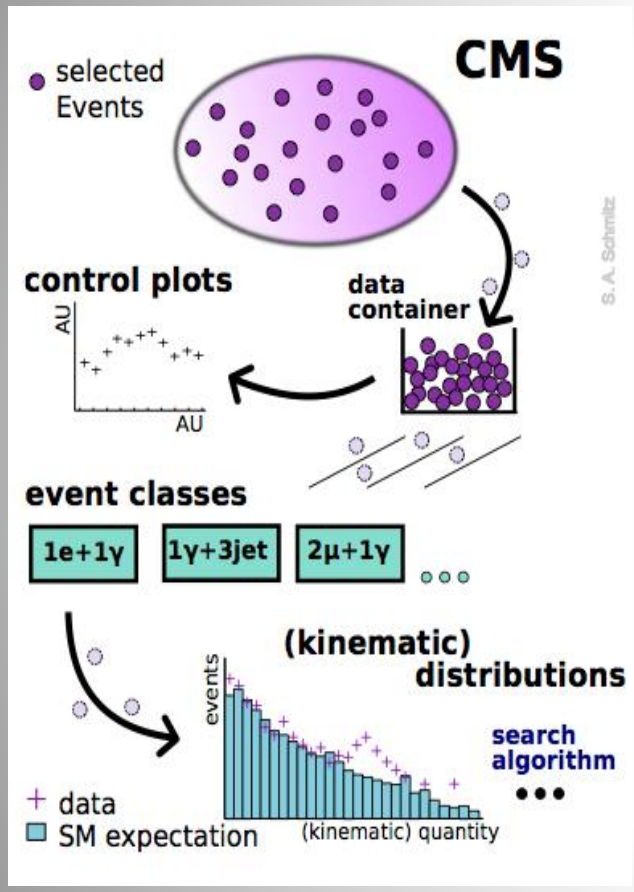
- Plenty!
  - Compositeness/excited quarks & leptons
  - Little Higgs Models
  - Colorons
  - Dark photons
  - String balls/T balls
  - Bi-leptons
  - SUSY+ Extra dimensions
  - Unparticles
  - Classicalons
  - Dark/Hidden sectors
  - Colored resonances
  - And more….



Have to keep our eyes open for all possibilities:
Food for MANY PhD theses!!

A Global View!

CMS-EXO-10-021



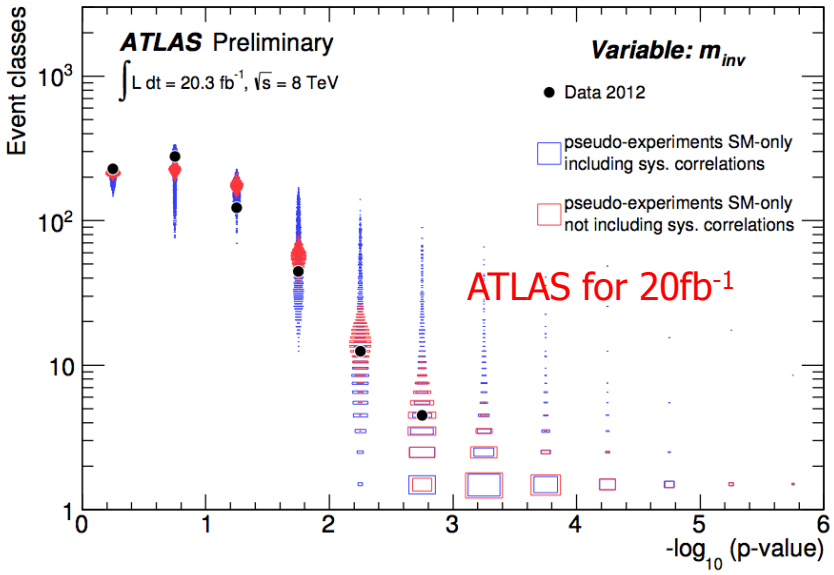
Model independent search

- Divide events into exclusive classes
- Study deviations from SM predictions in a statistical way

Distributions in each class

- $\sum p_T$ - Most general
- $M_{inv}^{(T)}$ - Good for resonances
- MET - Escaping particles

ATLAS-CONF-14-006



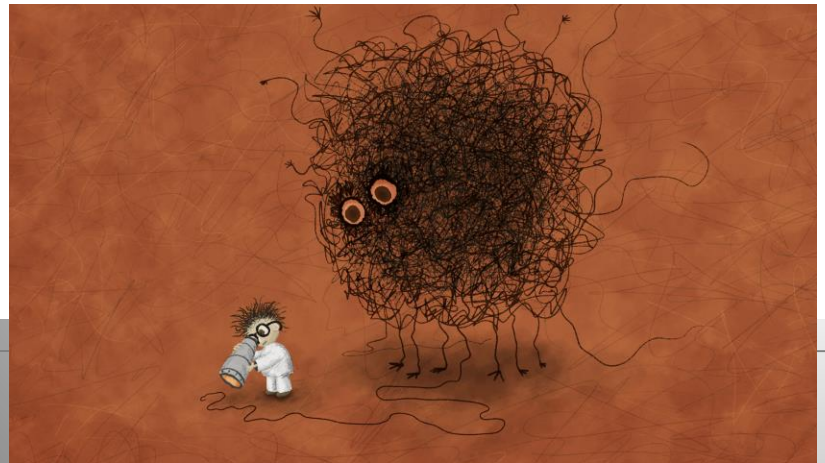
Probability distribution as expected for 35 pb^{-1} for CMS

→muons, electrons, photons, (b)jets, MET

Are we leaving no stone unturned?

- The LHC BSM searches are indispensable and should be continued in the new energy regime and with increasing statistics.
- But if we still do not see more than a 2 sigma at the end of run-III, the HL-LHC will be likely mostly a precision physics machine.
- Are we looking at the right place? Time for more effort in thinking of complementary searches?

Are we looking at the right place?



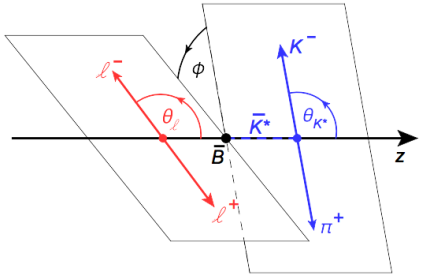
Leave no stone unturned!!

LHCb New Physics in Rare Decays?

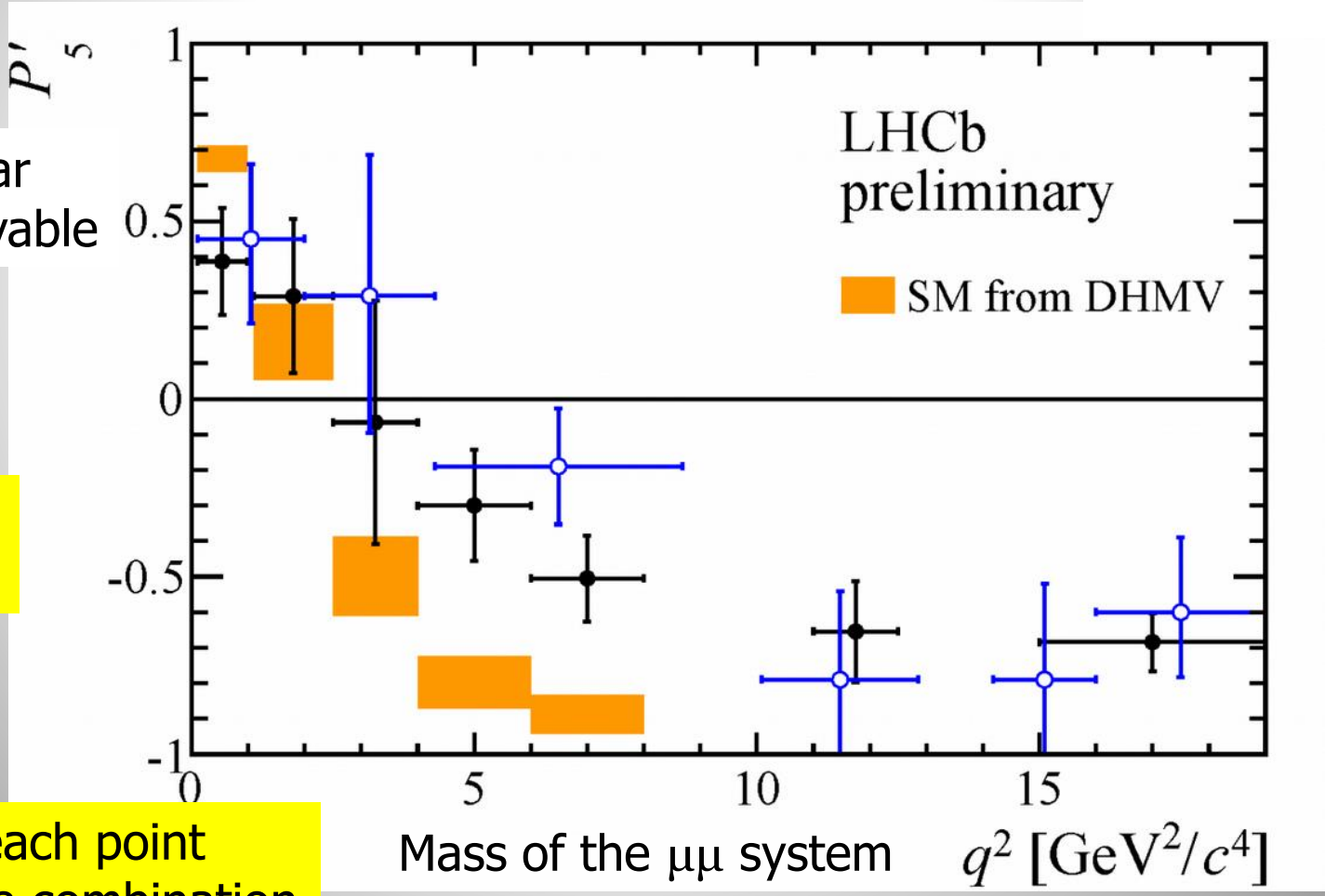
Analysis of the B0→K*μ+μ- decay (full run-I data-set)

http://lhcb-public.web.cern.ch/lhcb-public/Welcome.html#P5p

arXiv:1512.04442



Angular observable



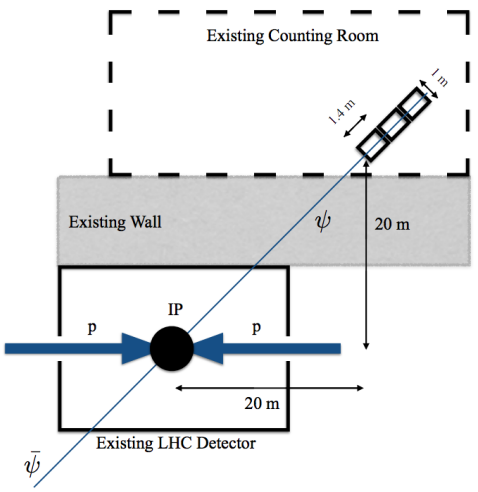
See LHCb lecture

2.9σ for each point
3.7σ naive combination

Particles with Milli-Charges?

CMS search for fractional charged particle arXiv:1210.2311
Q=1/3e > 140 GeV; Q=2/3e >310 GeV (95% CL. dE/dx)

A "new" idea -> Hunting for particles with charges ~ 0.1-0.001e arXiv:1410.6816

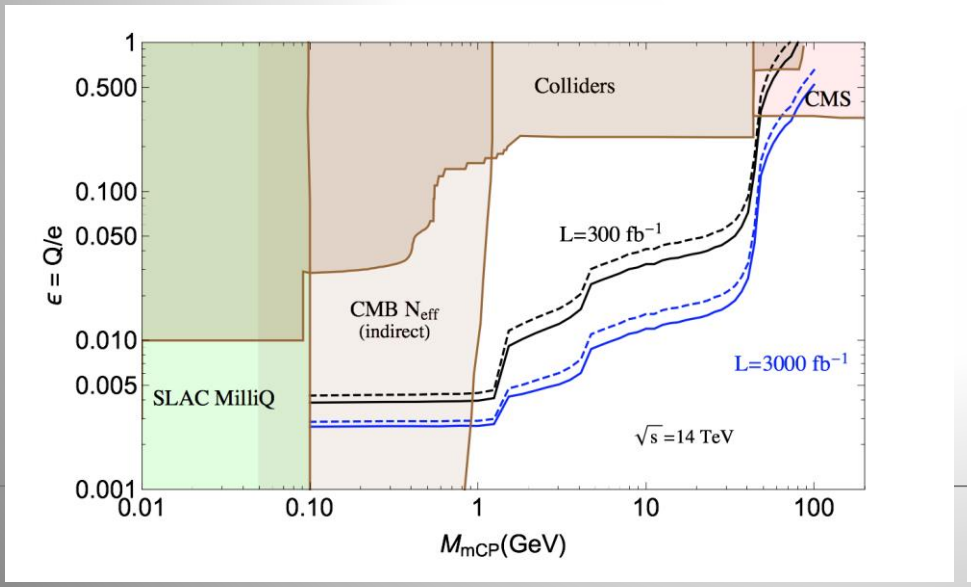


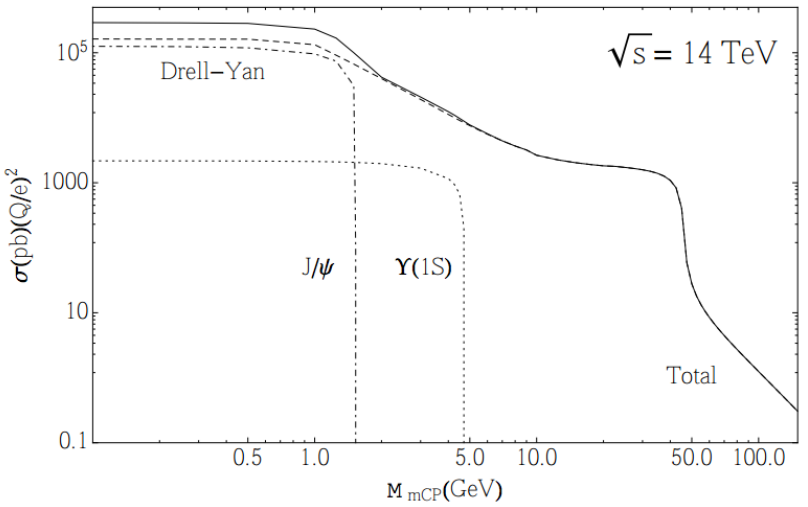
A Letter of Intent to Install a Milli-charged Particle Detector at LHC P5

arXiv:1607.04669

Austin Ball,[1] Jim Brooke,[2] Claudio Campagnari,[3] Albert De Roeck,[1] Brian Francis,[4] Martin Gastal,[1] Frank Golf,[3] Joel Goldstein,[2] Andy Haas,[5] Christopher S. Hill,[4] Eder Izaguirre,[6] Benjamin Kaplan,[5] Gabriel Magill,[7,6] Bennett Marsh,[3] David Miller,[8] Theo Prins,[1] Harry Shakeshaft,[1] David Stuart,[3] Max Swiatlowski,[8] and Itay Yavin[7,6]

MilliQan experiment proposal





Particles with Long Lifetimes?

New Detectors to Explore the Lifetime Frontier

John Paul Chou*
Department of Physics and Astronomy, Rutgers University, Piscataway, NJ 08854

David Curtin†
Maryland Center for Fundamental Physics, Department of Physics, University of Maryland, College Park, MD 20742 USA

H. J. Lubatti‡
Department of Physics, University of Washington, Seattle, WA 98195

(Dated: June 22, 2016)

contacts

arXiv:1606.06298

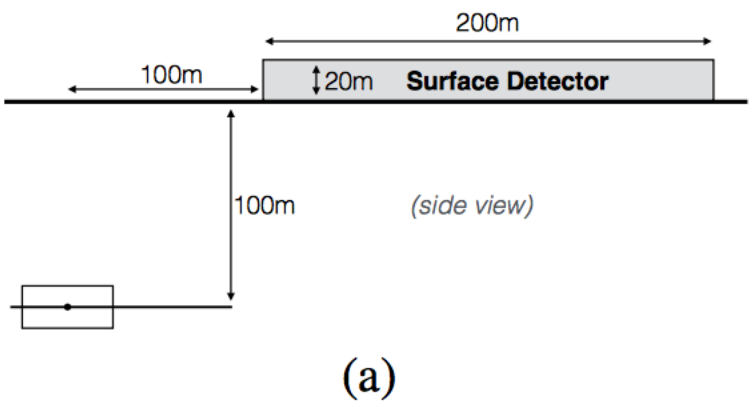
MATHUSLA

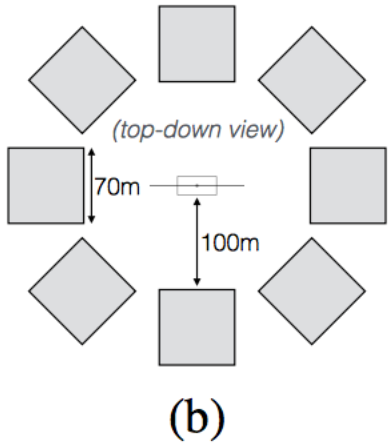
A proposal for a large area surface array to detect ultra long lived particles coming from the pp collisions

Aim to cover the range

$$c\tau \lesssim 10^7 - 10^8 \text{ m}$$

~ BBN constrained inspired

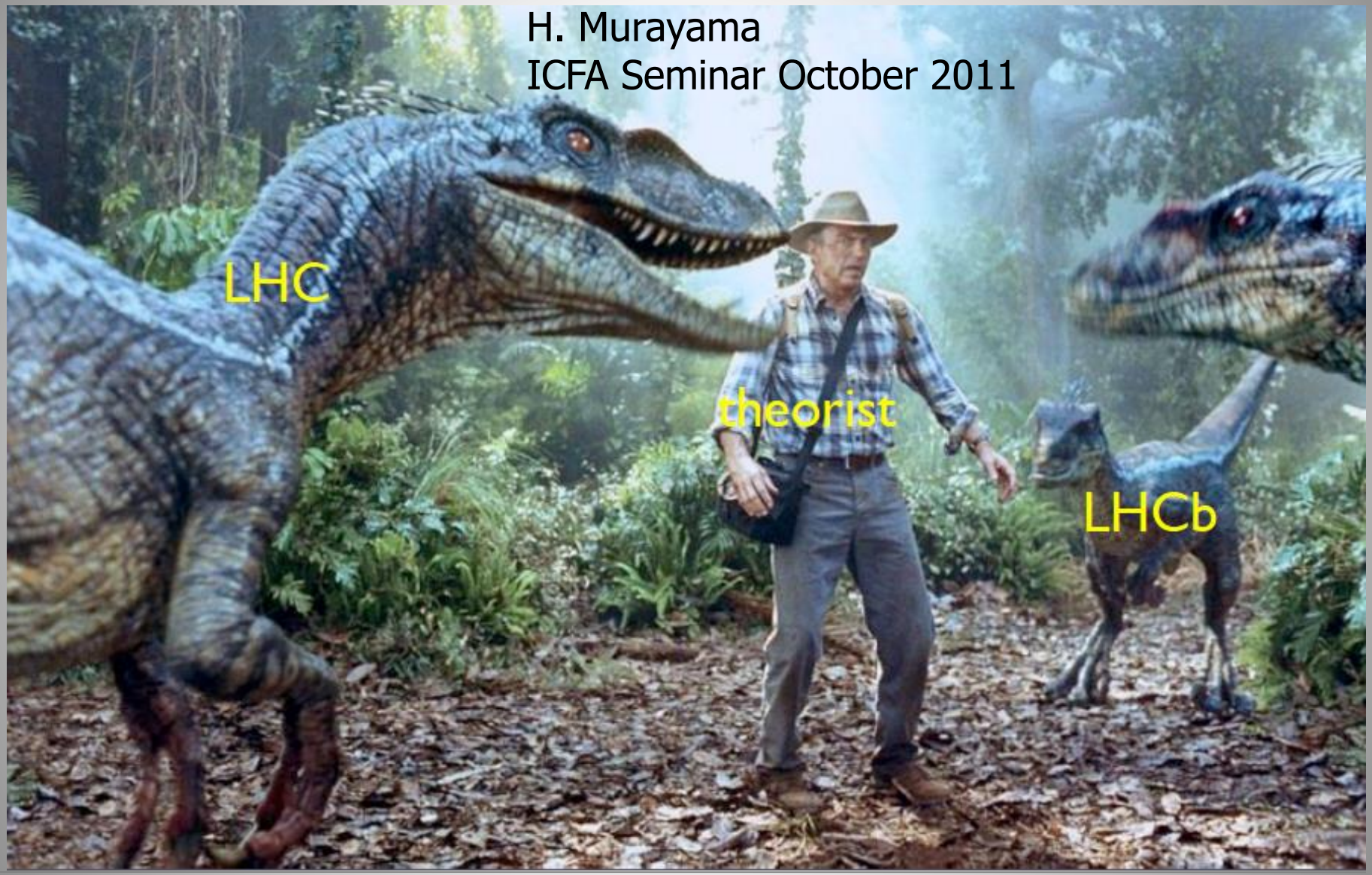




Possible detector surface array eg above ATLAS or CMS:

- $(200\text{m})^2$
- $8 \times (70\text{m})^2$

How does it feel to be a (BSM) Theorist?



The Future @ The LHC

The Future: Studying the Higgs…

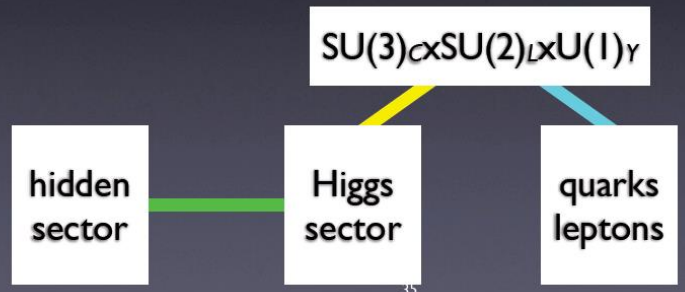
The Higgs is the new particle that may give us crucial insight into the new physics world
We will have to study it!!

Many questions are still unanswered:

- What explain a Higgs mass ~ 125 GeV?
- What explains the particle mass pattern?
- Connection with Dark Matter?
- Where is the antimatter in the Universe?
- ⑤

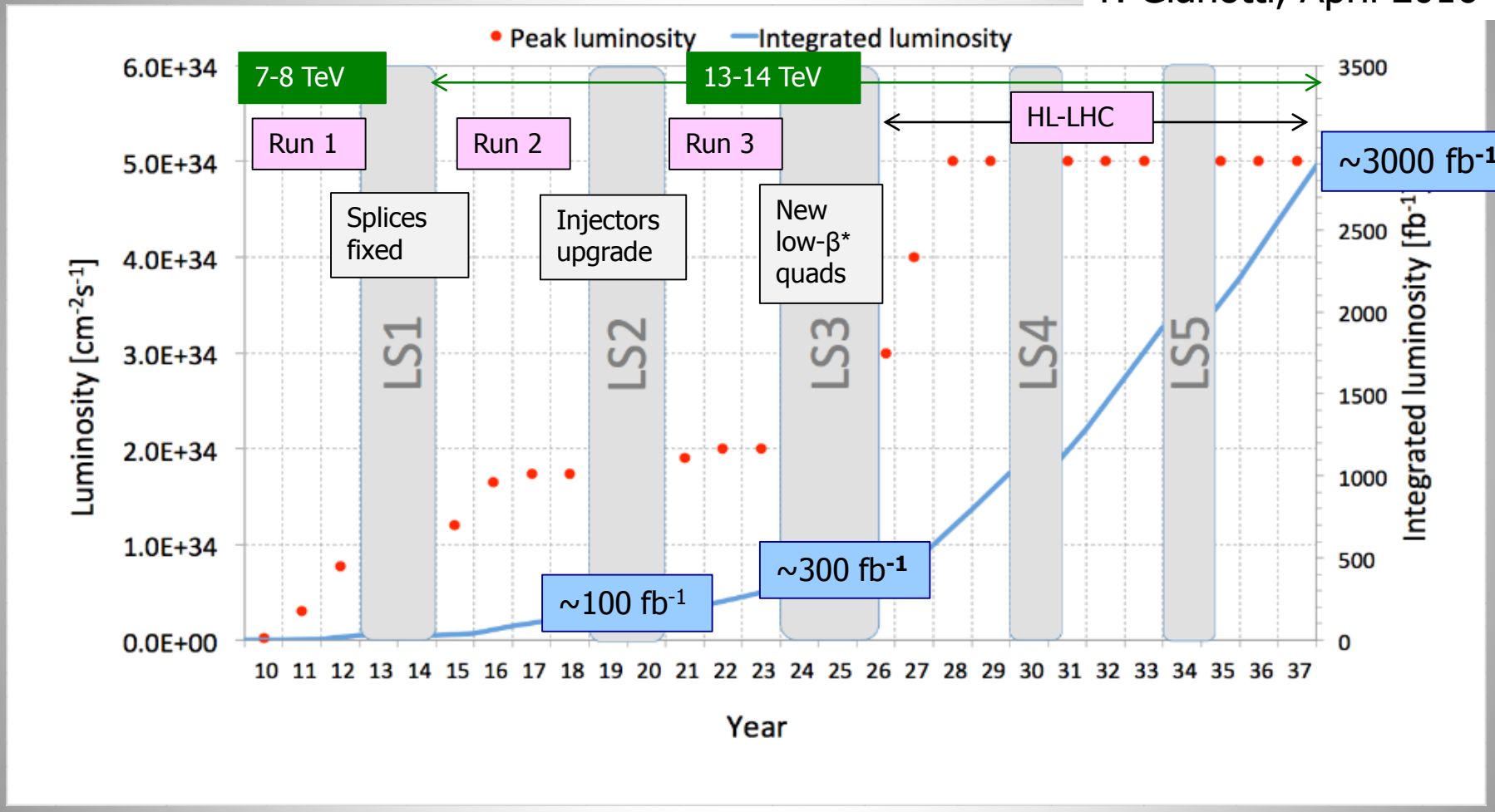
Higgs as a portal

- having discovered the Higgs?
- Higgs boson may connect the Standard Model to other "sectors"



LHC Outlook

F. Gianotti, April 2016

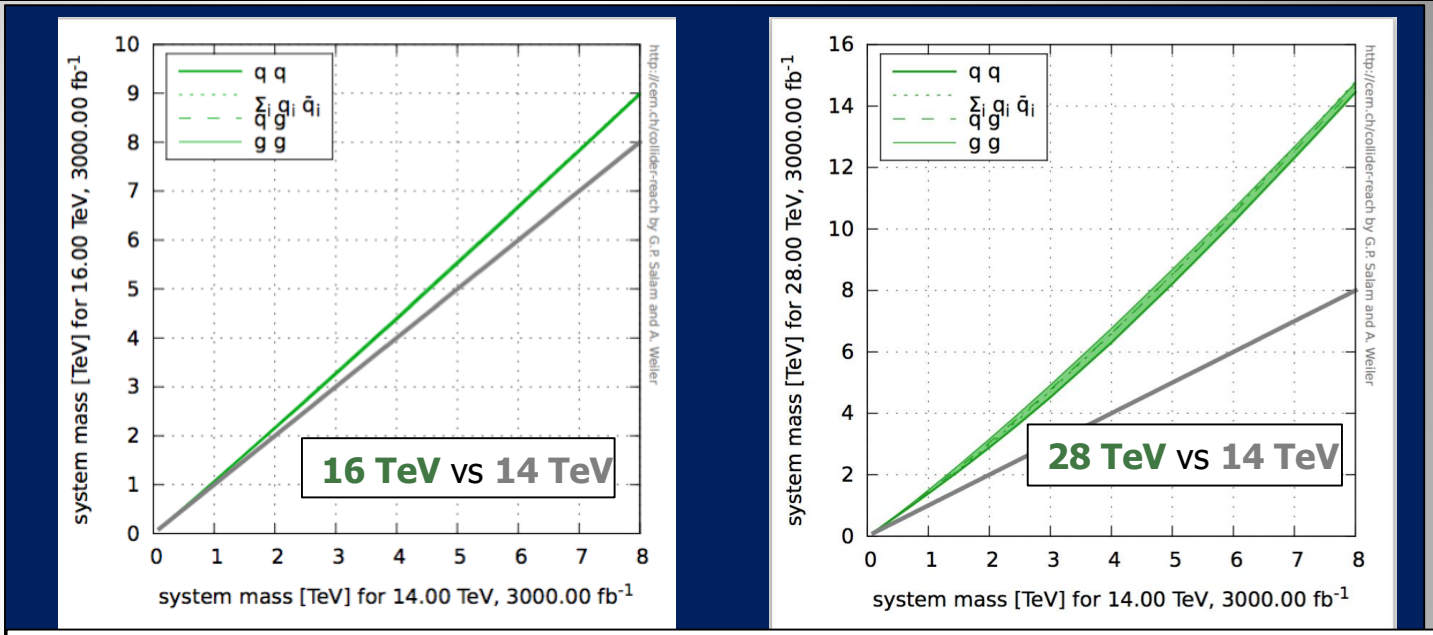


Approved program at CERN to collect 3000 fb^{-1} with the LHC (HL-LHC)

Maximize the reach for searches and for precision measurements (eg Higgs)

High-Energy LHC??

F. Gianotti
FCC meeting
Rome April 2016



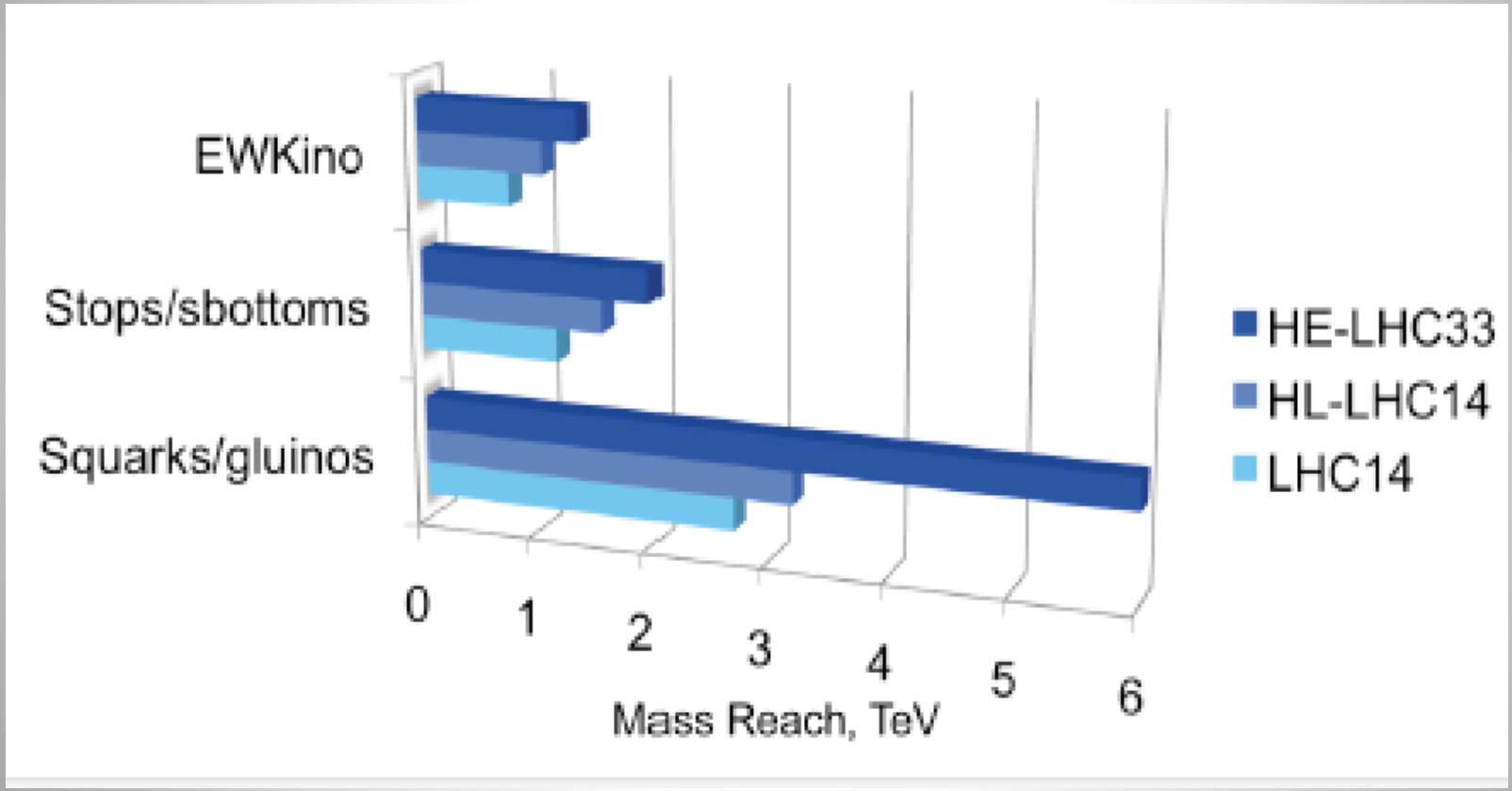
Various options, with increasing amount of HW changes, technical challenges, cost, and physics reach

WG set up to explore technical feasibility of pushing LHC energy to:
1) design value: 14 TeV
2) ultimate value: 15 TeV (corresponding to max dipole field of 9 T)
3) beyond (e.g. by replacing 1/3 of dipoles with 11 T Nb_3Sn magnets)
→ Identify open risks, needed tests and technical developments, trade-off between energy and machine efficiency/availability
→ Report on 1) end 2016, 2) end 2017, 3) end 2018 (in time for ES)

HE-LHC (part of FCC study): ~16 T magnets in LHC tunnel (→ √s~ 30 TeV)
- ❑ uses existing tunnel and infrastructure; can be built at fixed budget
- ❑ strong physics case if new physics from LHC/HL-LHC

Example: Searches for New Particles

Searches for pair produced SUSY particles



Energy is key for searches for massive particles!!

We Expect Answers from the LHC, but

Can LHC answer all questions?: Likely not

Some/all New Particles out of mass range?
Need for higher energies at colliders?

Higher precision measurements needed
Need for higher luminosity or e+e-?

Measuring details of the Higgs?
Need for a Higgs factory?

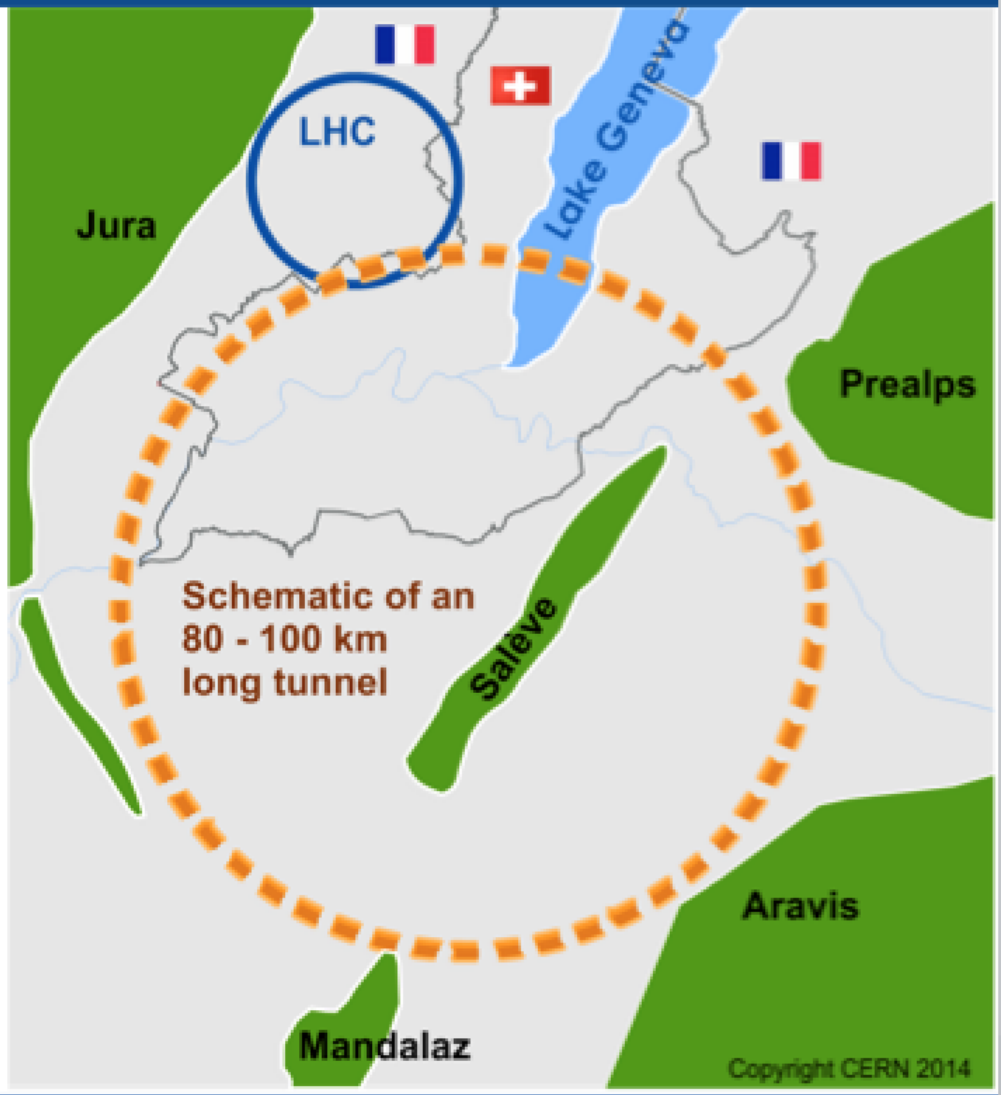
Many ideas are emerging for new accelerators since June 2012
So far only projects being studied, none is approved yet

Future Circular Collider Study
GOAL: CDR and cost review for the next ESU (2018)

International FCC collaboration (CERN as host lab) to study:

- ***pp*-collider *O(100) TeV* (*FCC-hh*)**
  → main emphasis, defining infrastructure requirements

  ~16 T ⇒ 100 TeV *pp* in 100 km
- **80-100 km tunnel infrastructure** in Geneva area
- ***e*⁺*e*⁻ collider (*FCC-ee*)** as potential intermediate step
- ***p*-*e* (*FCC-he*) option**
- **HE-LHC** with *FCC-hh* technology



Summary: The Searches are on!

- The LHC has entered a new territory. The ATLAS and CMS experiments are heavily engaged in searches for new physics. The most popular example is Supersymmetry, but many other New Physics model searches are covered.
- No sign of new physics yet in the first 20 fb^{-1} at 8 TeV and the first 13 TeV data… This starts to cut into the 'preferred regions' for a large number of models, like SUSY
- More exotic channels are now being covered: monopoles, fractional or multiple charged particles, long lived particles. Still many unexplored channels left to explore
- The LHC did its part so far with a great run-1 and is strong in run-2. Collected over 20 fb^{-1}@ 13 TeV

And maybe one day soon:

End of Lecture II