EXOTIC SEARCHES

PSI Summer School Exothiggs
Lyceum Alpinum Zuoz, 15-19 August 2016

Lecture 2: Dark Matter, Long-lived particles, prospects

DIPARTIMENTO DI FISICA

SAPIENZA
UNIVERSITÀ DI ROMA

Shahram Rahatlou
http://www.roma1.infn.it/people/rahatlou/

REFERENCES

- Exotica
  - ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults
  - CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO
    http://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G

- SUSY results
  - ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults
  - CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

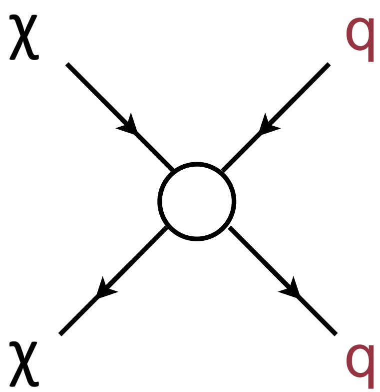
Outline

- Motivation for New Physics
- Exotic searches
- Dark Matter at Colliders
- Long-Lived Particles
- Supersymmetry (maybe)
- Prospects at 13 TeV and beyond

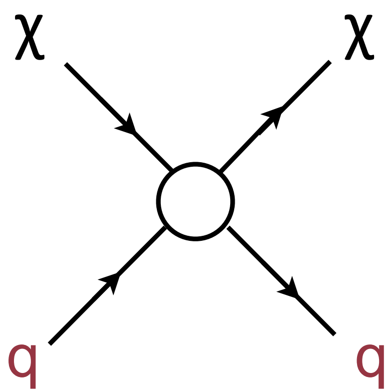
X + MET

DARK MATTER INTERACTION

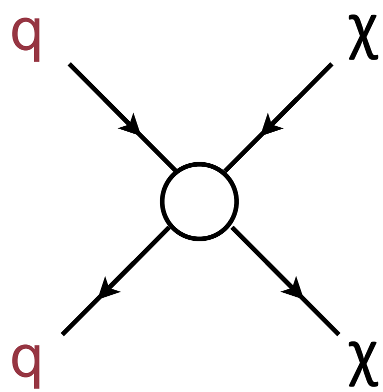
- Exact interaction of DM with ordinary matter determines relic abundance



Indirect Detection



Direct Detection

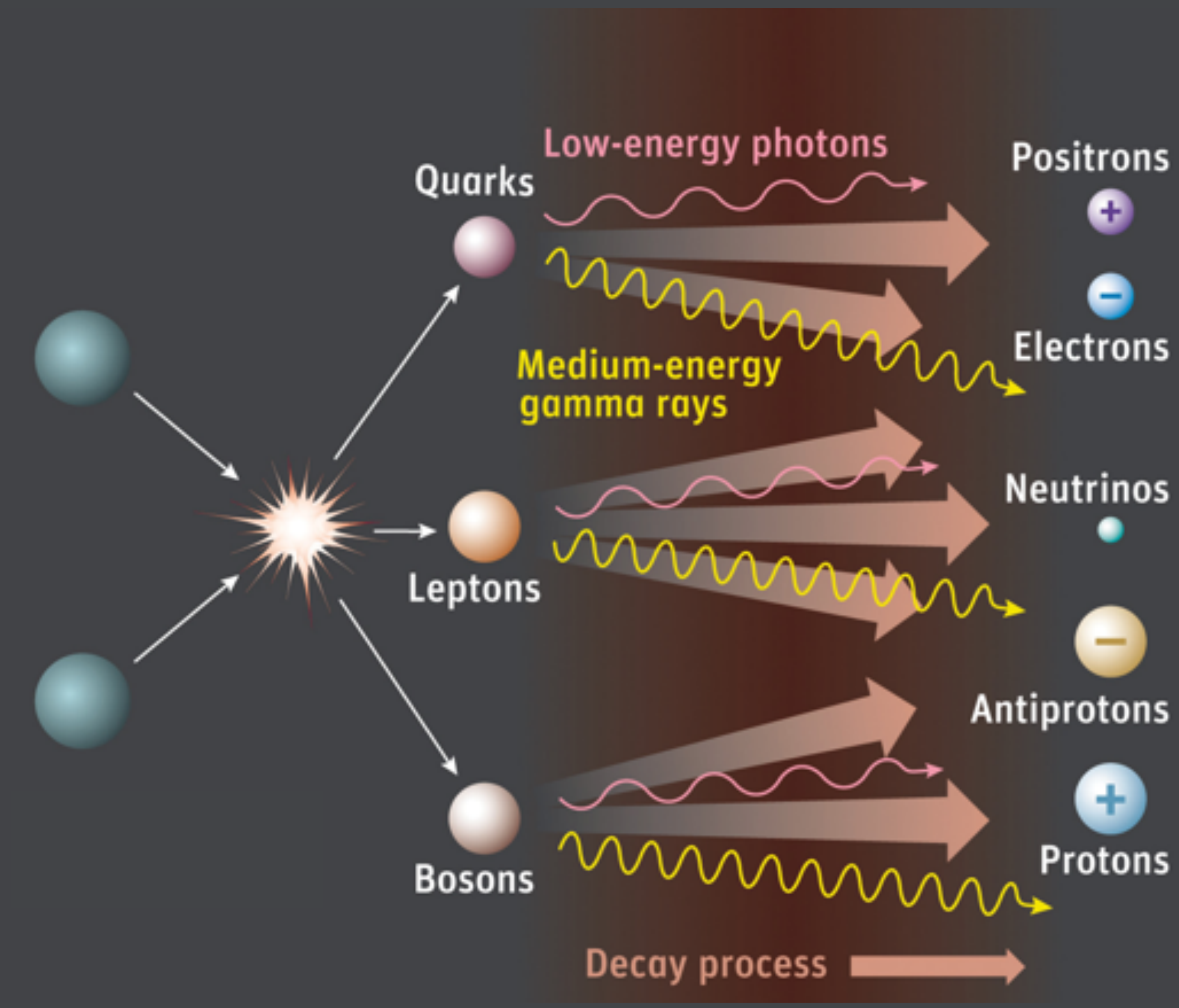


Production at Colliders

- Each type of interaction requires different experimental technique and types of detector to be studied

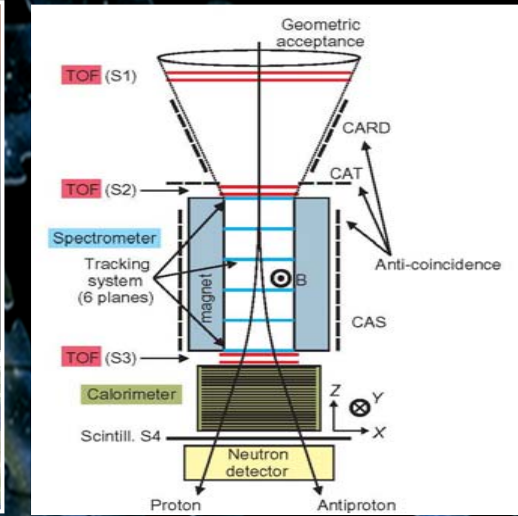
INDIRECT DETECTION

- Annihilation in high energy photons, particle-anti-particle pairs
- search for ultra-relativistic objects produced in galactic halo
  - observatory on earth or with satellites

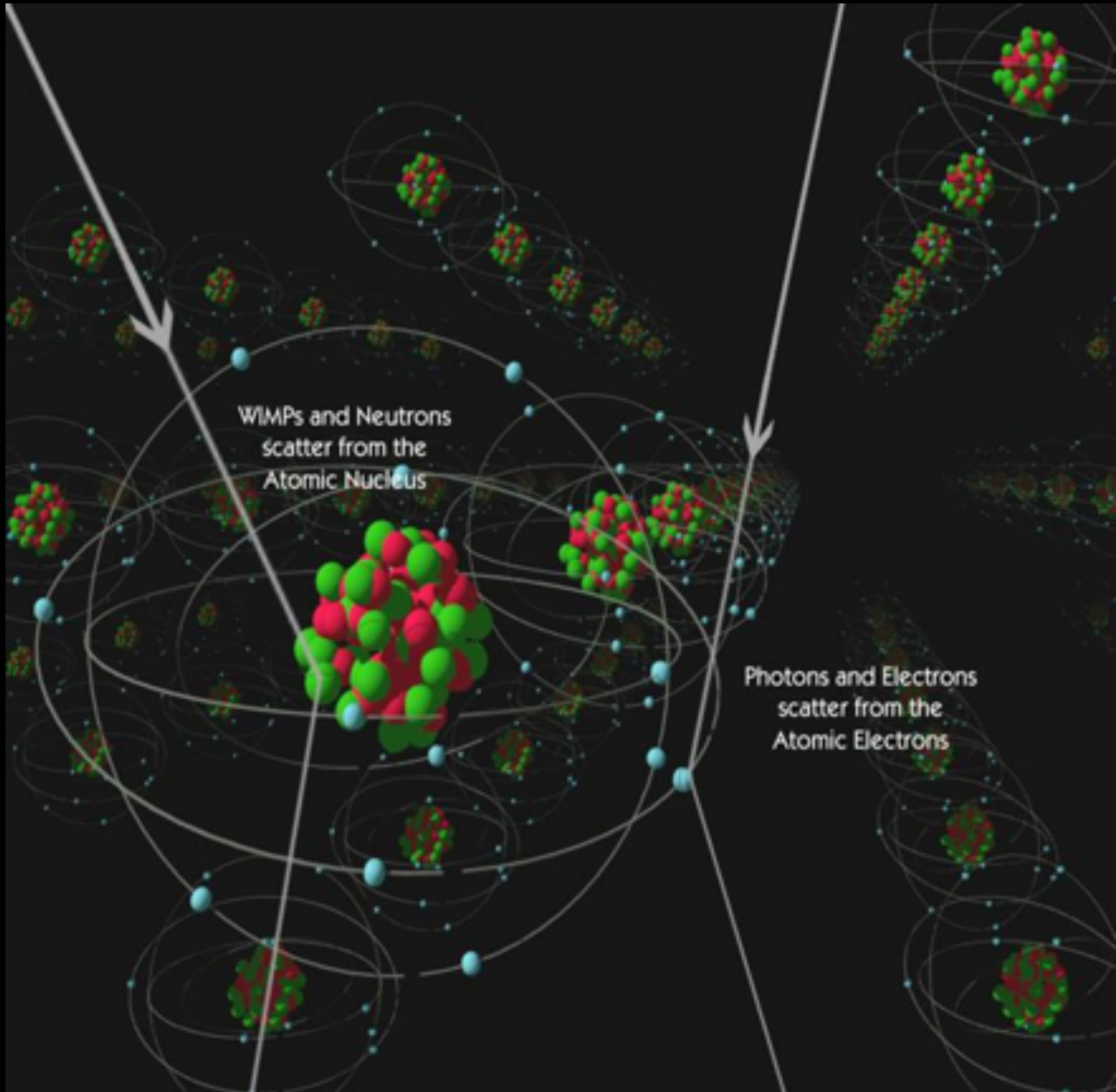


INDIRECT DETECTION

PAMELA

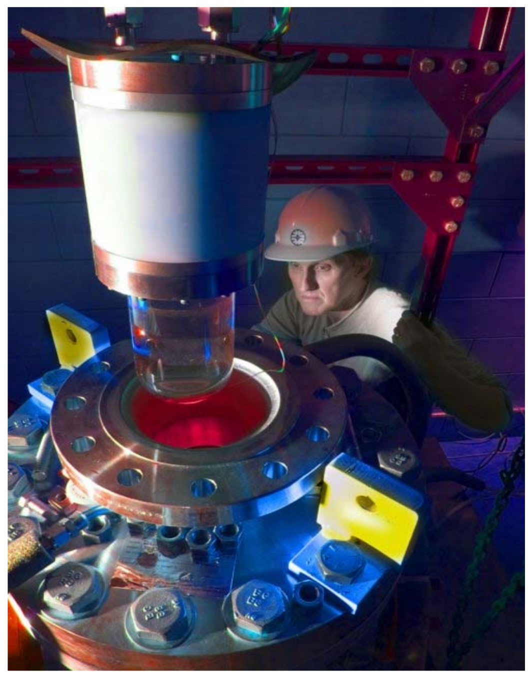


DIRECT DETECTION

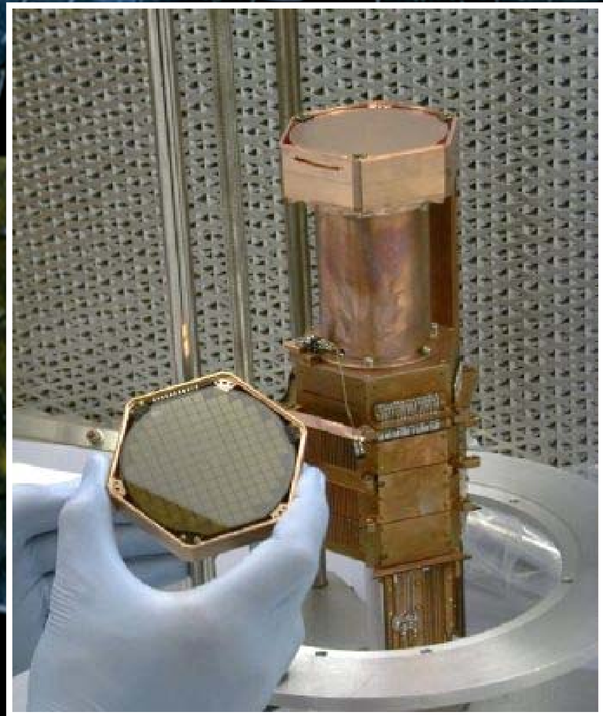


DIRECT DETECTION

COUPP



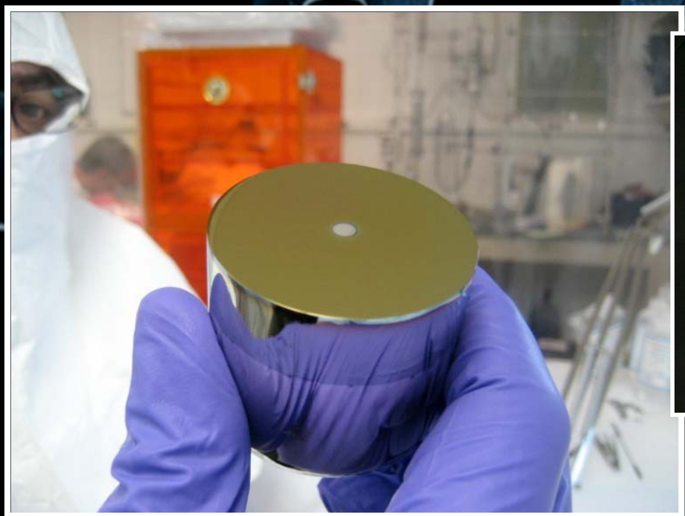
CDMS

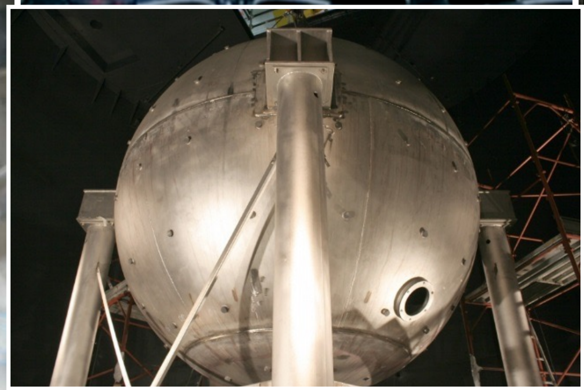


CRESST

DAMA

CoGeNT

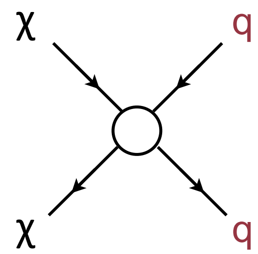


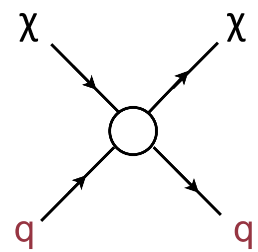


Darkside

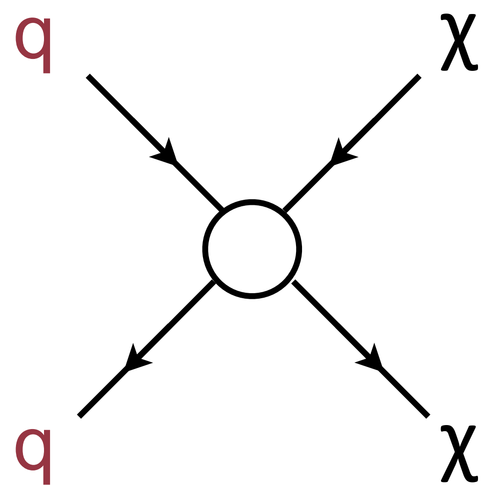
DARK MATTER AT LHC

- 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

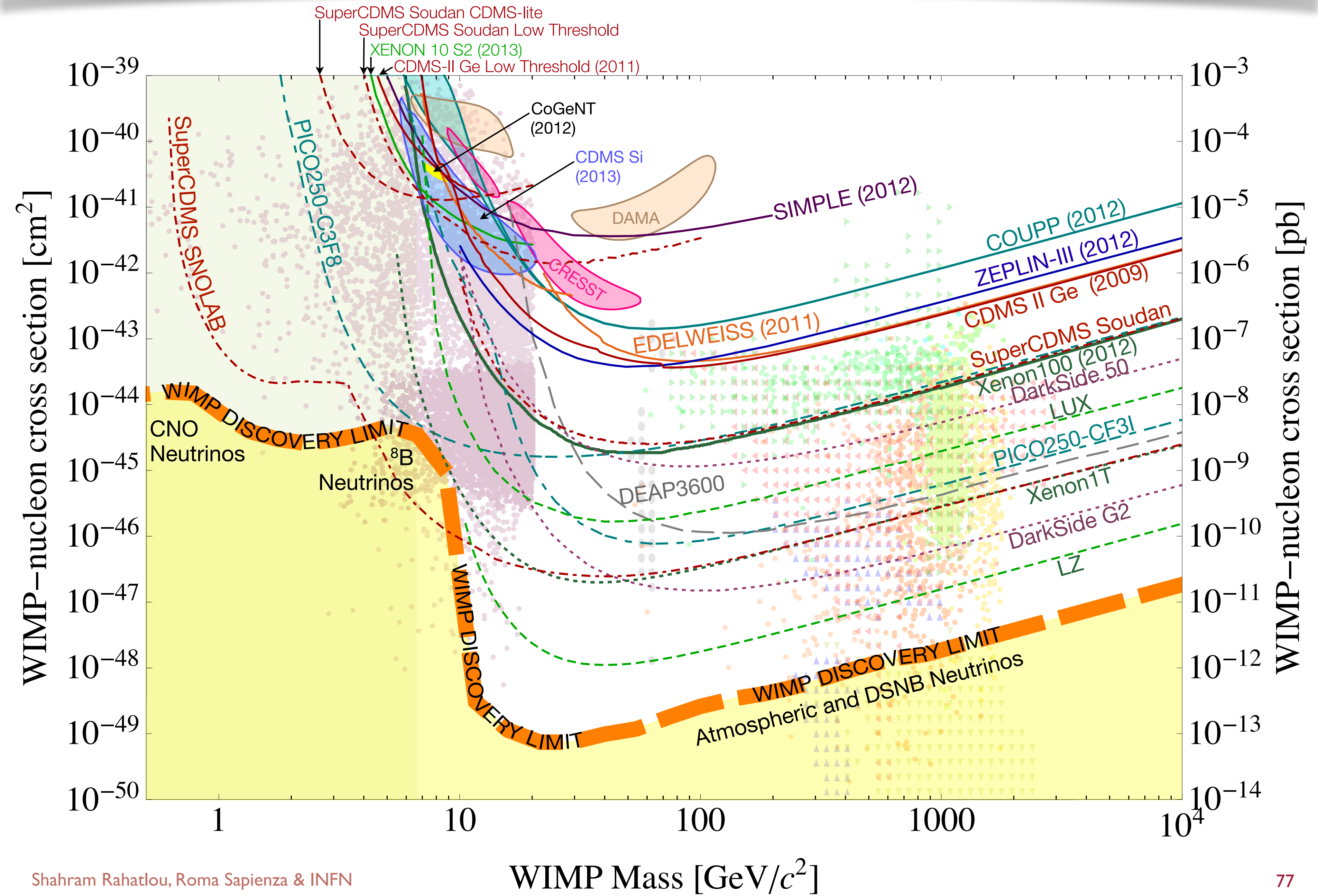




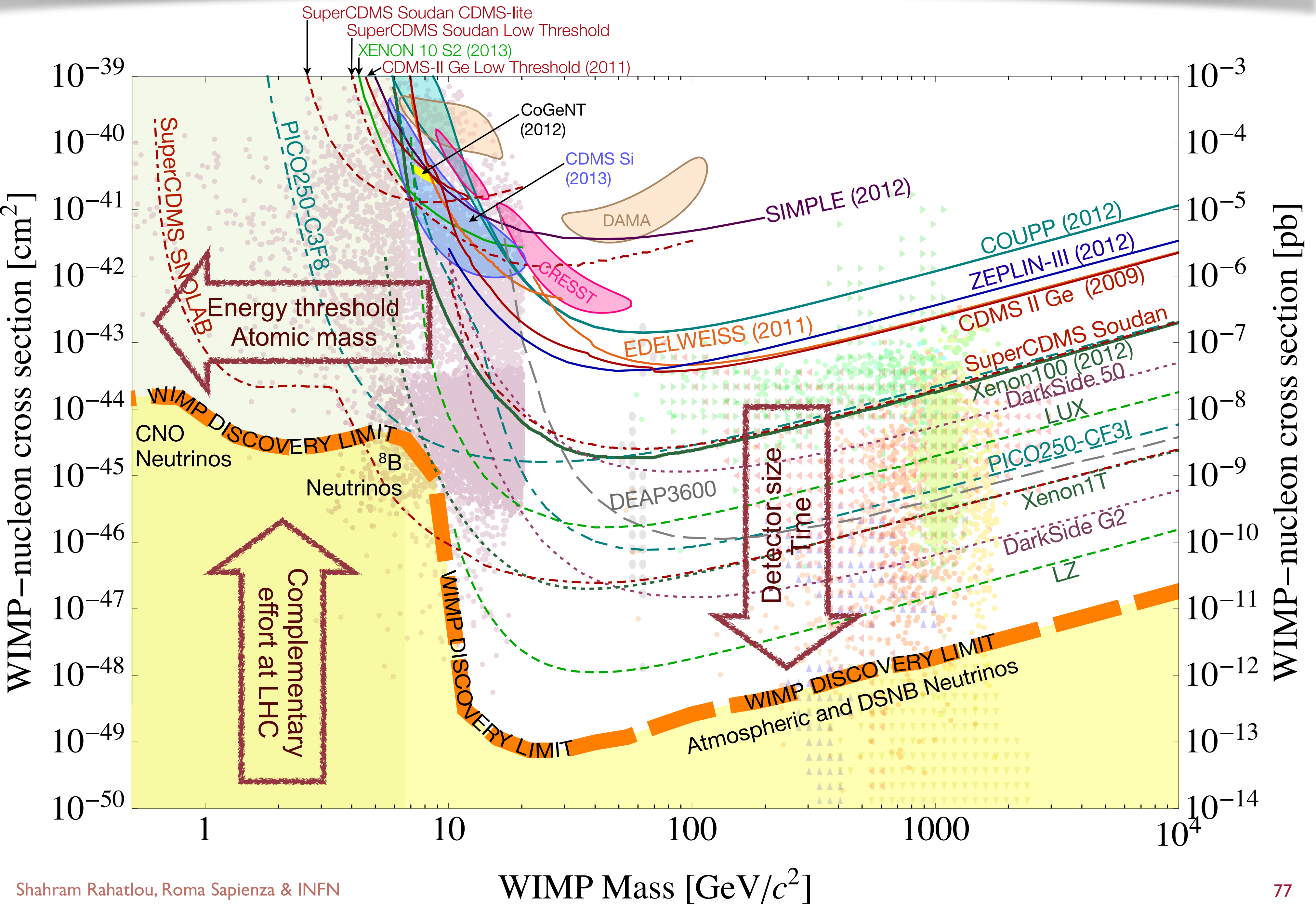
- Pair production at LHC
  - large missing energy in the detector
  - need to identify and *trigger* events of interest



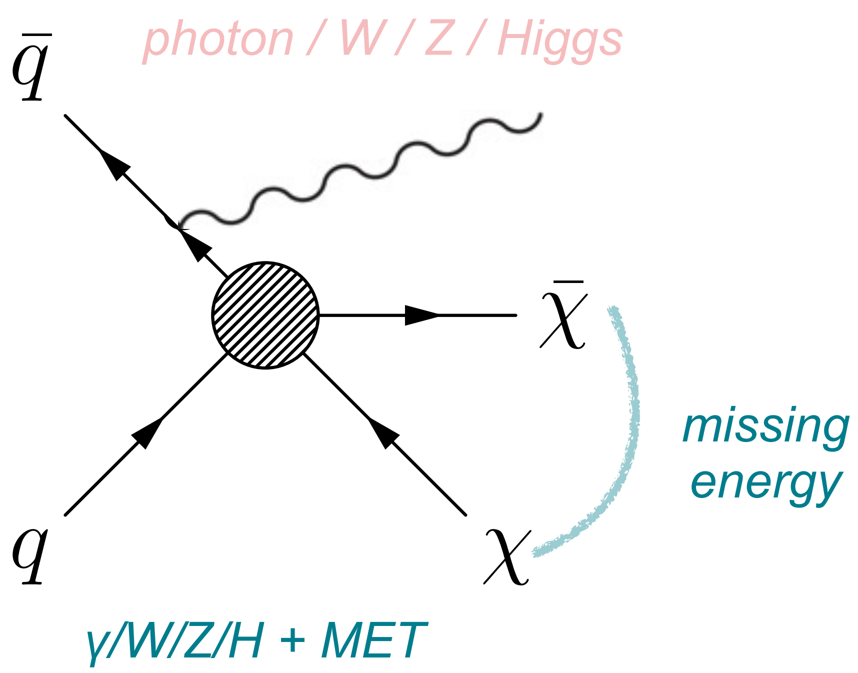
DIRECT DARK MATTER SEARCHES

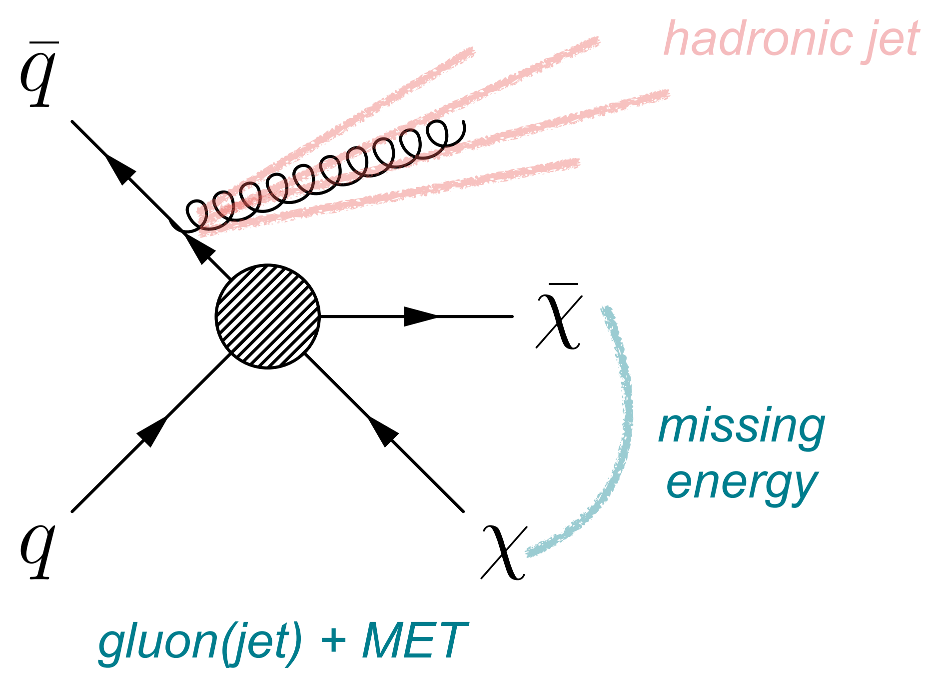


Direct Dark Matter Searches

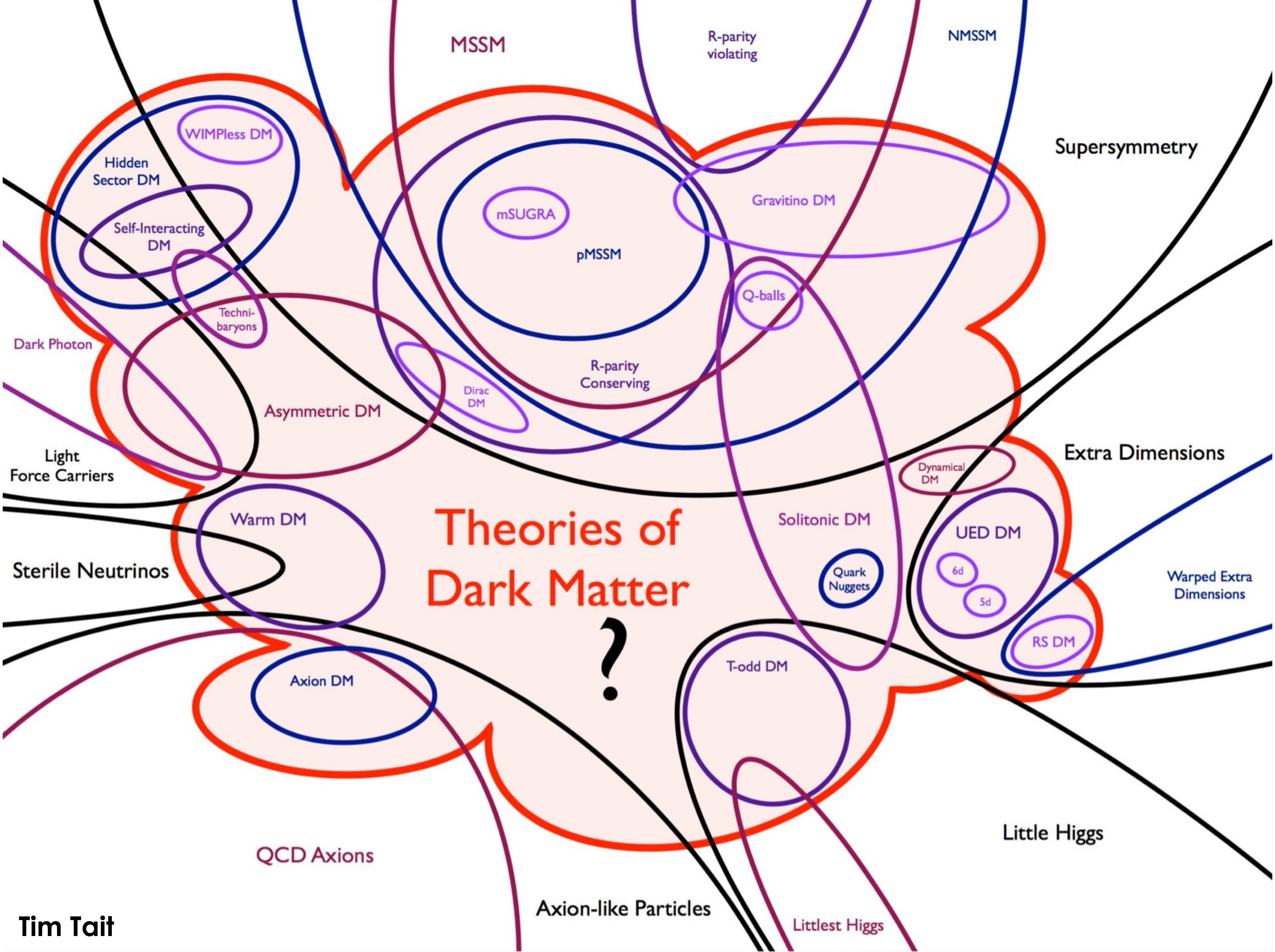


X + MET





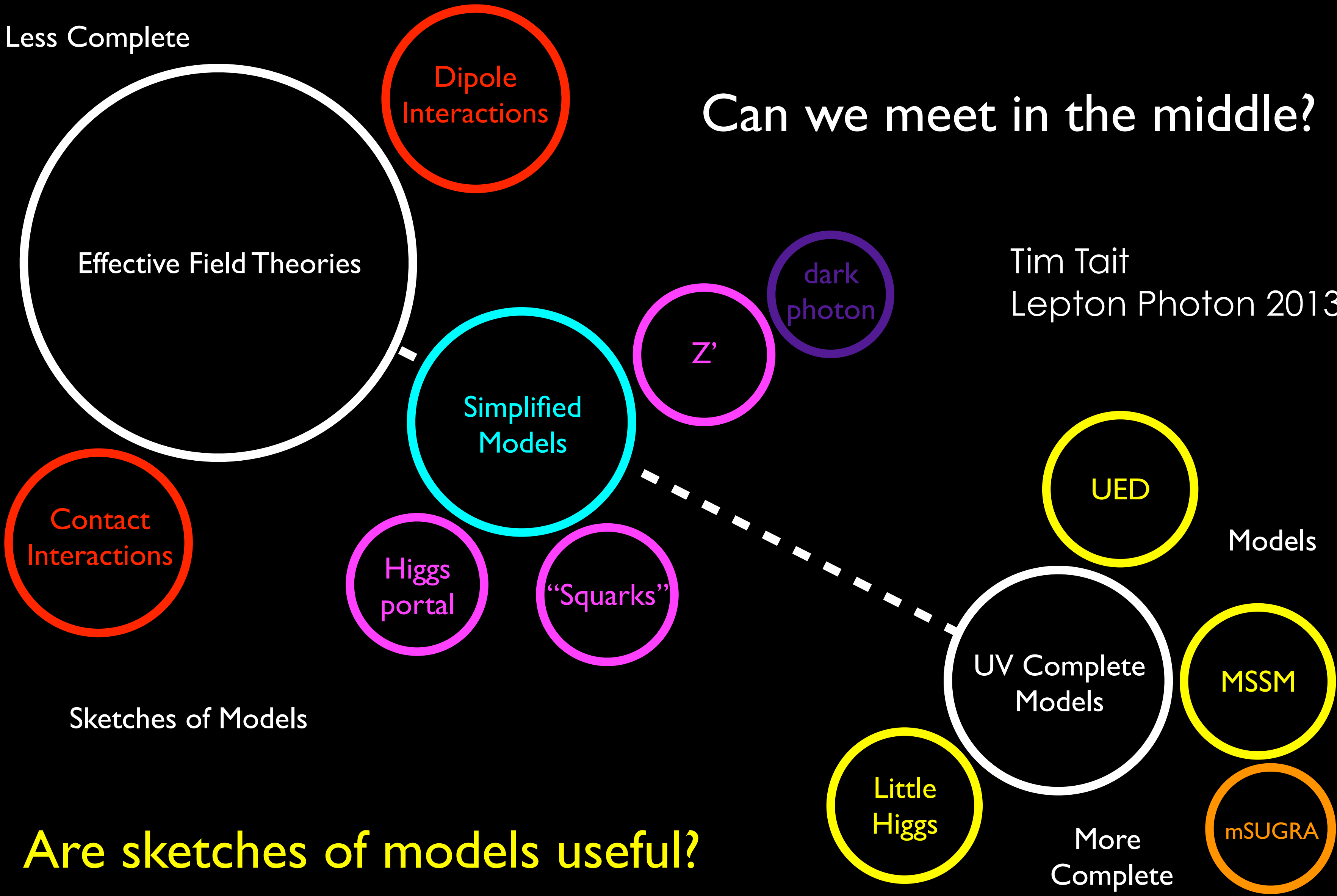
- Radiated by initial partons necessary to trigger the event
- Presence of high energy photon/W/Z/Higgs or jet(s) *in addition* to large missing transverse energy
- Results interpreted in terms of cross section on nucleons
  - limitations due to (in)validity of effective theories



MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
mSUGRA
pMSSM
Gravitino DM
Q-balls
Techni-baryons
Dark Photon
Dirac DM
R-parity Conserving
Asymmetric DM
Light Force Carriers
Dynamical DM
Extra Dimensions
Warm DM
Theories of Dark Matter
?
Solitonic DM
UED DM
6d
5d
Sterile Neutrinos
Quark Nuggets
Warped Extra Dimensions
RS DM
Axion DM
T-odd DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs

Tim Tait

Spectrum of Theory Space



Can we meet in the middle?

Tim Tait
Lepton Photon 2013

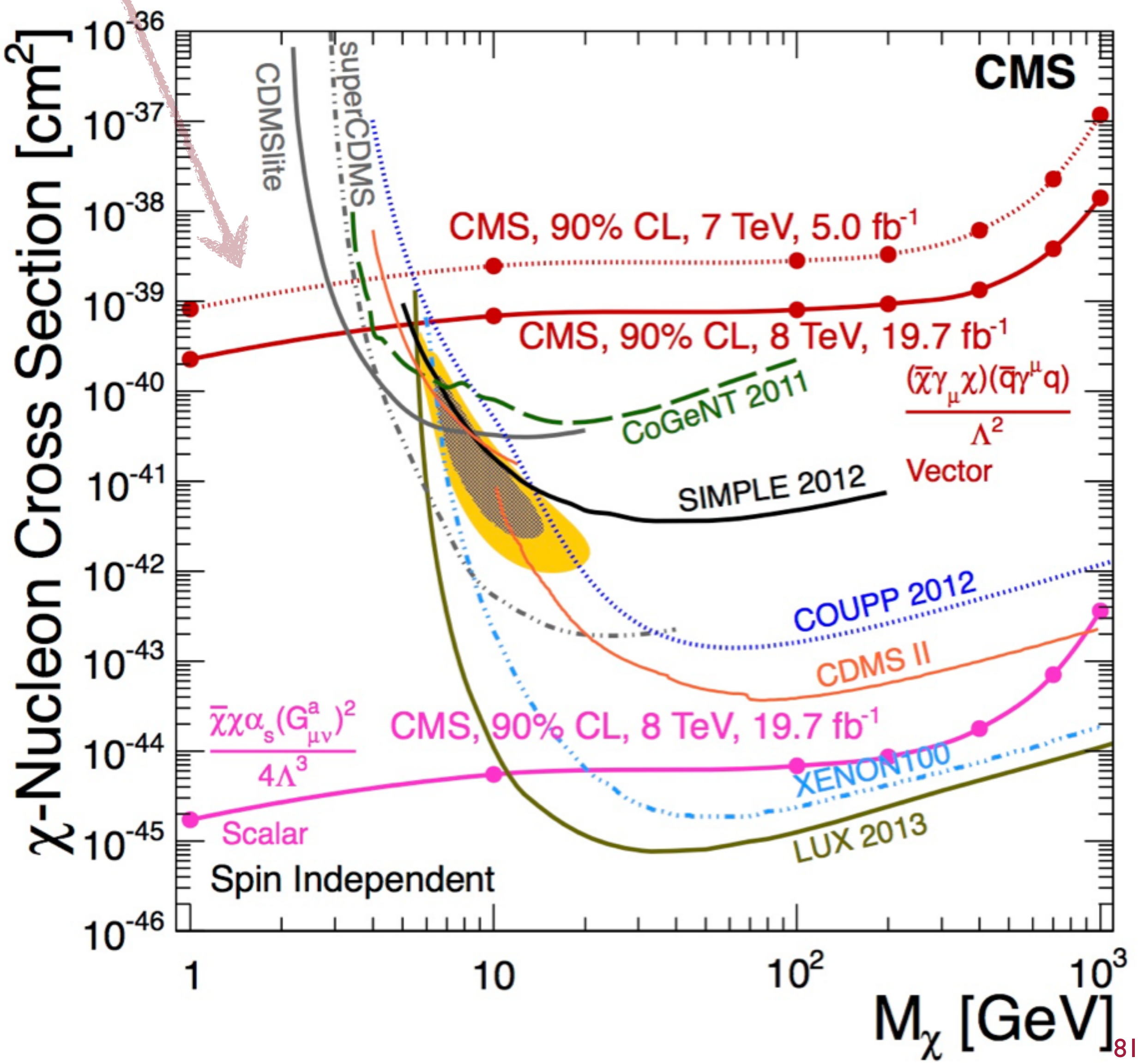
Are sketches of models useful?

X + MET Interpretation

- Original intent
  - *complementary approach to direct searches at low mass*

- Criticism to use of effective theories
  - *mediator mass assumed to be negligible at LHC*

- But keep in mind:
  - *robust measurement* free of assumptions
  - only *interpretation* affected by *theoretical assumptions*

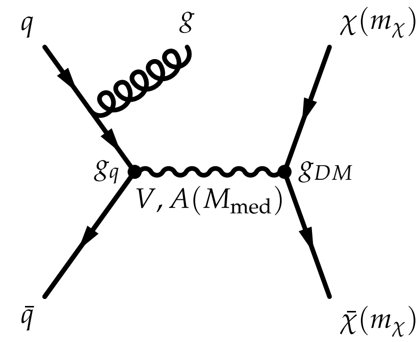


MODELLING THE DM INTERACTION

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

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

~ 1/Λ^4 E^2 for $M \to$ 40 TeV (EFT)



- 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

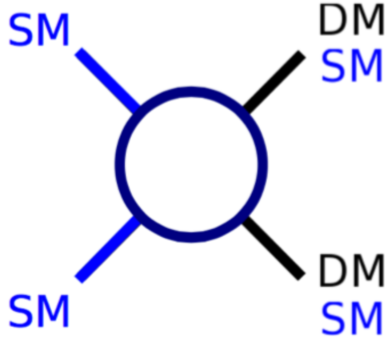
$$\sigma_{SI} = 9\frac{\mu^2}{\pi\Lambda^4} \qquad \Lambda = M/\sqrt{g_\chi g_q}$$

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

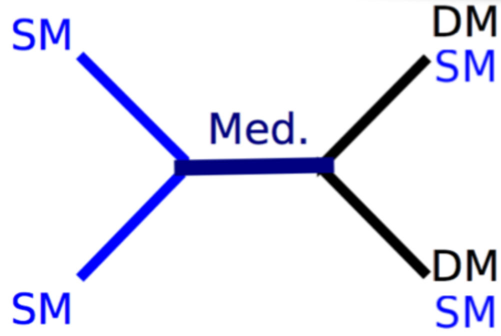
[Bai, Fox and Harnik, JHEP 1012:048 (2010)]
[Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu, Phys.Rev.D82:116010 (2010)]
[Beltran, Hooper, Kolb, Krusberg, Tait, JHEP 1009:037 (2010)]

FROM EFT TO SIMPLIFIED MODELS

https://arxiv.org/abs/1507.00966

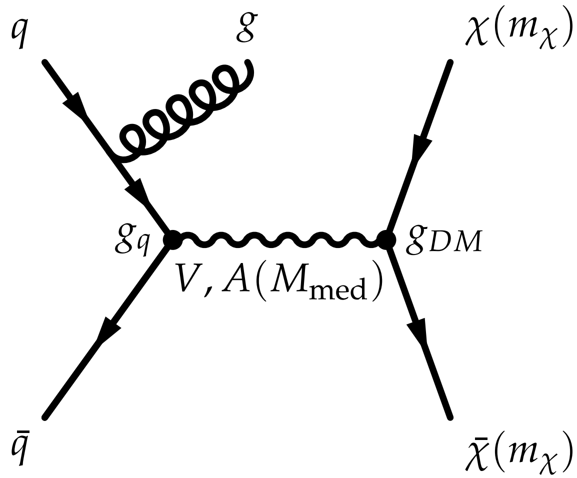


Colliders (EFT)



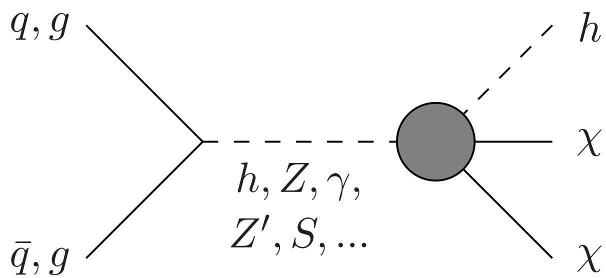
Colliders
(Simplified Model)

- Use SUSY approach
  - *simplified models for final state*
  - *Four parameters*
  - *provide 2D constraints in (m_χ, $m_{mediator}$) plane*
    - *assumptions for g_q and g_{DM}*

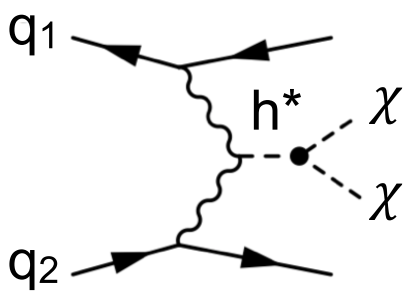


HIGGS PORTAL TO DARK MATTER

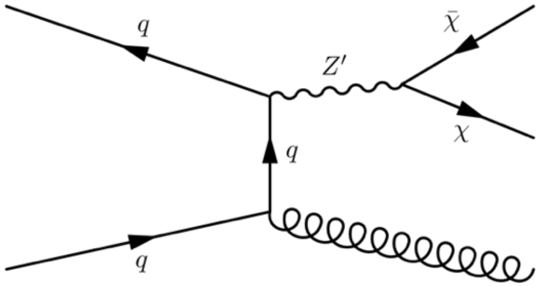
- Discovery of Higgs has opened new doors to Dark matter
- New searches to investigate coupling of dark matter candidates to Higgs boson
- mono-Higgs: Higgs + missing energy through new operator
  - produced via both quarks and gluons

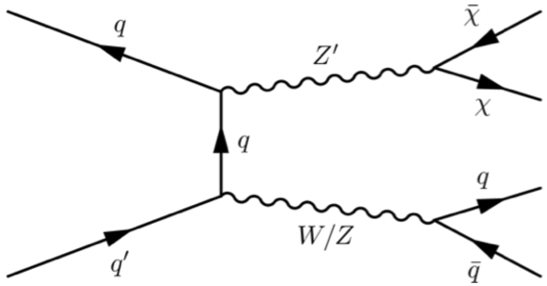


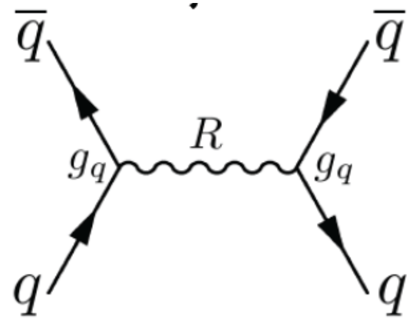
- Higgs mediation: dark matter candidate couples only to Higgs and no other SM particle
  - $m_{DM} < m_H/2$: Higgs decay to DM pair
    - Currently branching ratio of invisible Higgs decays < ~30%
      - ➡ expect to reach BR < 0.2-0.3% with 3000 fb^{-1}
  - $m_{DM} > m_H/2$: DM pair from virtual Higgs
    - Distinctive signature with forward jets

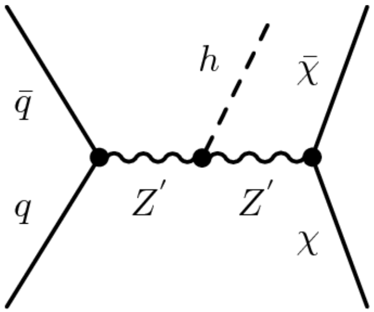


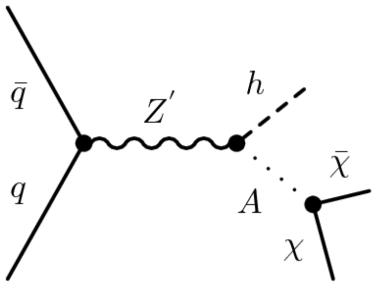
X + MET Signatures after Run1

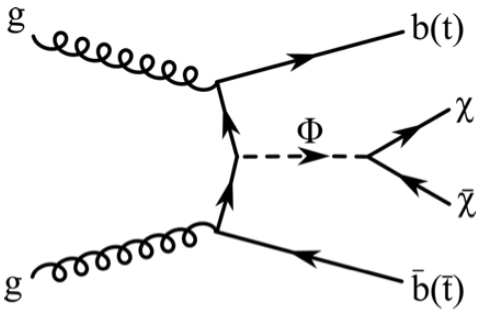


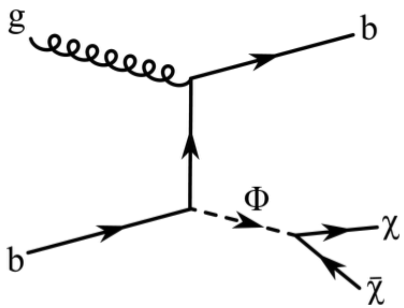




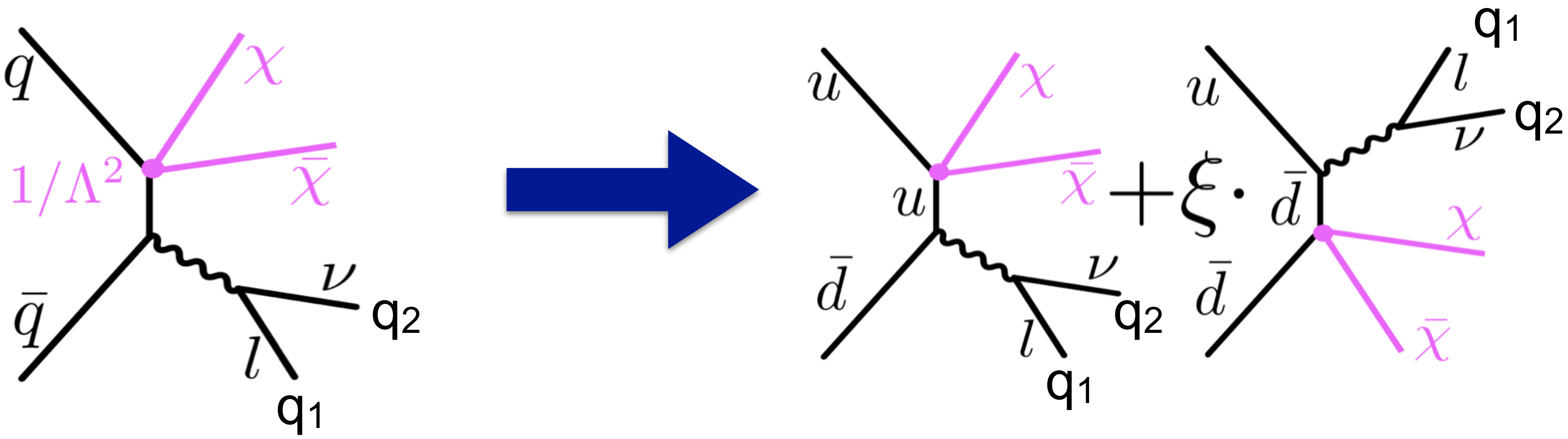








MONO-W + MET

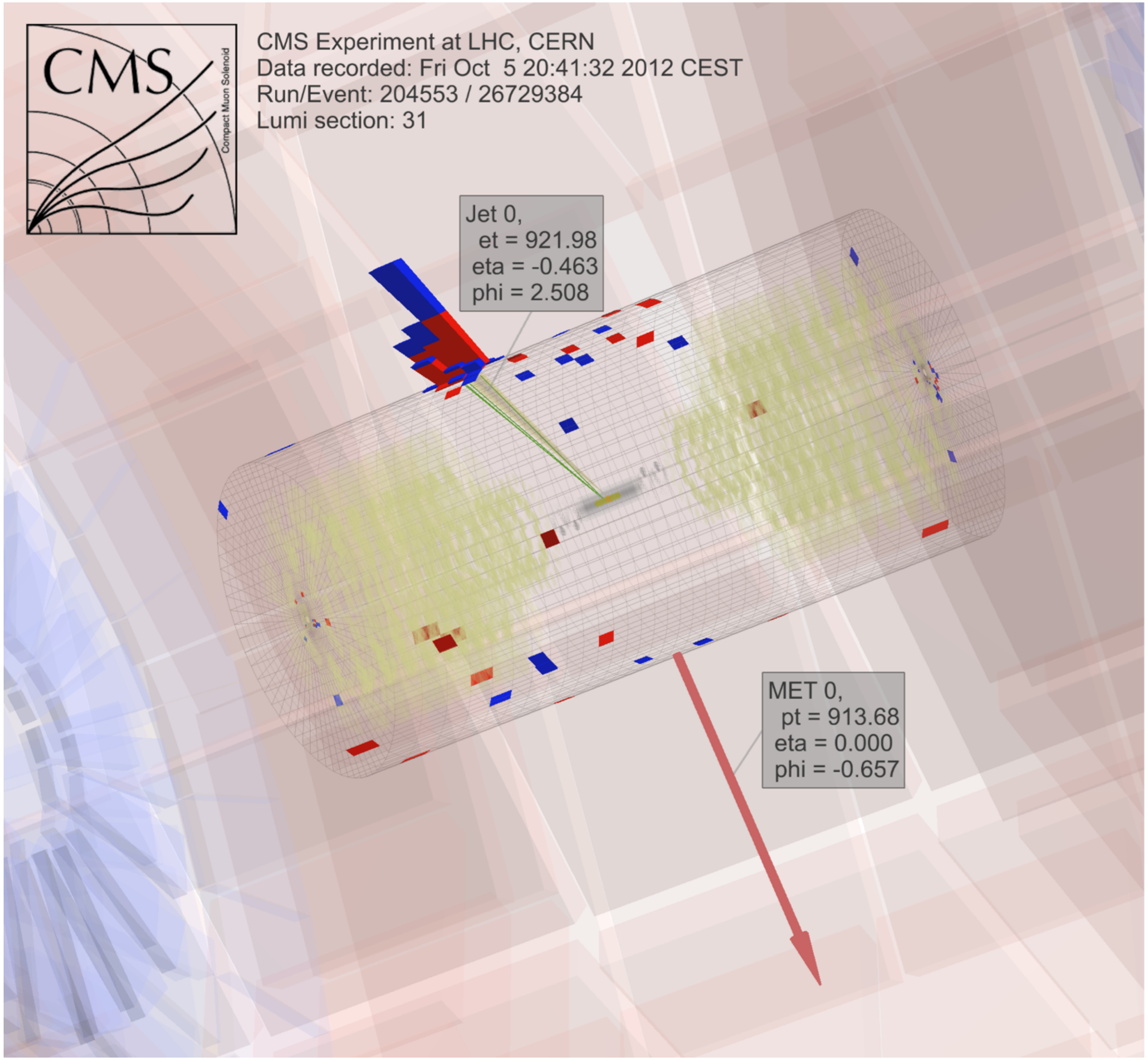


- W being charged can distinguish between u and d quarks
  - Need to account for interference
- Leptonic W decays
  - pro: clean high-pt lepton signature; single-lepton trigger
  - con: small branching ratio
- Hadronic W decays
  - pro: large branching ratio
  - con: large SM backgrounds

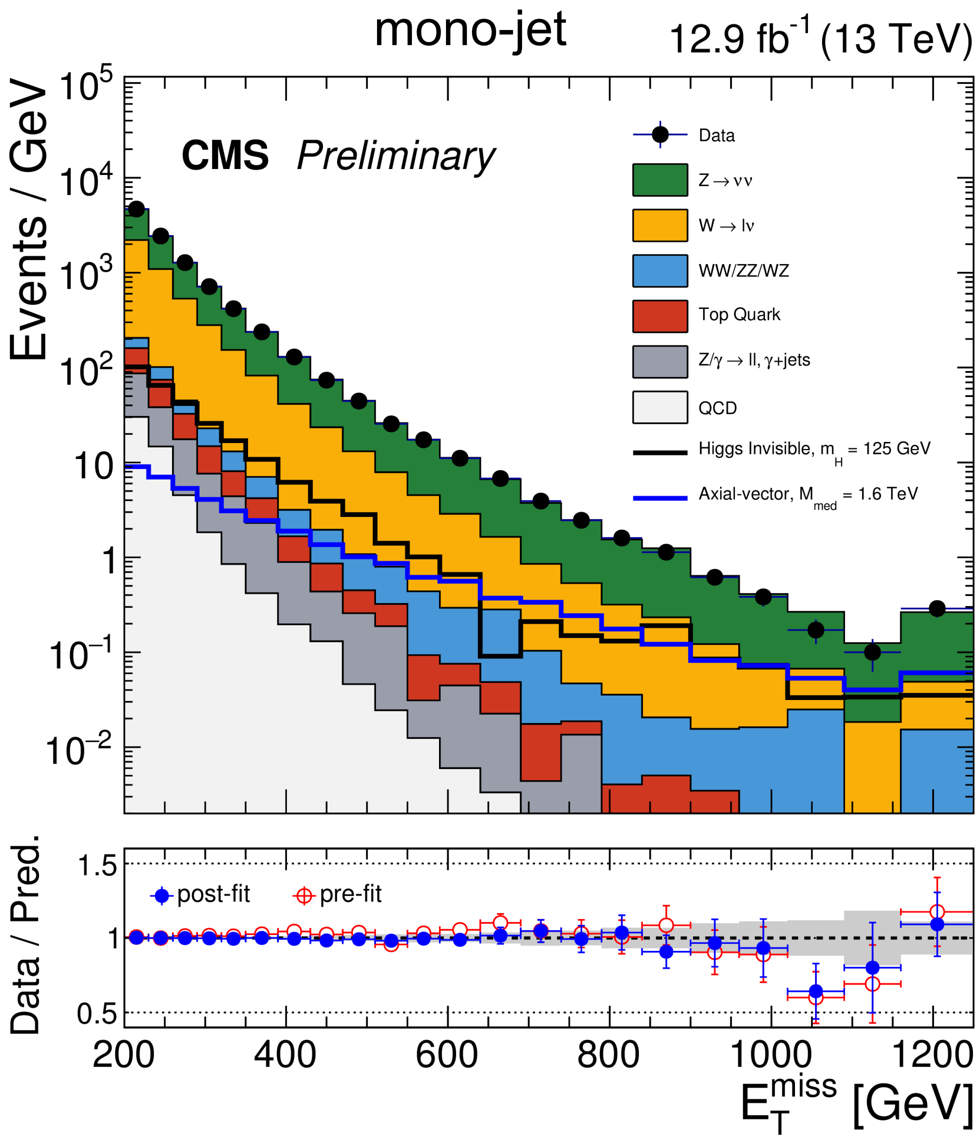
SUMMARY OF CURRENT SEARCHES

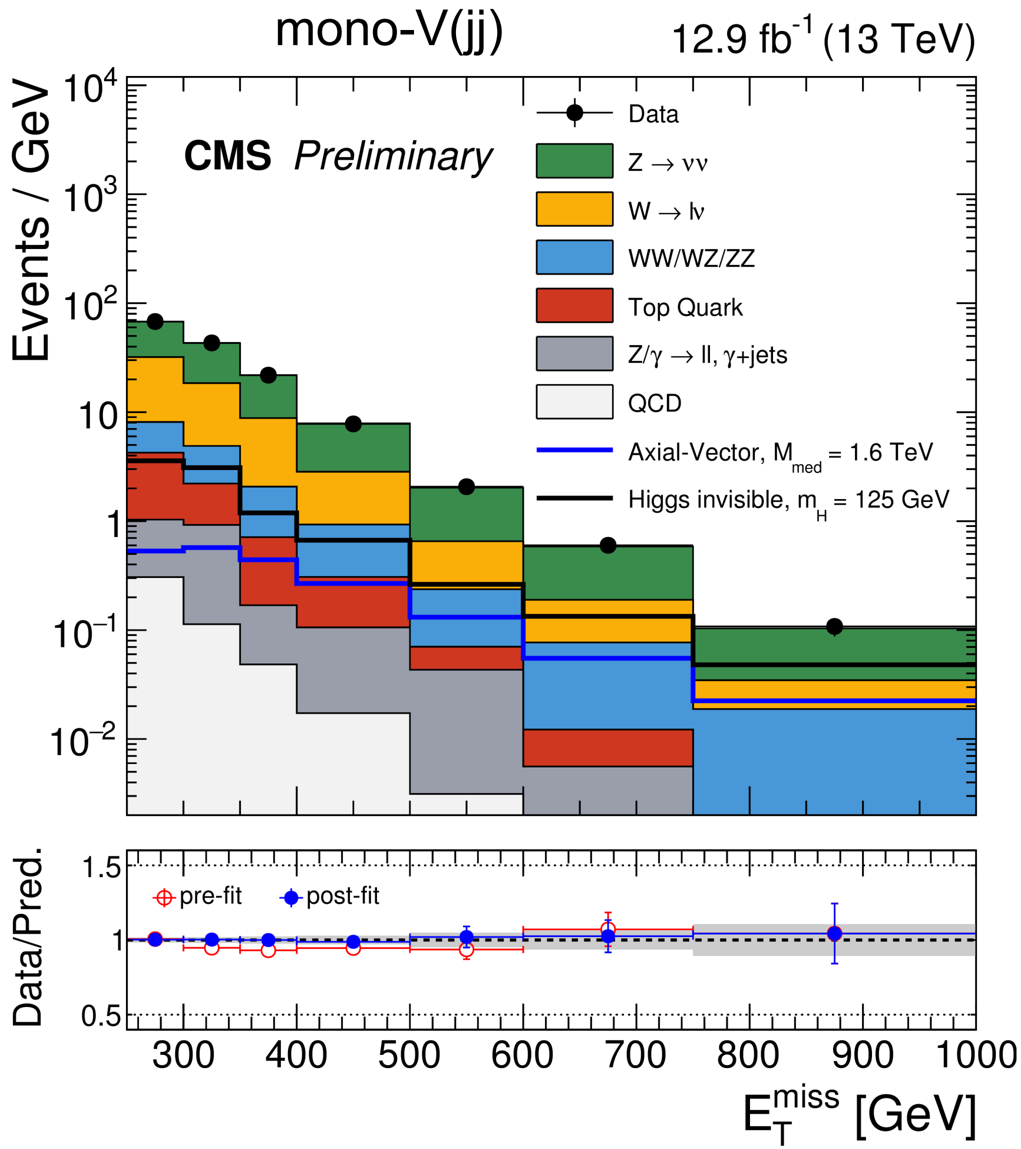
- mono-jet
  - strongest constraints
- mono-photon
  - more challenging for background estimation
  - less powerful: EW vs. strong interaction
- mono-W/Z leptonic
  - clean signature and simple trigger
  - penalized by W/Z branching fraction
- mono-W/Z hadronic
  - larger statistics with larger background
- mono-t/b
- ttbar/bbbar + MET
- Search for mediator in dijet final state

MONO-JET CANDIDATE

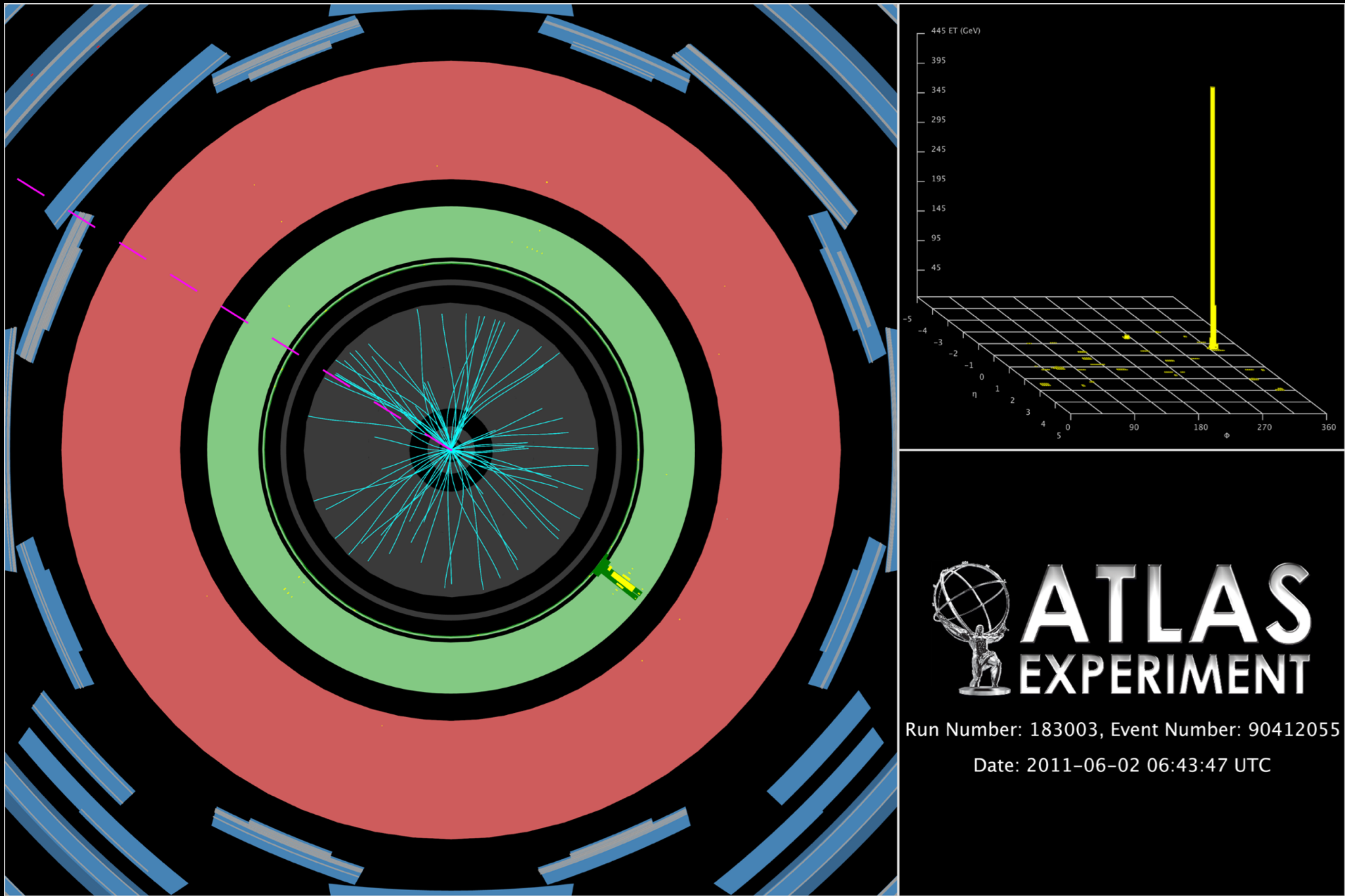


MONO-JET SPECTRUM

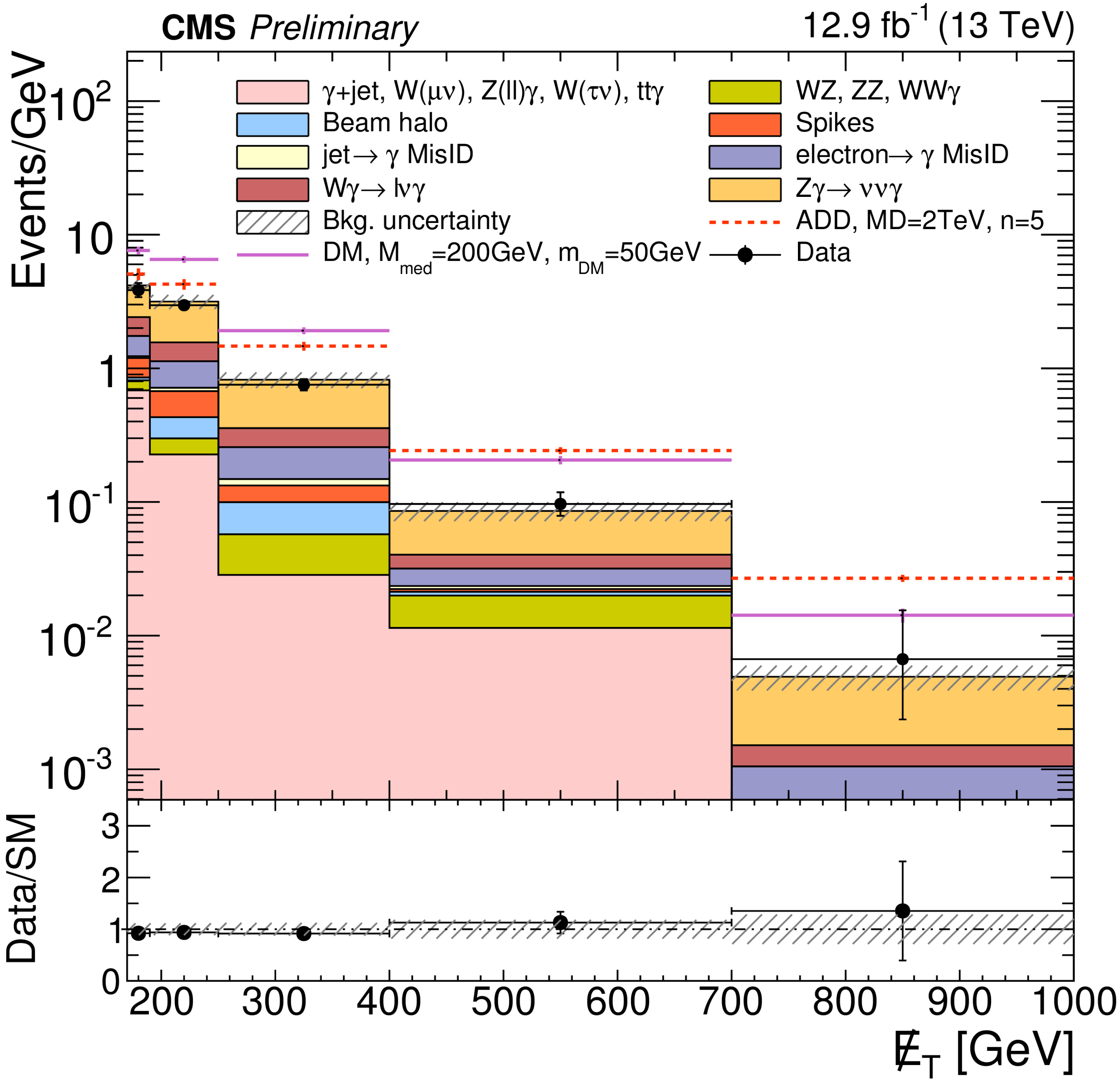


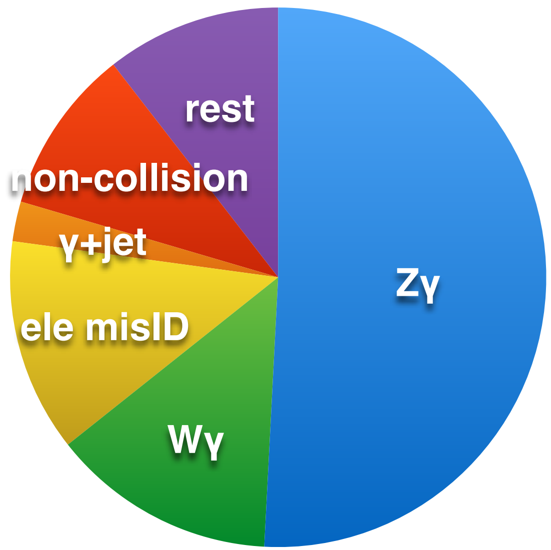


Mono-Photon Candidate

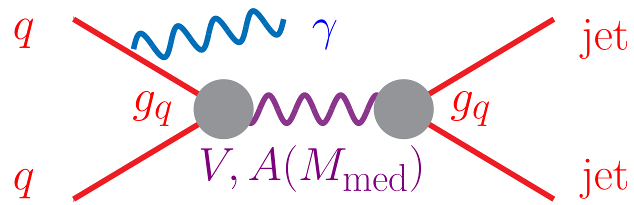


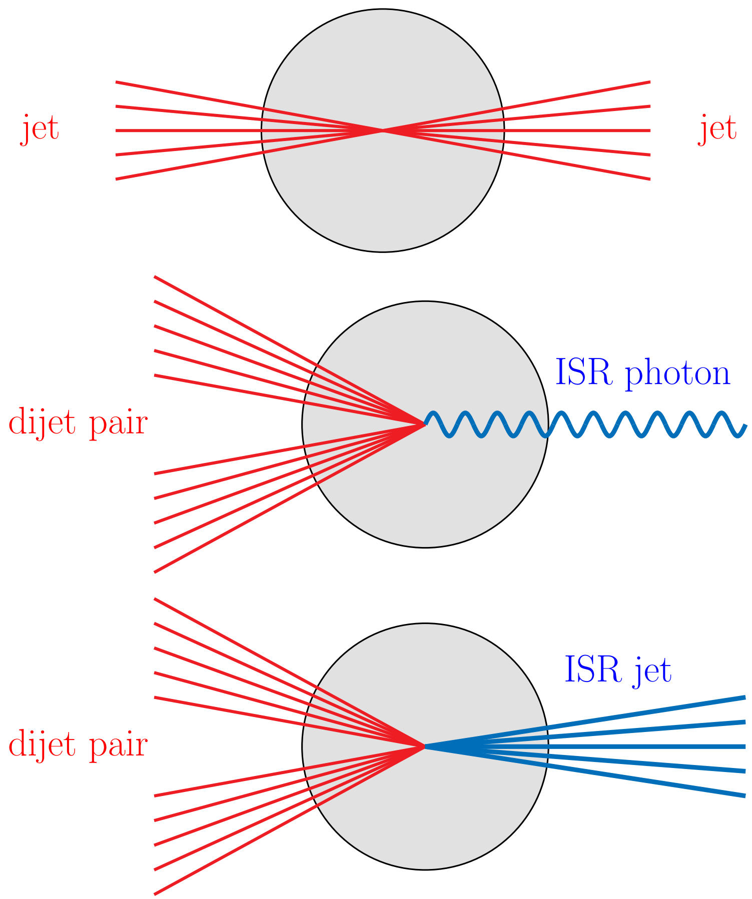
MONO-PHOTON SPECTRUM

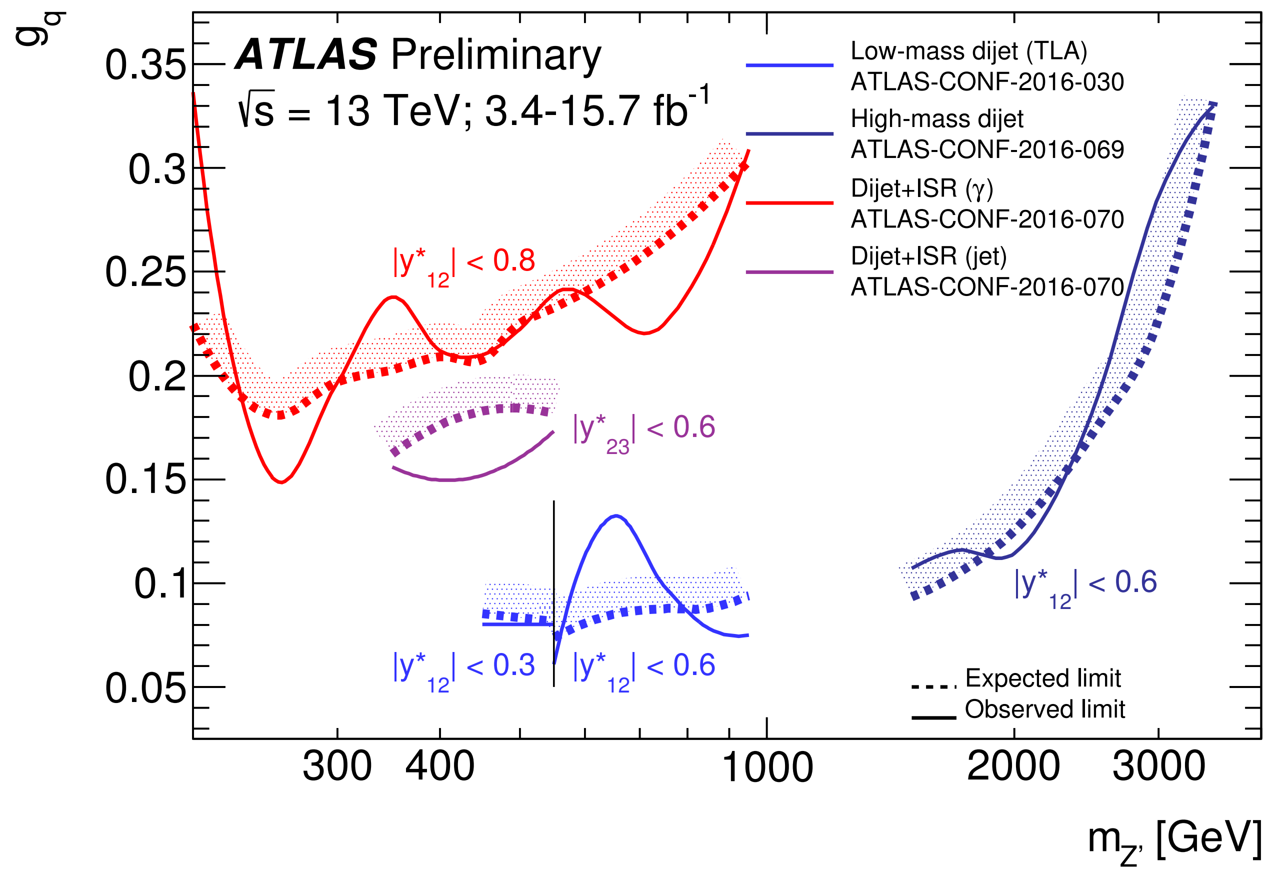




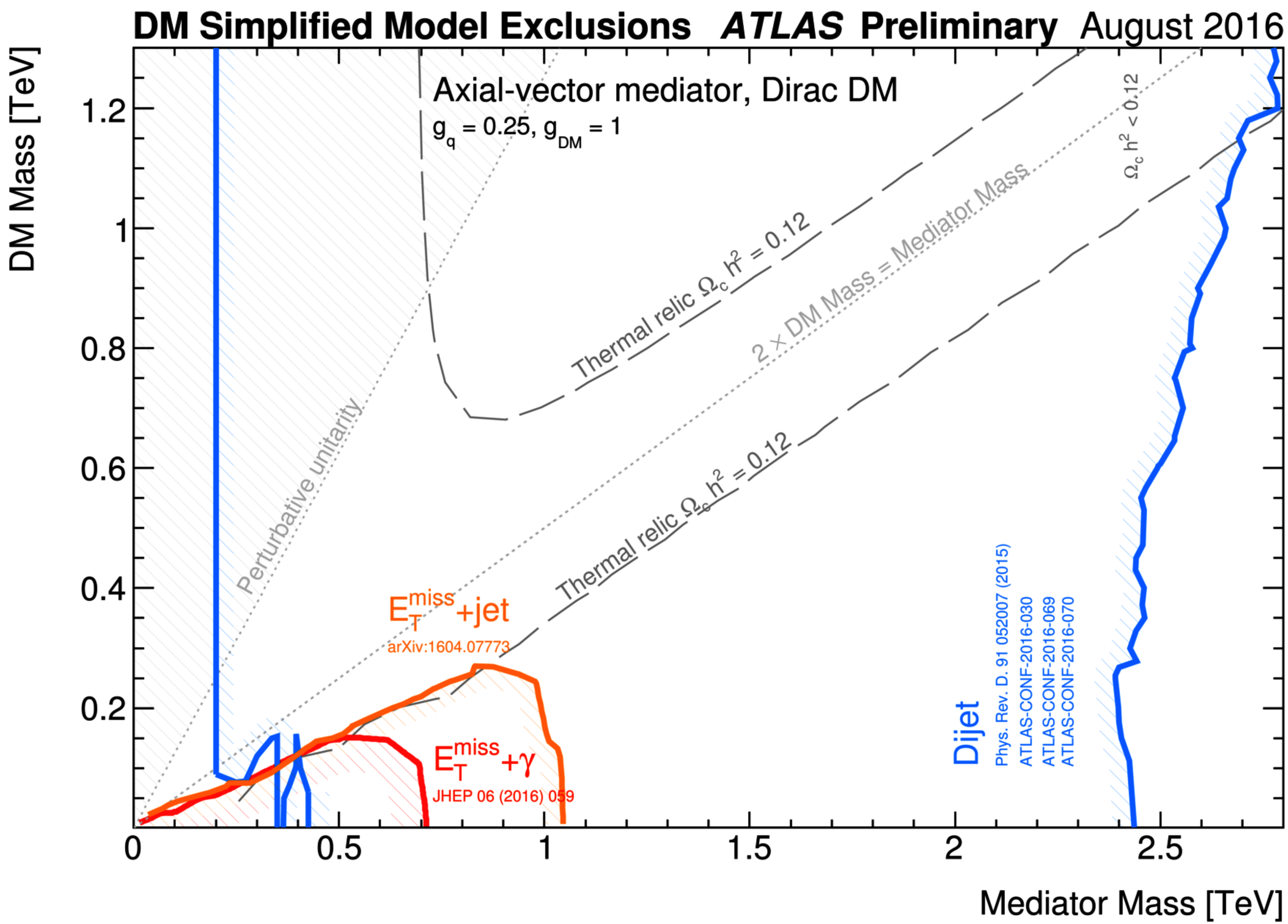
SEARCH FOR MEDIATOR







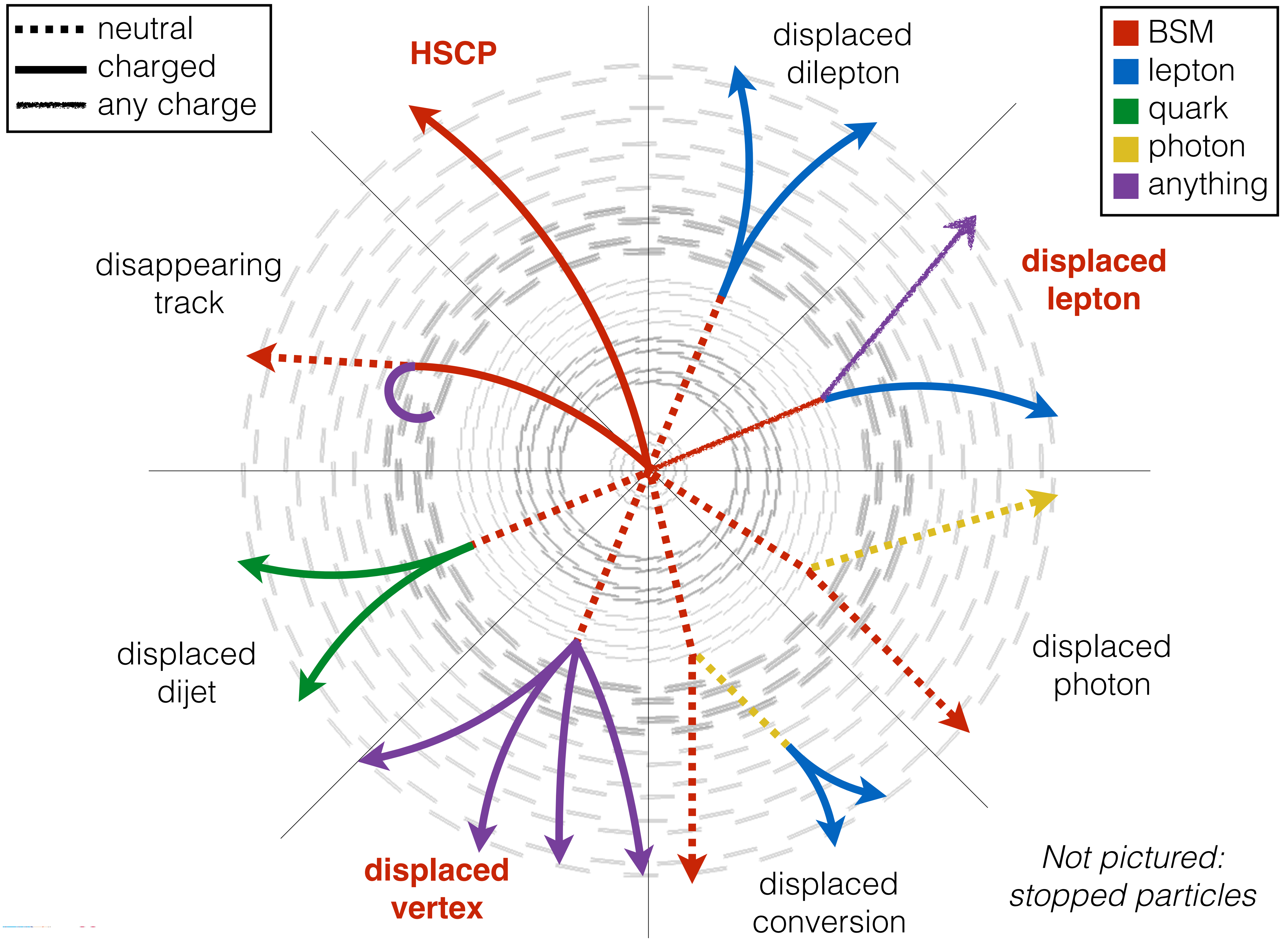
INTERPRETATION



Long-Lived Particles

LONG-LIVED PARTICLES

- Most exotic part of exotic program
- Search for long-lived particles relies on detector features more than other exotic searches
  - dedicated trigger
    - stopped particles
  - dedicated reconstruction algorithms
    - muon reconstruction: heavy stable charged particles
    - tracking: disappearing tracks
  - dedicated detector calibration
    - calorimeter time calibration
- Many searches in Run1 but no discrepancy or excess


neutral
charged
any charge
BSM
lepton
quark
photon
anything
HSCP
displaced dilepton
displaced lepton
disappearing track
displaced dijet
displaced vertex
displaced conversion
displaced photon
Not pictured: stopped particles

Long-Lived Approaches

- Delayed tracks
  - classic heavy stable charged particles
- Tracks with large impact parameters
  - standalone muons in muons system
  - two or more tracks displaced from primary vertex
- Spatially displaced vertices
  - both for high and low mass particles
  - some dedicated tracking to increase efficiency for tracks displaced from primary vertex
- Displaced jets
  - relies on displaced tracks
- Delayed photons
  - measurement of time of flight with ECAL
  - photon conversions

Long-Lived Timeline

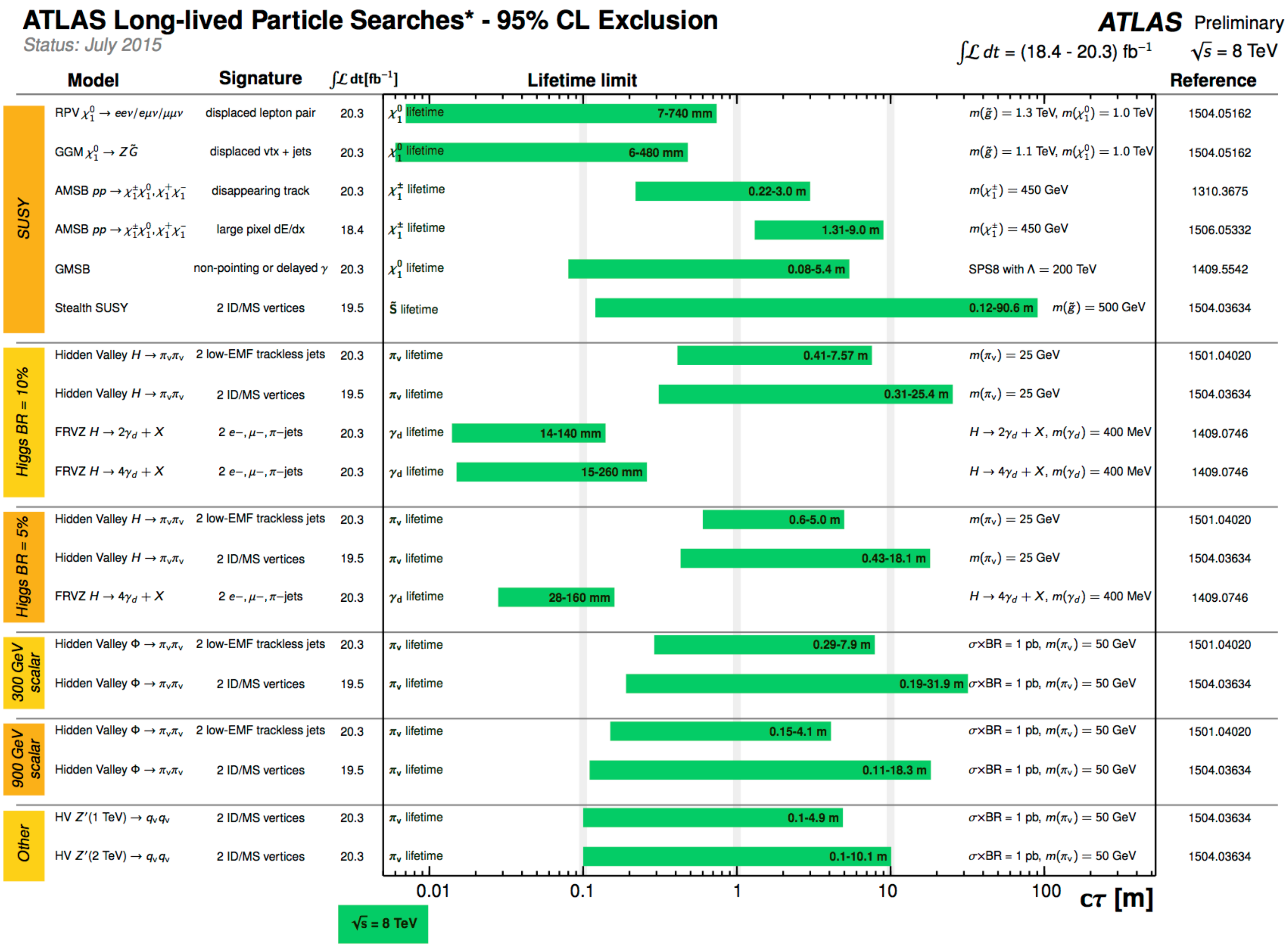
Detector Understanding (time)

- Delayed charged tracks
- Tracks with large impact parameters
- Spatially displaced vertices
- Displaced Jets
- Delayed photons

Models for Reinterpretation

ATLAS SUMMARY

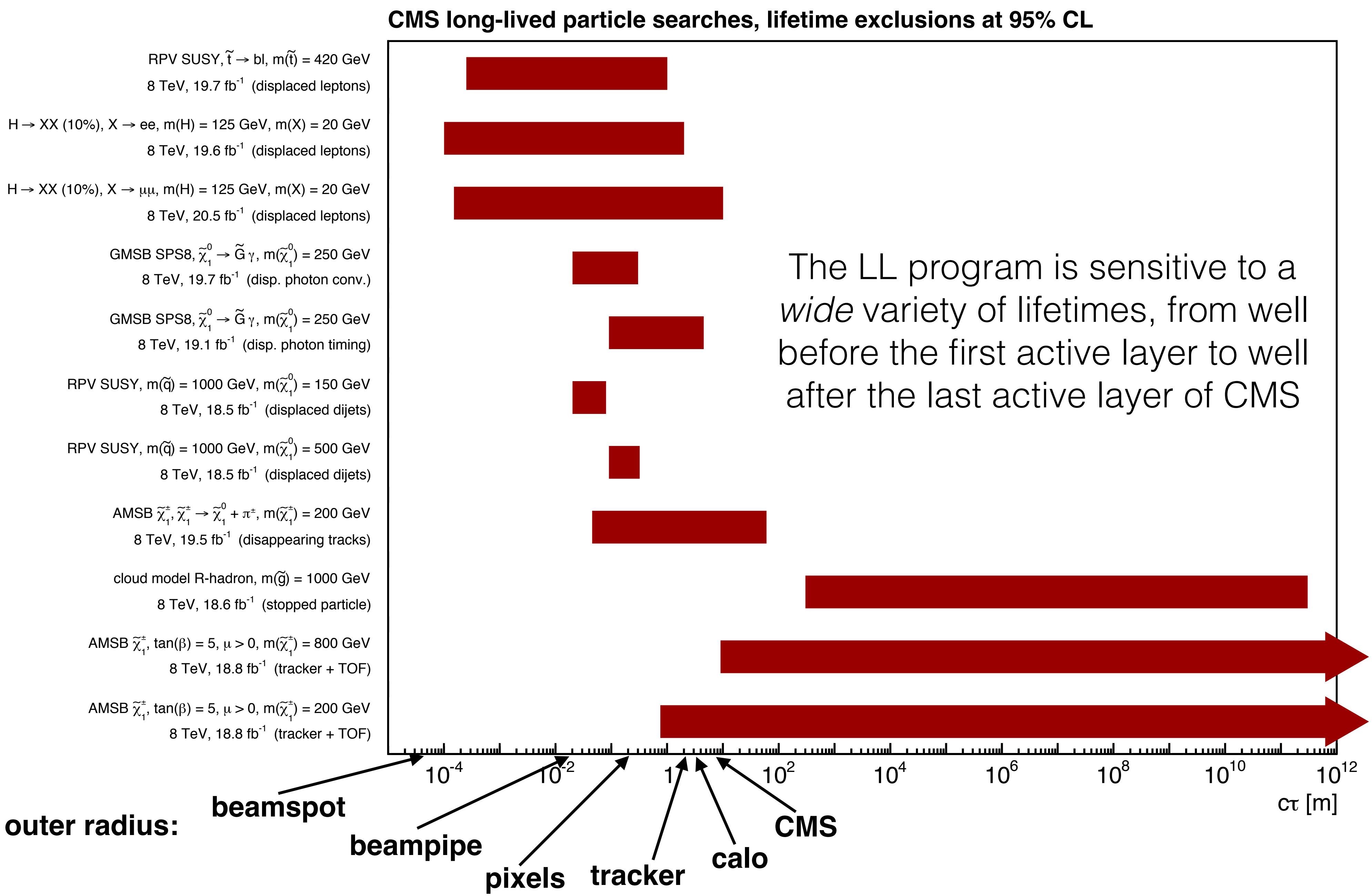
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/ATLAS_Exotics_LLP_Summary/ATLAS_Exotics_LLP_Summary.pdf



*Only a selection of the available lifetime limits on new states is shown.

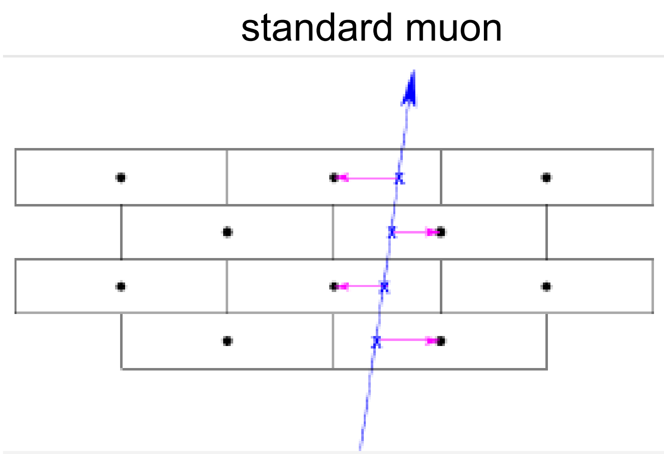
CMS Summary

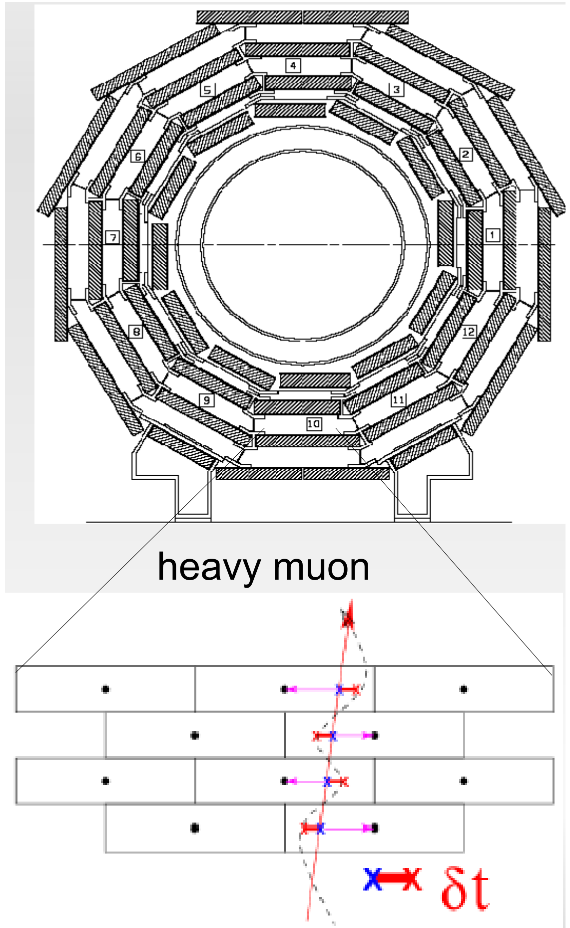
https://twiki.cern.ch/twiki/pub/CMSPublic/PhysicsResultsCombined/exo-limits_LL_Moriond_2016.pdf



Heavy Stable Charged Particles

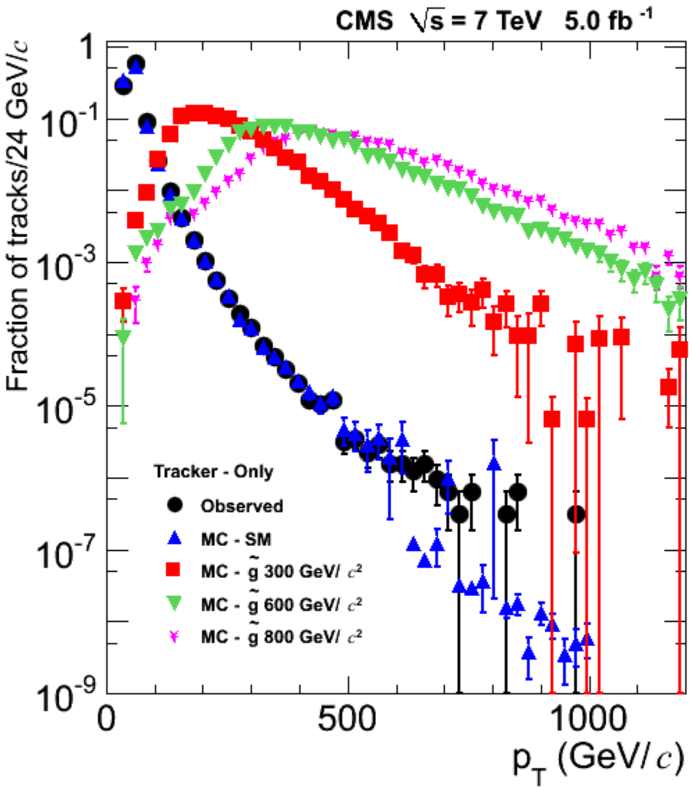
- In many flavors of SUSY, LSP is a heavy charged particle, stau, stop, gluino
  - split SUSY, GMSB, KK tau from some universal extra dimension models
- Behave like very heavy muon through tracking and muons detectors
  - β<1 so later time of arrival in detectors compared to common relativistic particles from collisions
  - Smaller velocity implies larger ionization energy loss
- Search for muon like particles and measure dE/dx energy loss
- Dedicated muon reconstruction because of late arrival compared to standard muon

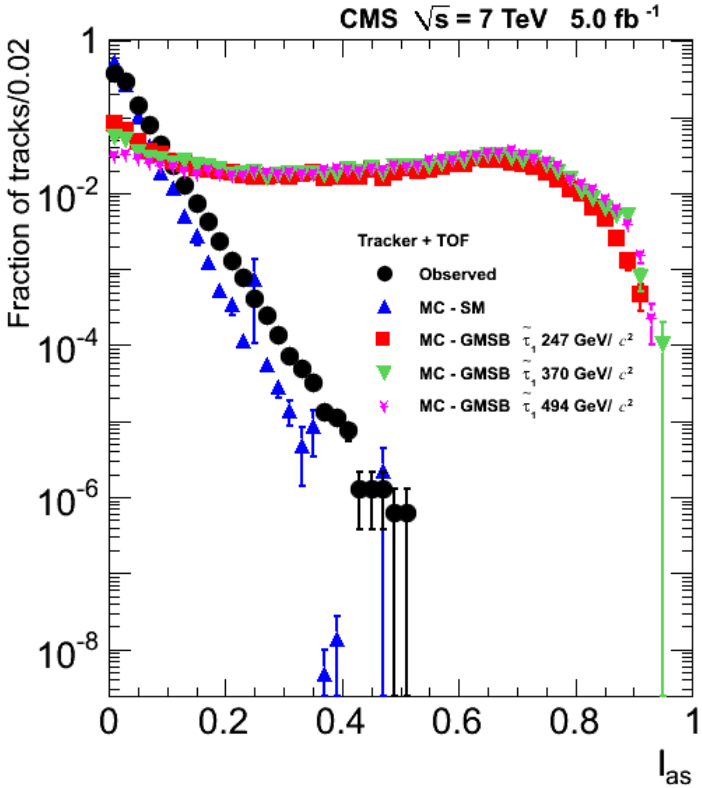


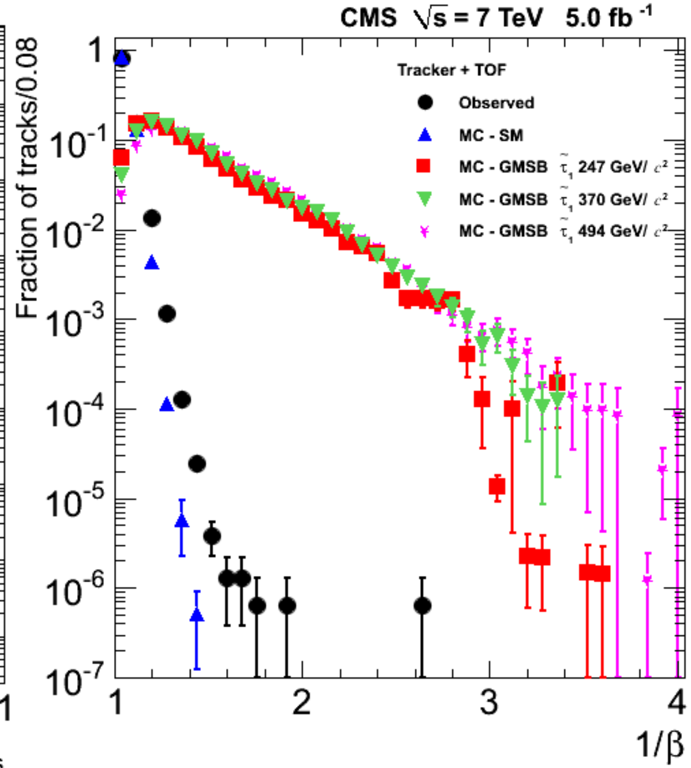


ANALYSIS METHOD

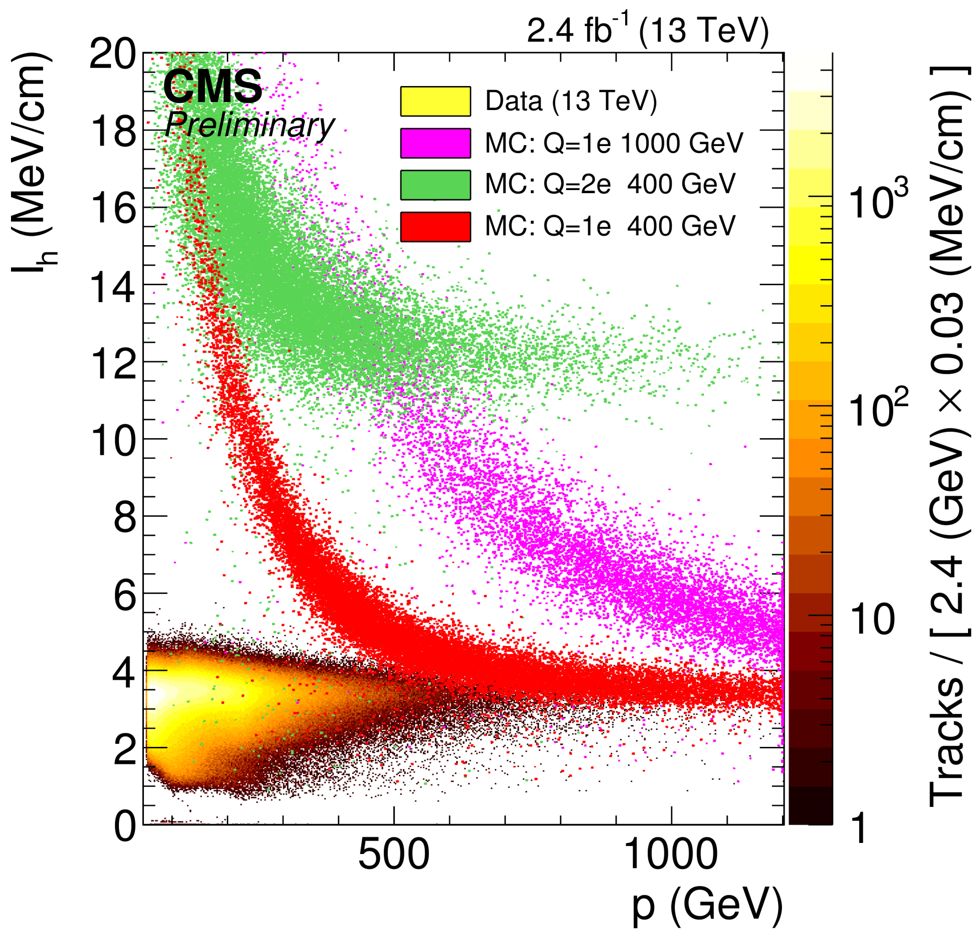
- Discriminating variables
  - –High pt tracks
  - –ionization energy loss
  - –time of flight

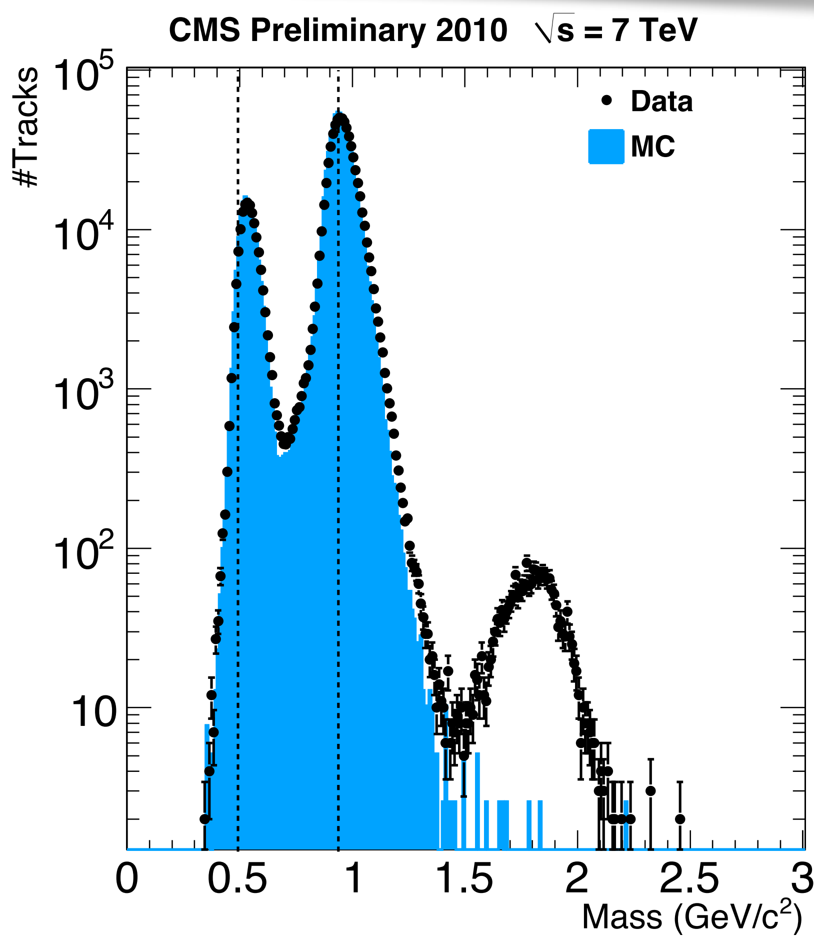






Mass Measurement from dE/dx

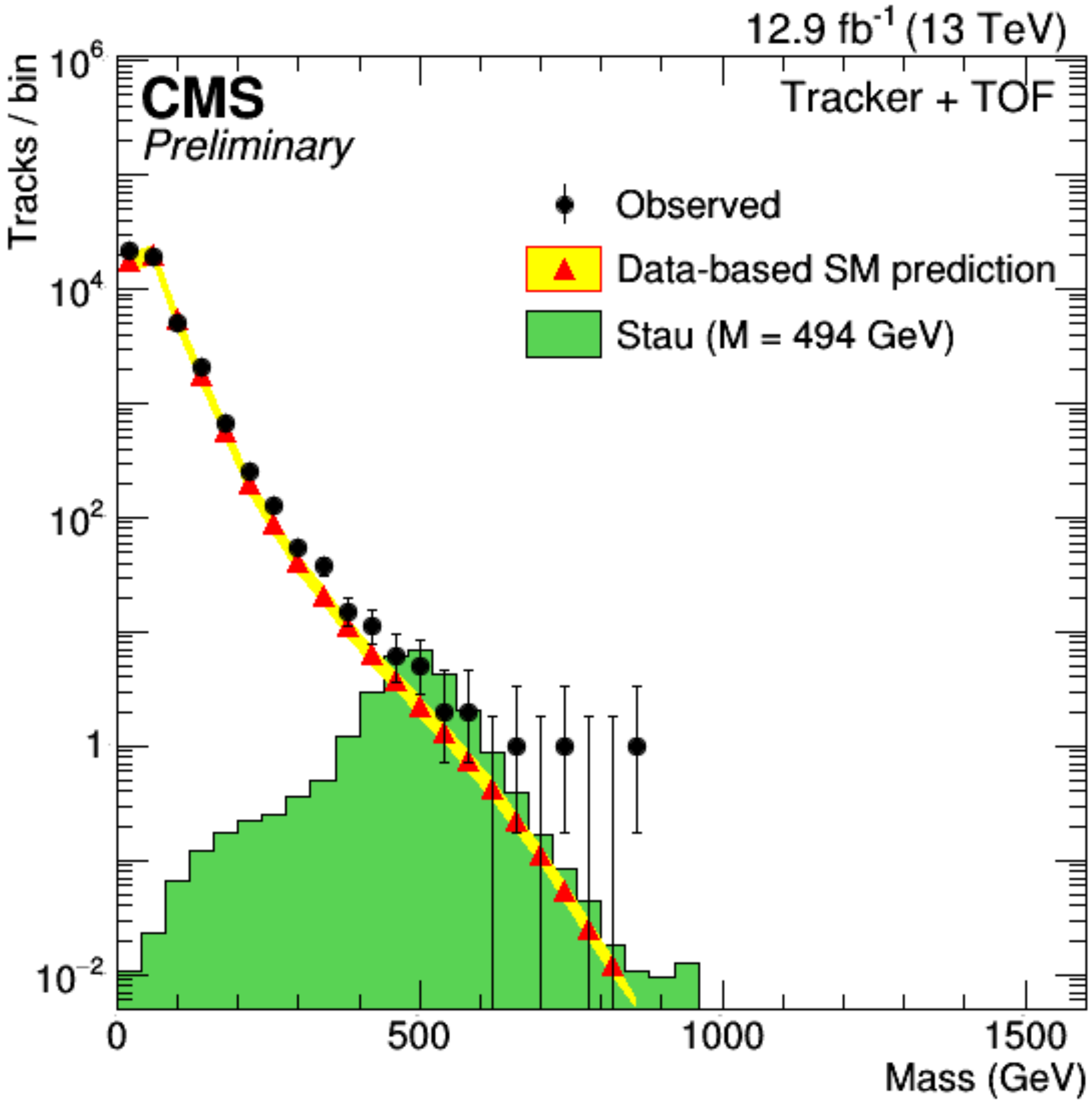




$$I_h = K\frac{m^2}{p^2} + C$$

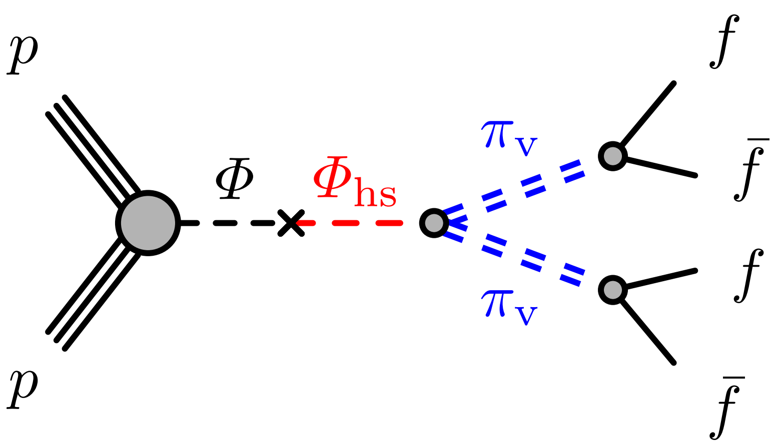
- Quadratic relation between measured energy loss I_h and mass
- Determine K and C from fit to known particles (pions, kaons, protons)
- Determine mass of heavy particles based on measured I_h and momentum p

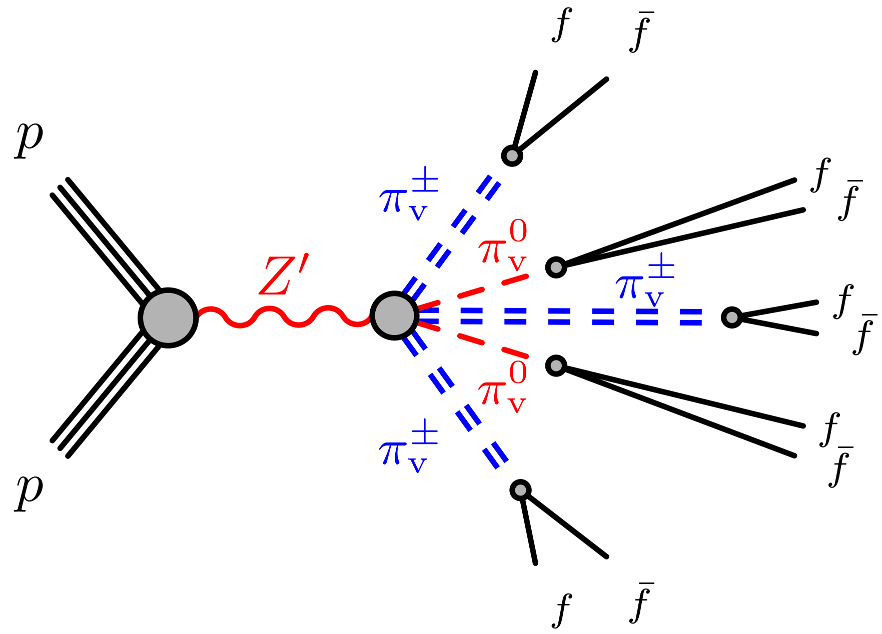
HSCP MASS



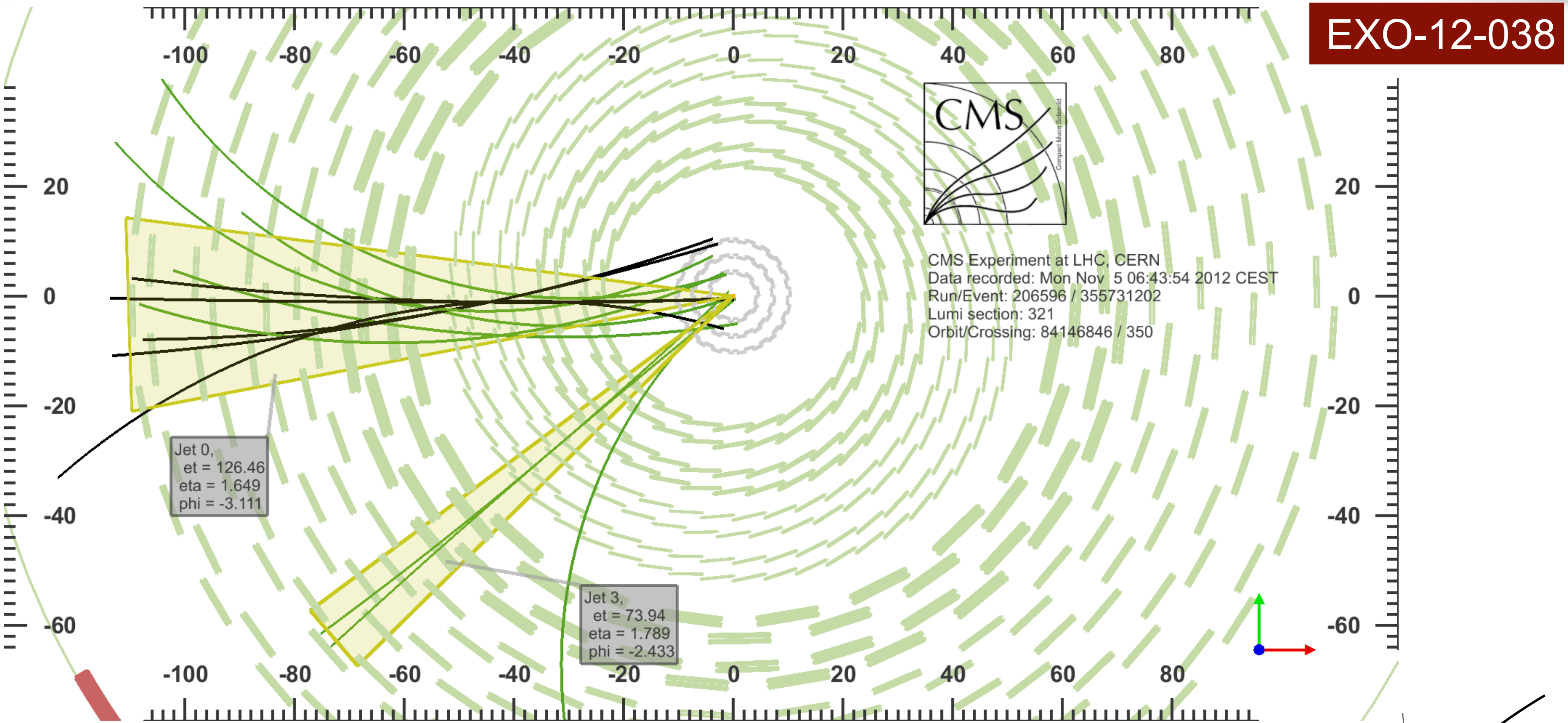
12.9 fb-1 (13 TeV)
CMS
Preliminary
Tracker + TOF
Observed
Data-based SM prediction
Stau (M = 494 GeV)
Tracks / bin
Mass (GeV)

DISPLACED JETS

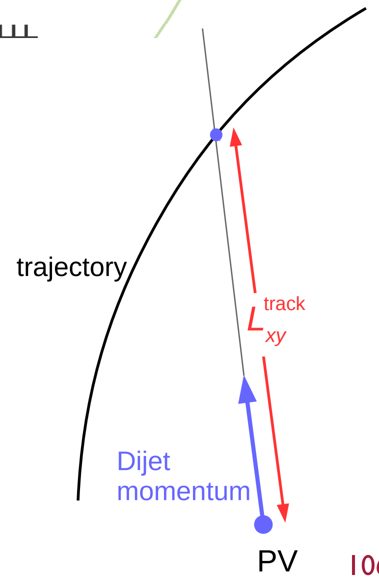




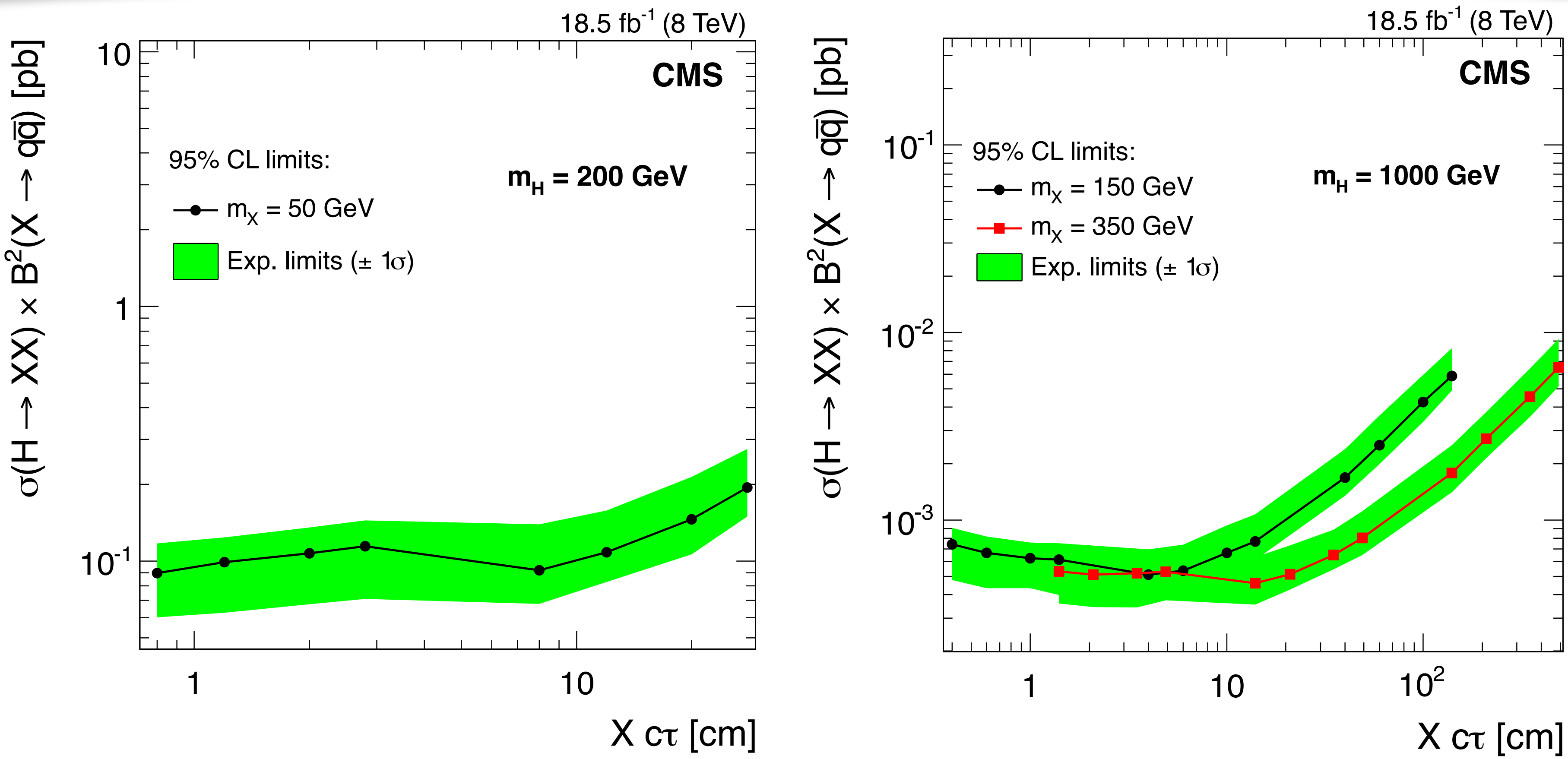
DISPLACED JETS



- Dedicated trigger
  - 2 jets with displaced tracks selected at High Level Trigger
- Only track and vertex information used

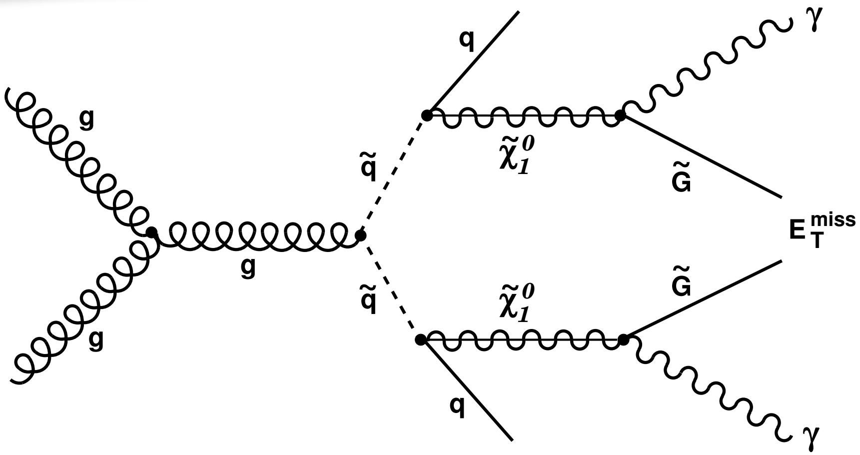


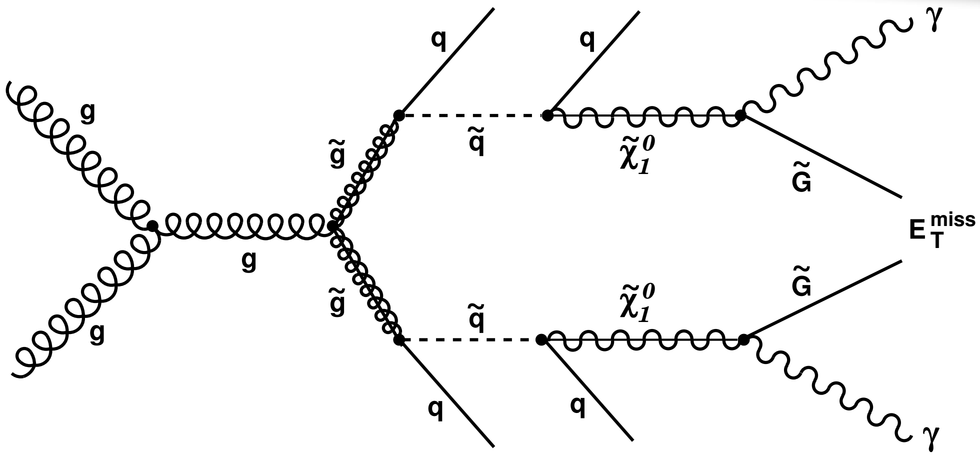
DISPLACED JET INTERPRETATION

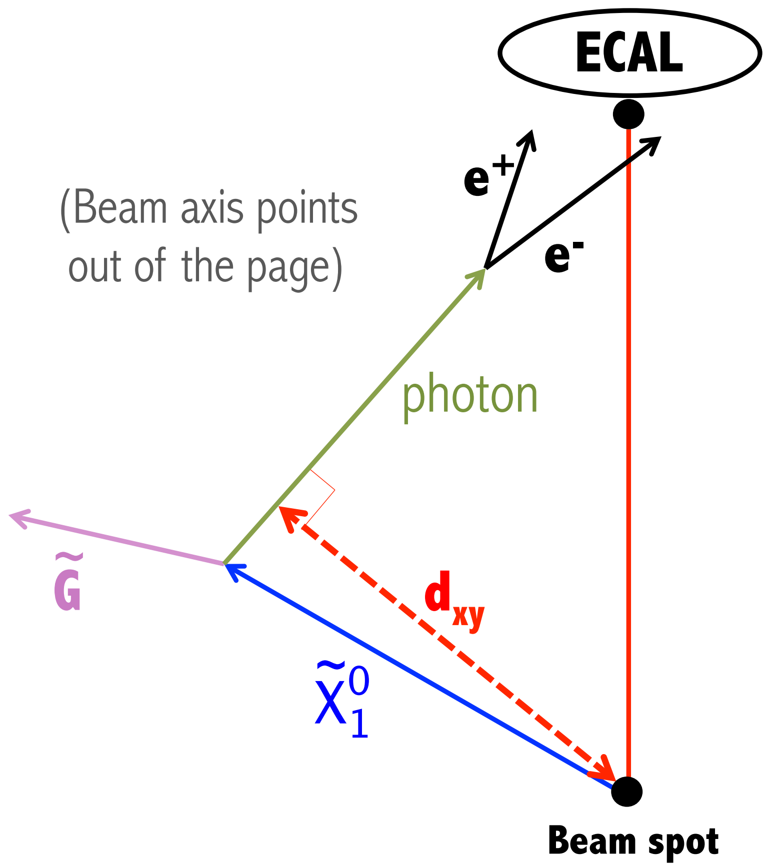


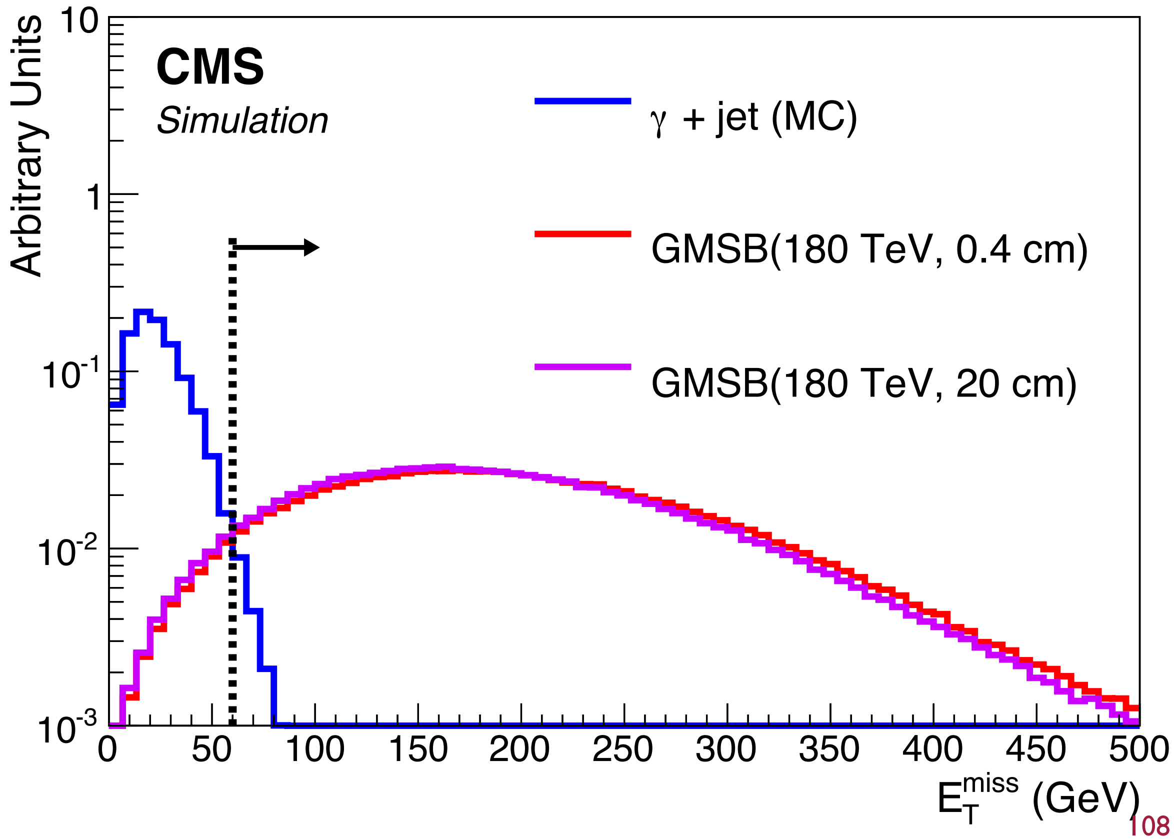
- Higgs-like interpretation remains a favorite benchmark
- Addition of calorimeter time information in Run2 under study

Delayed Converted Photons

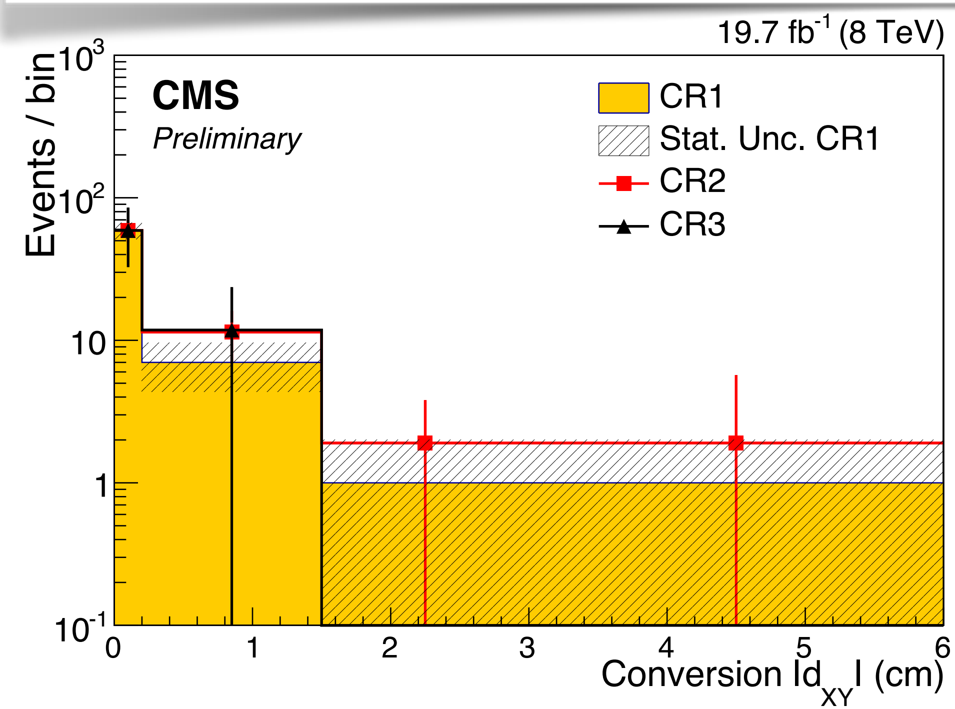




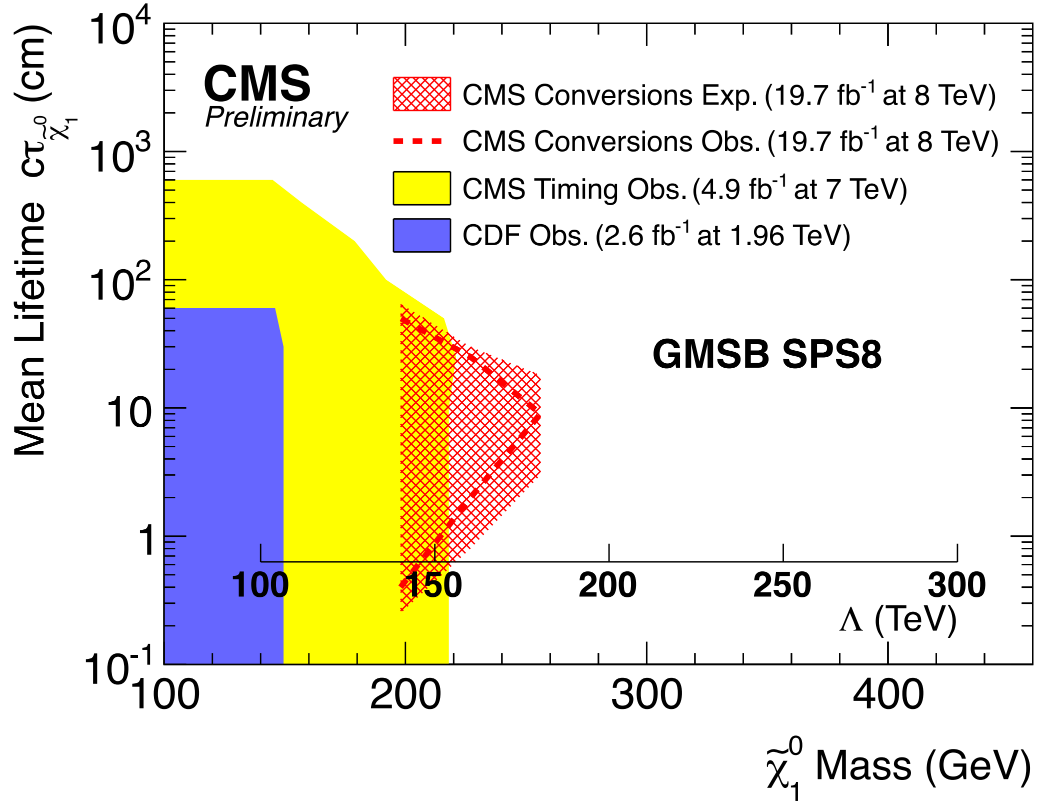


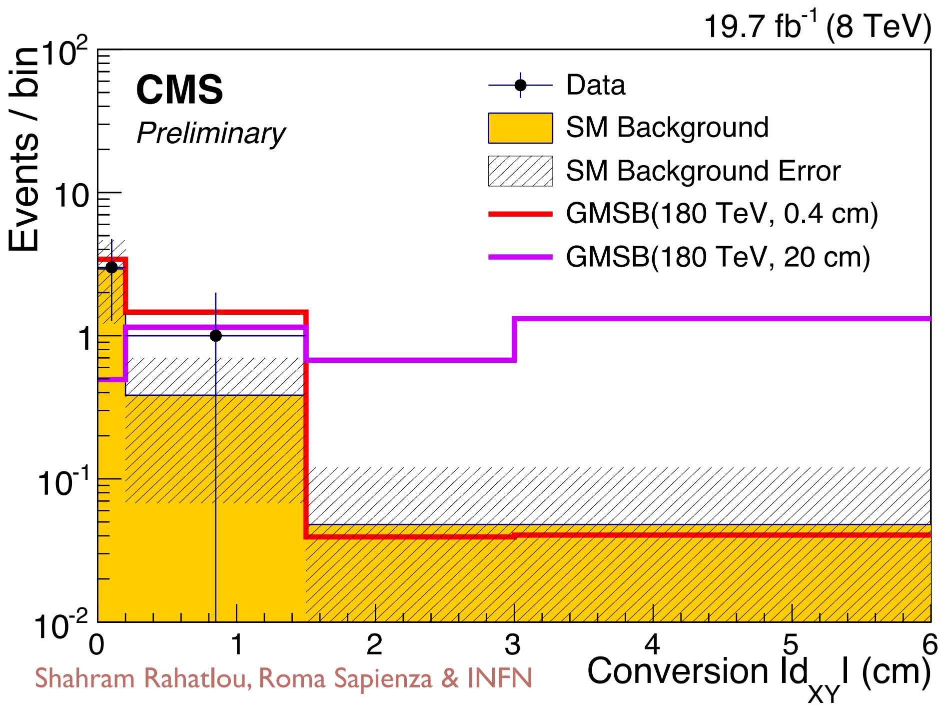


LONG-LIVED NEUTRALINO



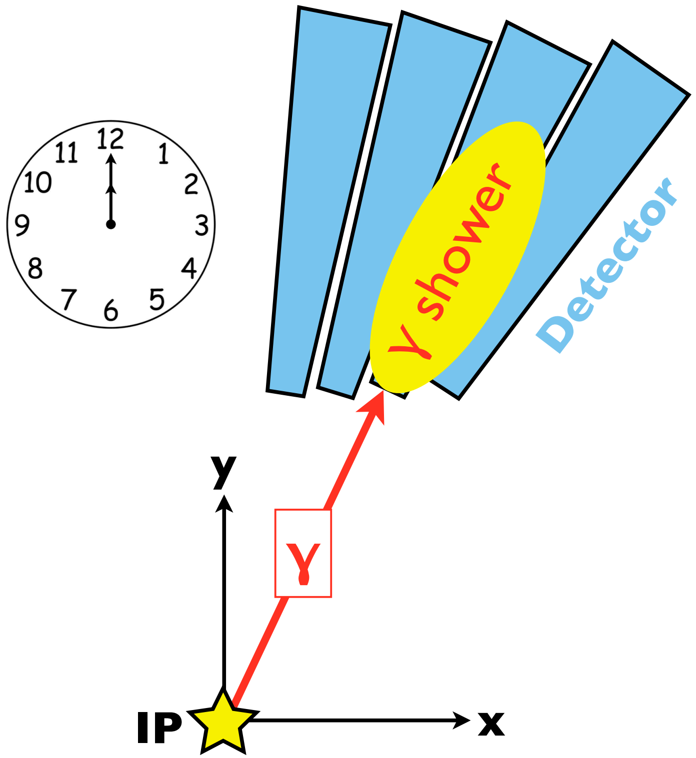
EXO-14-017





DELAYED PHOTON WITH TIMING

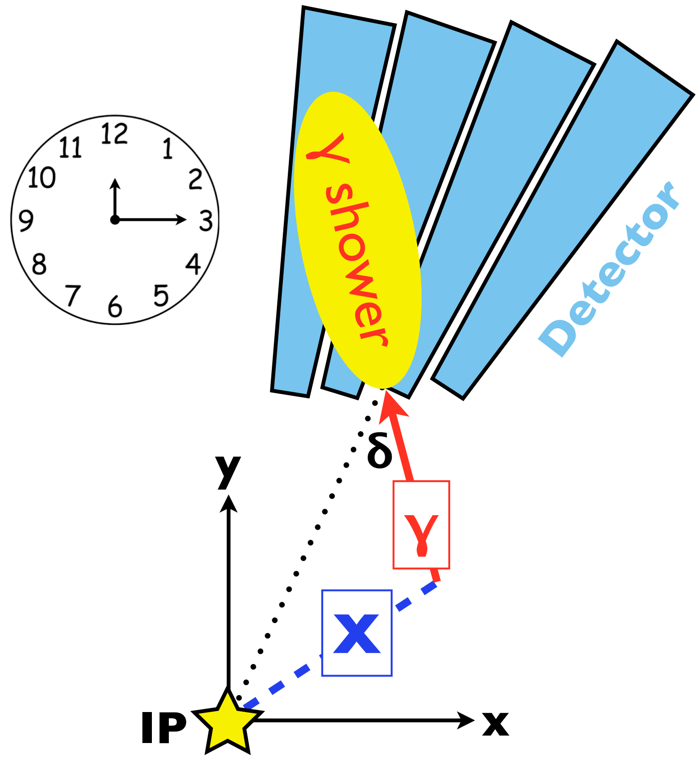
Zero lifetime



In-time photon

➡Arrival time compatible with that of a relativistic particle from the IP

Non-zero lifetime

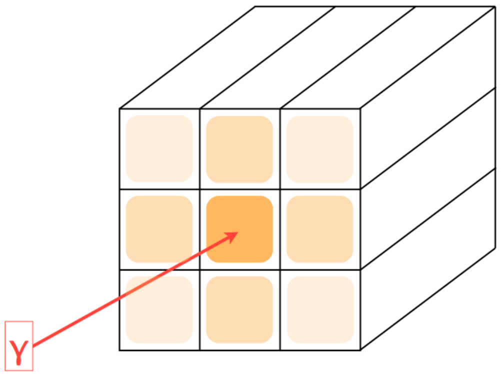


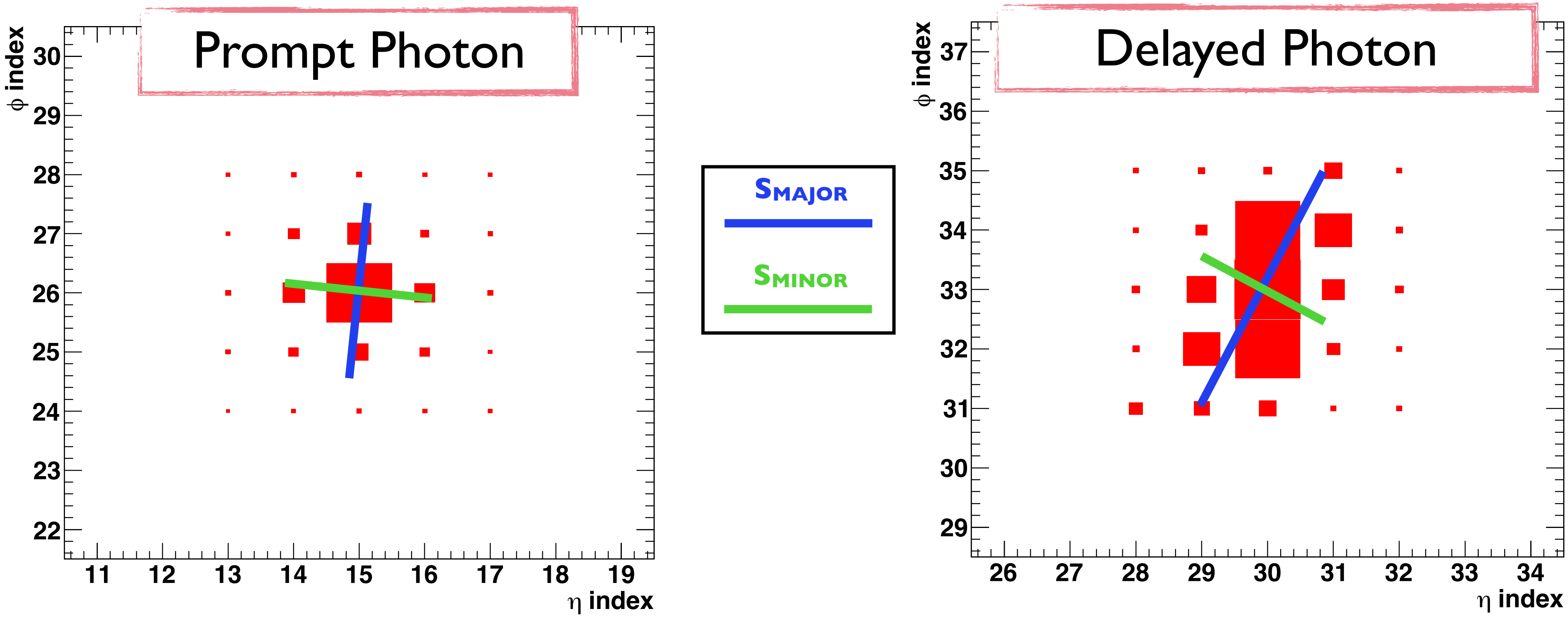
Off-time photon

➡Arrival time sensibly increases with parent particle lifetime

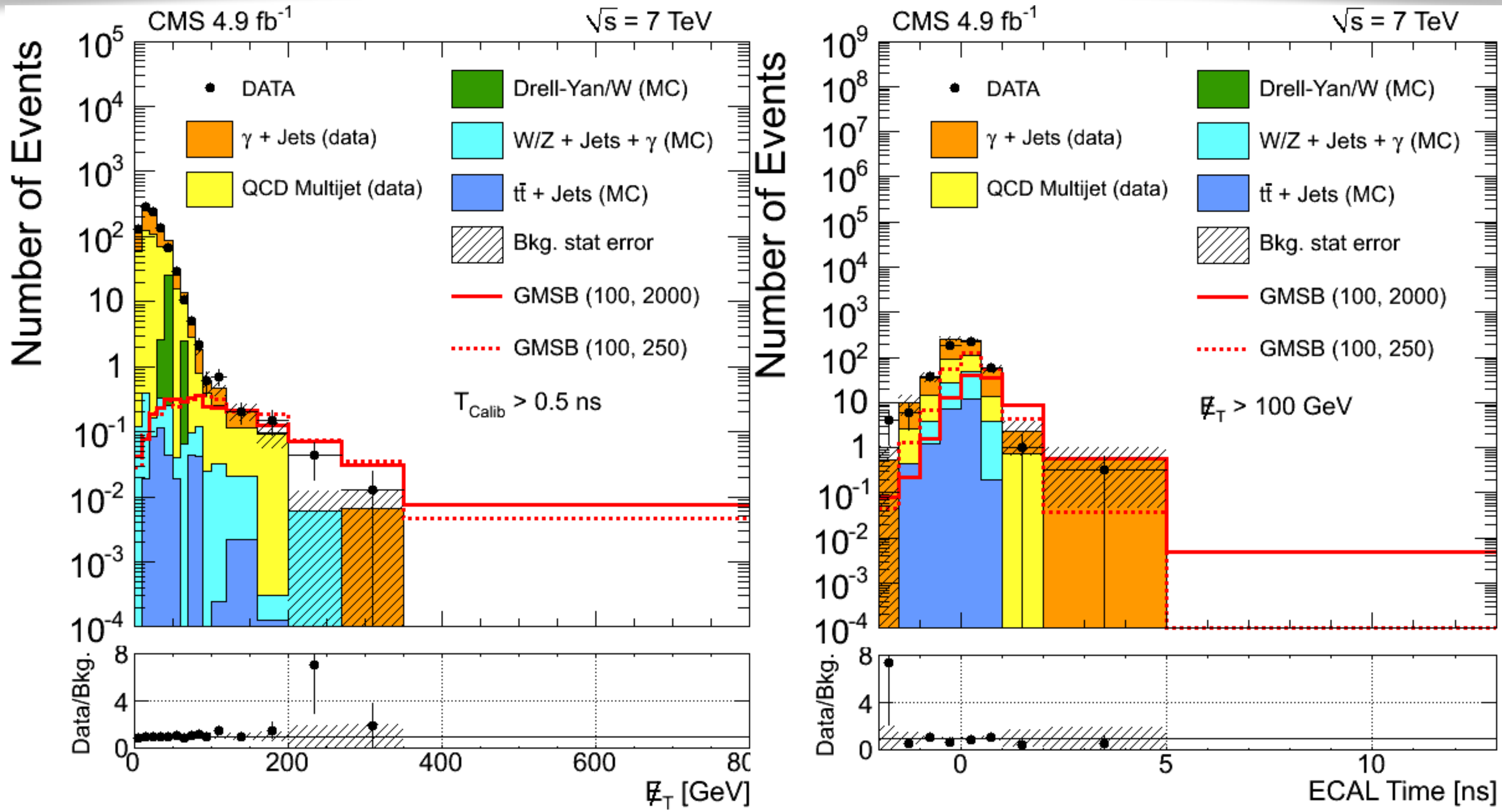
➡ΔT~O(ns)

Shape of Photons in Calorimeter





DELAYED PHOTONS IN 7 TEV DATA



- This analysis requires detailed study and calibration of ECAL time measurement
  - No other physics client than this analysis so far

EXO-11-035

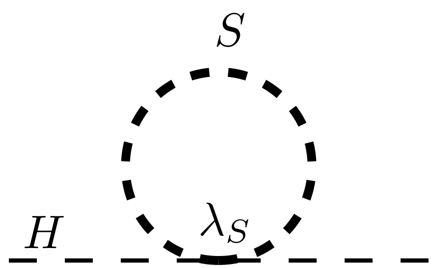
LONG-LIVED SUMMARY

- Search for long-lived particles use simple and basic detector information
  - unlike some of *sophisticated* variables needed in many Higgs and BSM searches
- Deeper understanding of detector response typically implies longer time scale for long-lived searches
  - and longer term detector activity commitment
- Displaced vertices remain perhaps most profitable approach
  - results can be interpreted in many models, specially in terms of some flavor of some Higgs-like particle
    - *Higgs remains a catchy name*
- Time of flight for photons and electrons requires heavy investment in detector studies but can pay dividends
  - clean experimental signature
  - unfortunately not enough theoretical models to get people excited

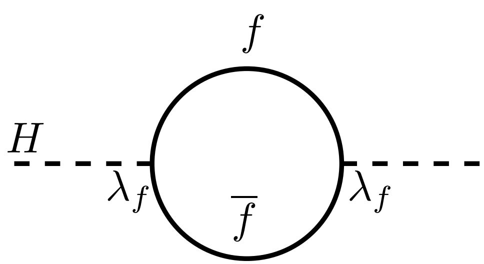
Supersymmetry

A SOLUTION TO HIGGS MASS DIVERGENCE

- scalar particles contribution to Higgs mass also quadratically divergent with MUV
- Contribution with opposite sign compared to fermions



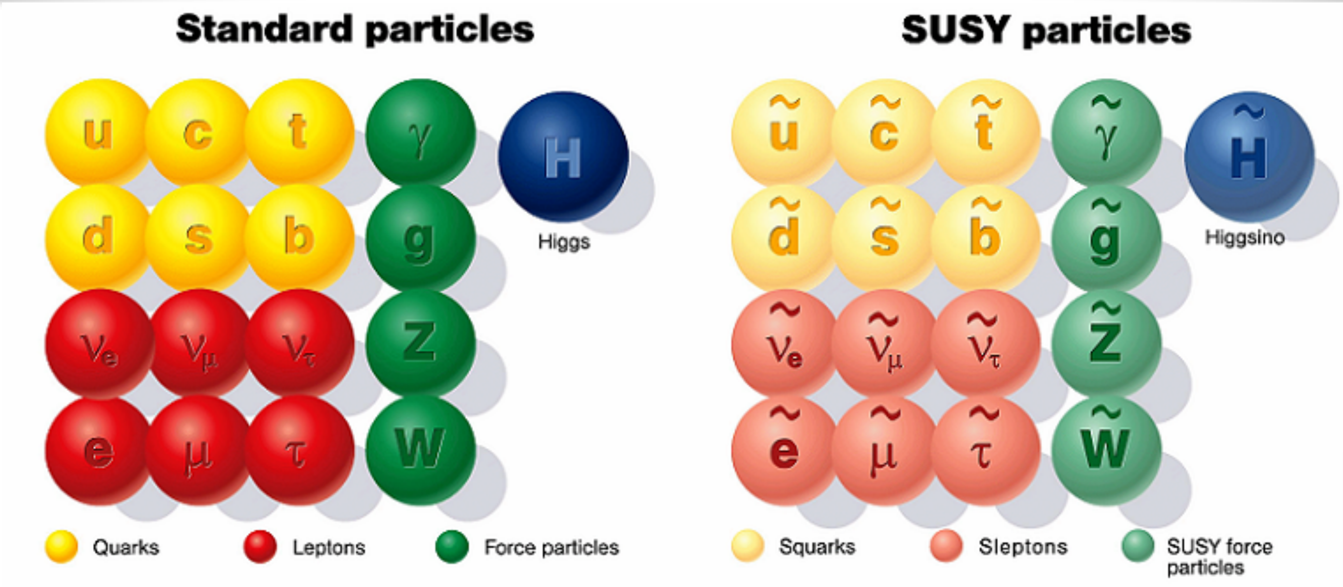
$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}\left[M_{\rm UV}^2 - 2m_S^2 \ln\left(M_{\rm UV}/m_S\right) + \ldots\right]$$



$$\Delta m_H^2 = \frac{\lambda_f^2}{16\pi^2}\left[-2M_{\rm UV}^2 + 6m_f^2 \ln\left(M_{\rm UV}/m_f\right) + \ldots\right]$$

- If such scalar particles existed, fermion and scalar contributions could cancel each other exactly and naturally without fine tuning
- Such conspiracy is generally known as a symmetry of the theory!

SUPERSYMMETRY (SUSY)



- Elegant new symmetry of Nature
- For each ½-integer spin particle (Fermion) there is an integer spin partner (Boson) and vice versa
  - Complete spectrum of partners to standard model particles
  - Their spins are different by ½ unit
- Predicts 5 Higgs bosons, the lightest very similar to that in Standard Model
- *Requires observation of new predicted particles and phenomenology*

WHERE ARE SUSY PARTICLES?

- Many SUSY particles have already been observed
  - leptons, quarks, W, and Z
  - same particles included in SM
- But no SUSY partner of SM observed yet!
- If SUSY is an exact symmetry, we should have seen SUSY partners of known particles with the same mass
- SUSY is certainly broken!
- Spontaneous SUSY breaking must be added by hand and still avoid divergences in Higgs mass corrections
- *Different symmetry breaking mechanisms on the market*

NEW SYMMETRY: R-PARITY

$$R = (-1)^{3(B-L)+2S}$$

- Add new conservation law to protect against lepton and baryon number violation
- R-parity combines spin, baryon, and lepton quantum numbers
  - particles: R = +1
  - SUSY particles: R = -1
- Important phenomenological consequences
  - SUSY particles can only be produces in pairs
  - R = -1 particles must always decay in final states with at least one R = -1 particle
    - lightest SUSY particle (LSP) must be stable
  - Two R = -1 particles can annihilate and produce ONLY R = +1 particles
    - important for Dark Matter searches

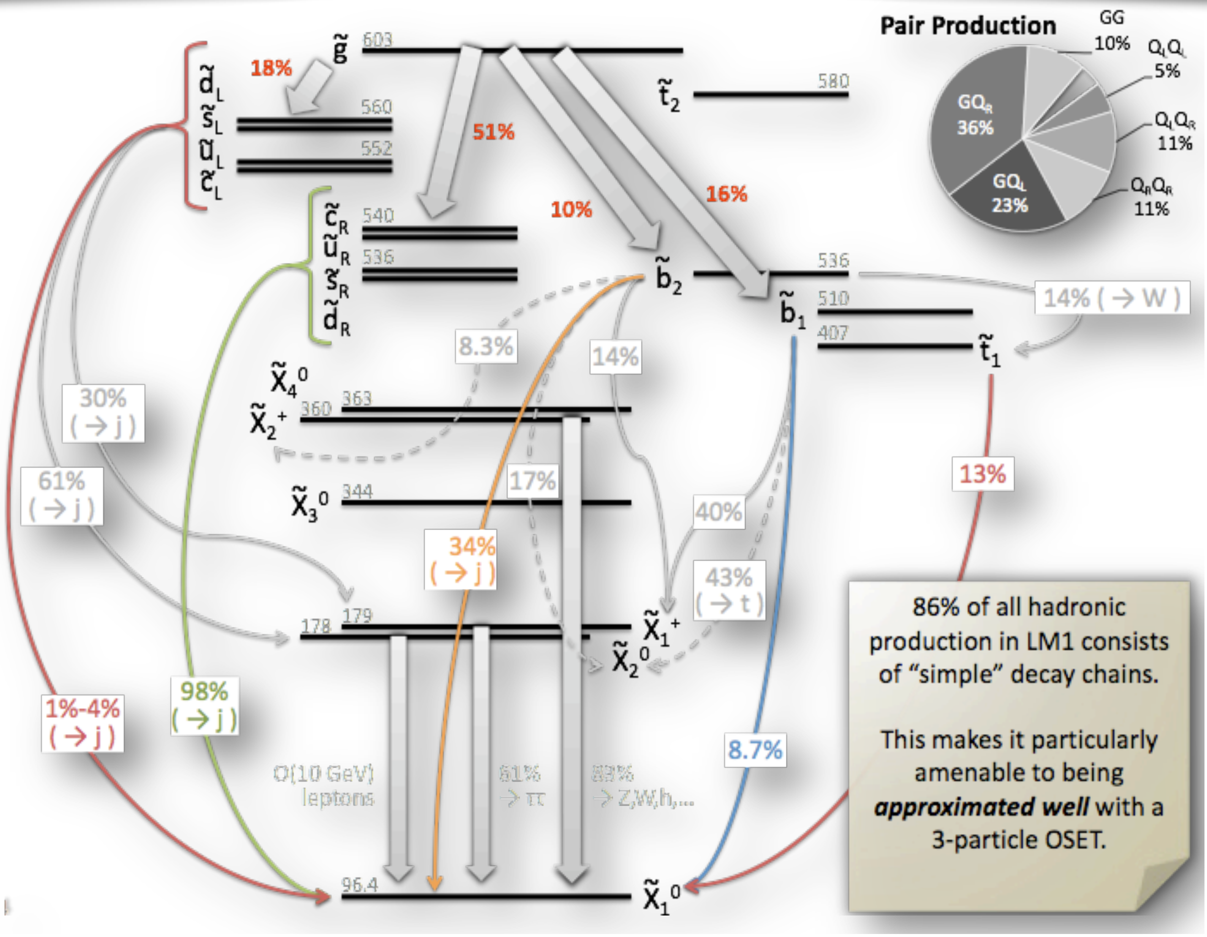
LIGHTEST SUPERSYMMETRIC PARTICLES

- Two particles play crucial role in SUSY searched

- Lightest supersymmetric particle must be stable and hence escape detection
  - missing energy in SUSY processes
  - SUSY masses are expected to be large therefore expect large missing energy

- Next to lightest supersymmetric particle (NLSP)
  - Because of R-parity conservation must always decay to LSP
    - two body decay of NLSP → X + LSP
  - X will always be an ordinary R = +1 particle
  - distinctive kinematic signature for X helps searching for NLSP

SUSY SPECTRUM

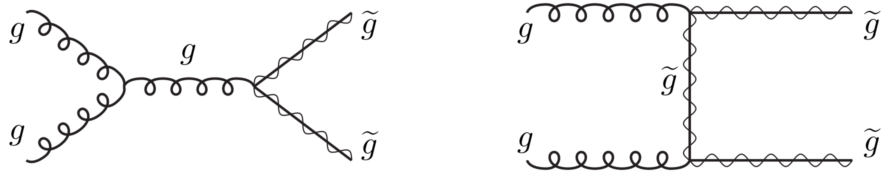


- Lightest supersymmetric particle (LSP) stable and escapes detection
  - missing energy in SUSY processes
- Next to lightest supersymmetric particle (NLSP)
  - R-parity conservation: NLSP → X + LSP
  - *Potentially long proper lifetime*

$$R = (-1)^{3(B-L)+2S}$$

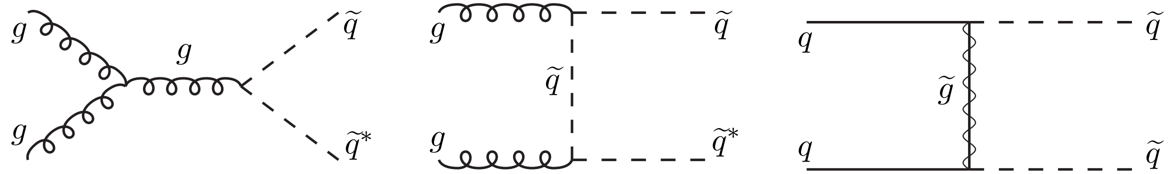
SUSY PRODUCTION VIA QCD

Gluino pairs



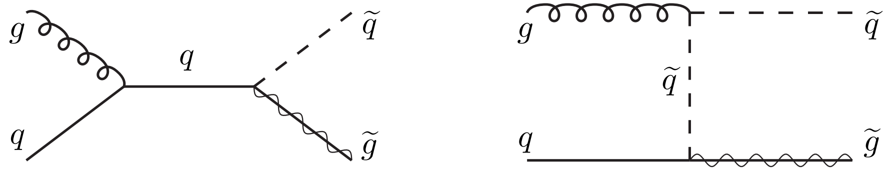
etc.

Squark pairs



etc.

Squark + gluino

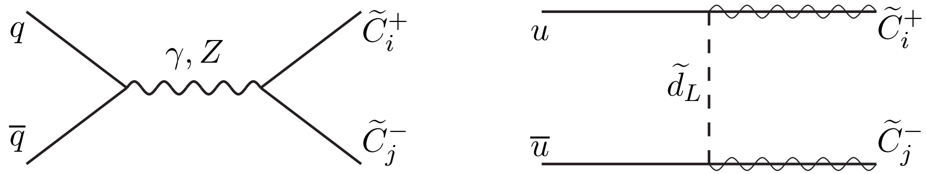


etc.

- QCD production dominates but given heavy mass for SUSY, cross section strongly depends on squark and gluino masses

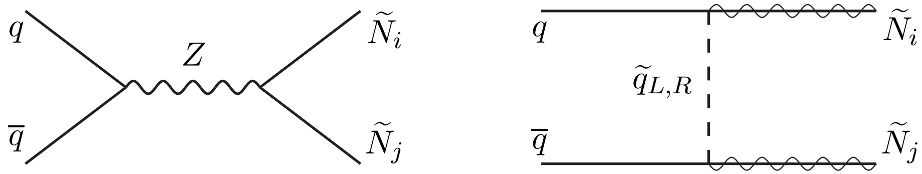
SUSY Production via Electroweak

Chargino pairs

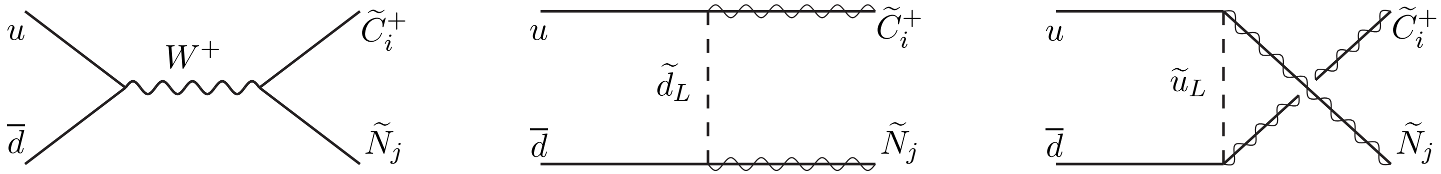


etc.

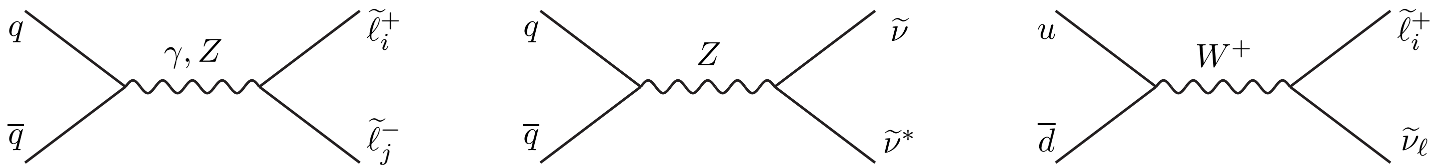
Neutralino pairs



Chargino + neutralino

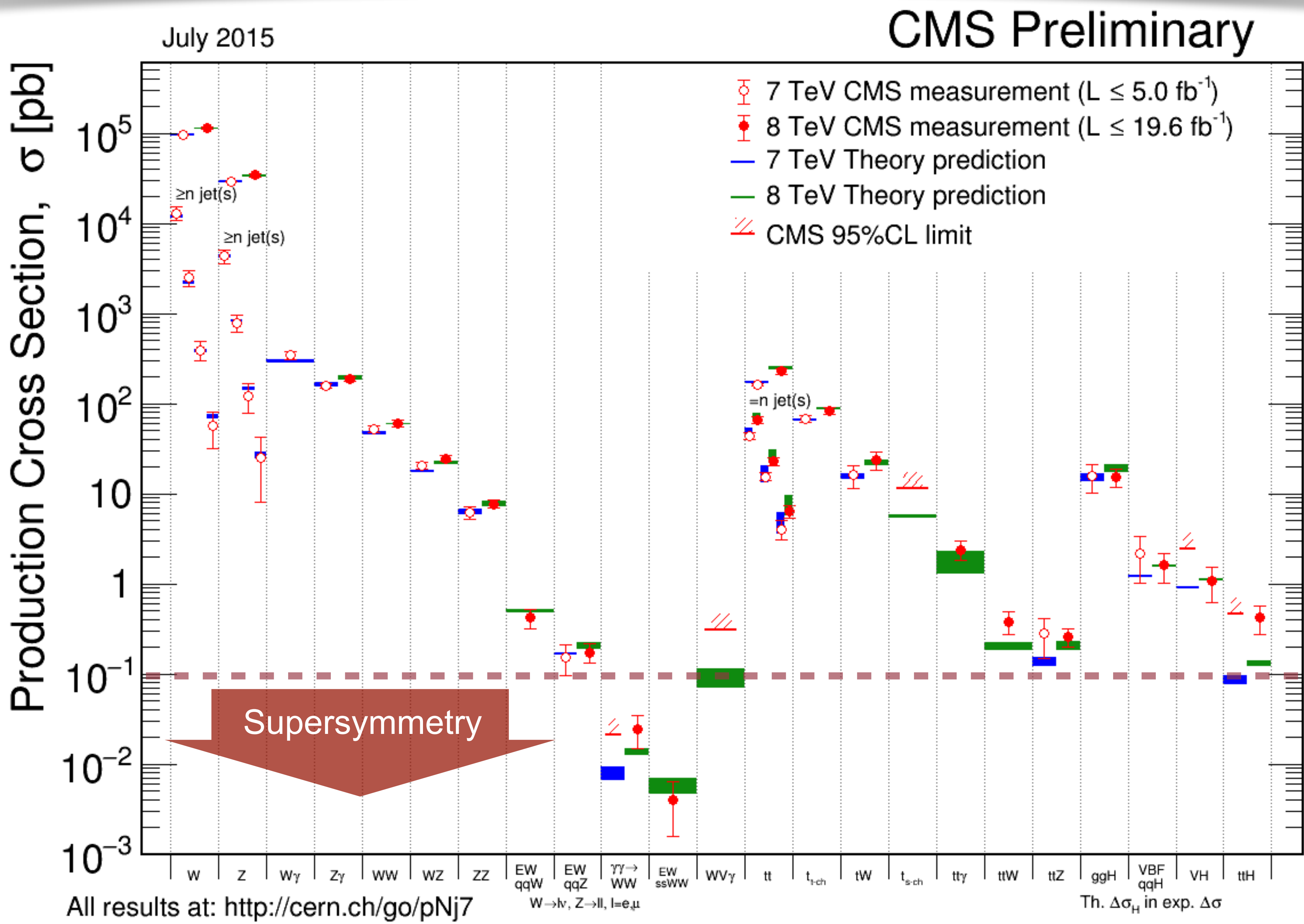


Slepton pairs



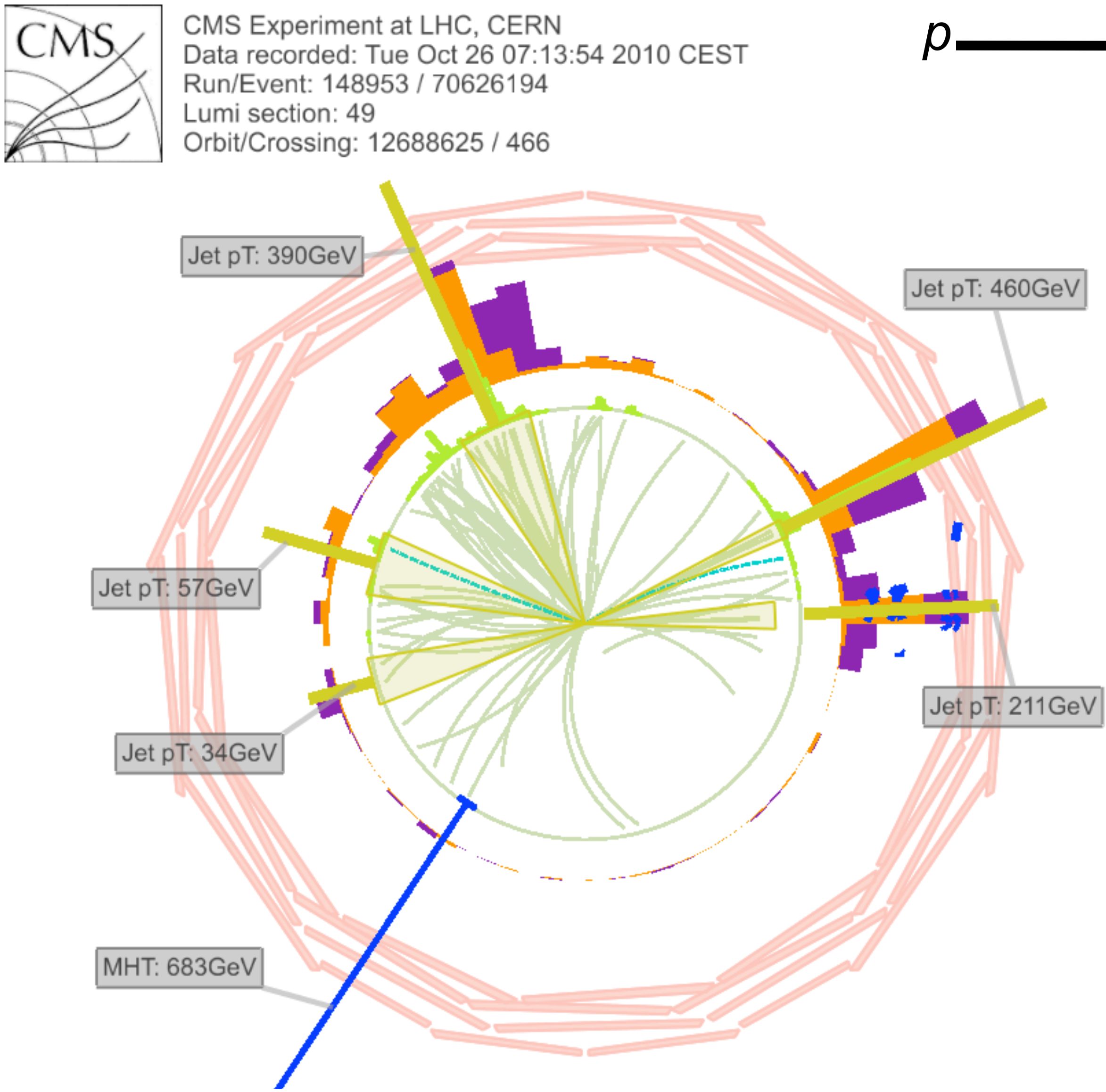
- Smaller cross section since EW coupling is smaller compared to QCD

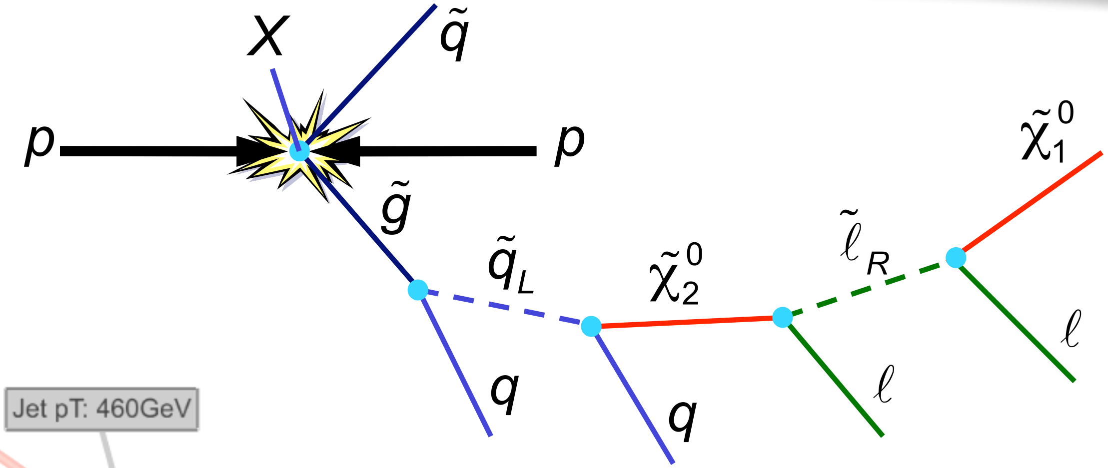
SUSY vs. Standard Model

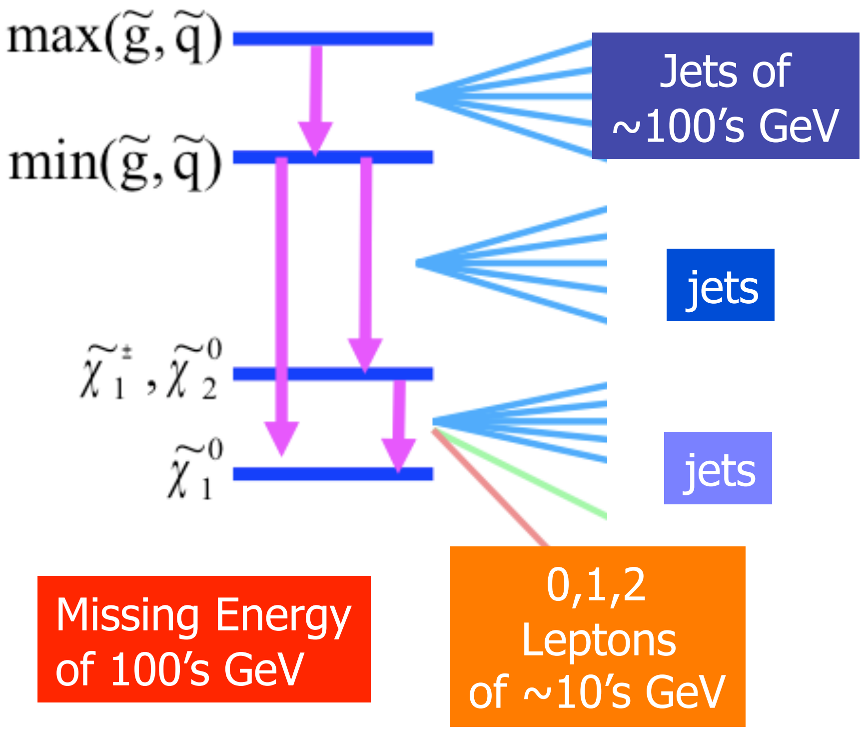


SUSY PHENOMENOLOGY

SUSY PHENOMENOLOGY

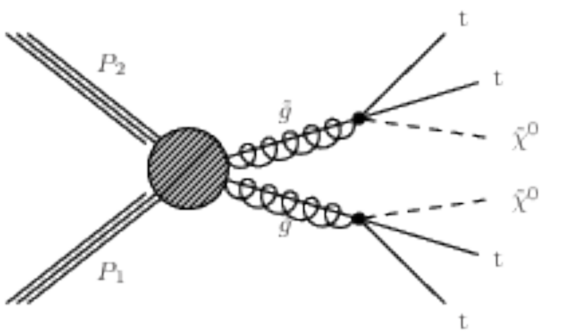


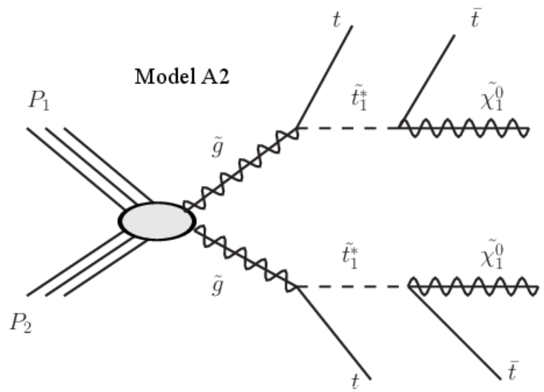


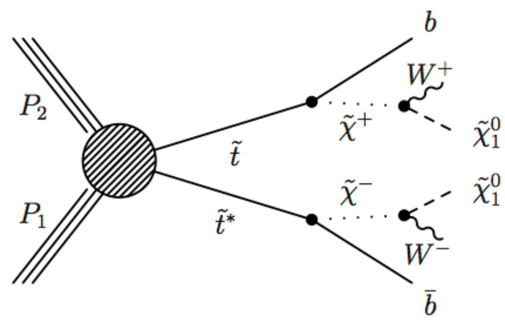


SIMPLIFIED MODELS (SMS)

- Very productive industry of SUSY flavors and models
  - early results at 7 TeV have flourished new ideas
- Simulating each and every model across parameter space not feasible (and perhaps not reasonable)
- Luckily, final experimental signature in common between many models
- Define search strategy to maximize coverage of distinct experimental final states



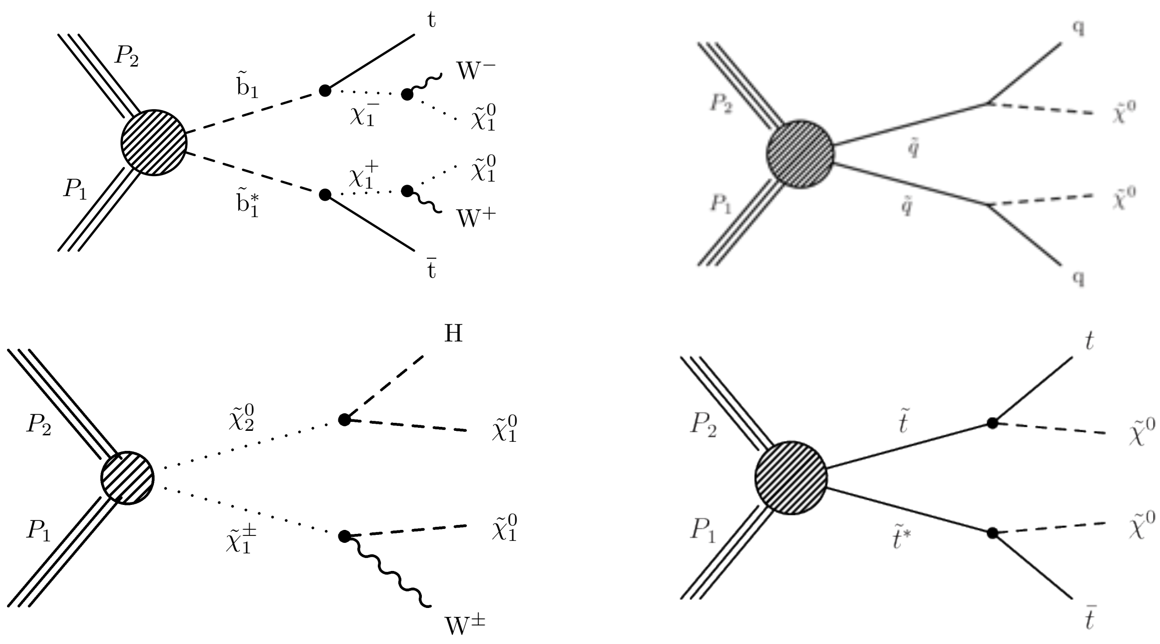




SIGNATURE-BASED SEARCH STRATEGY

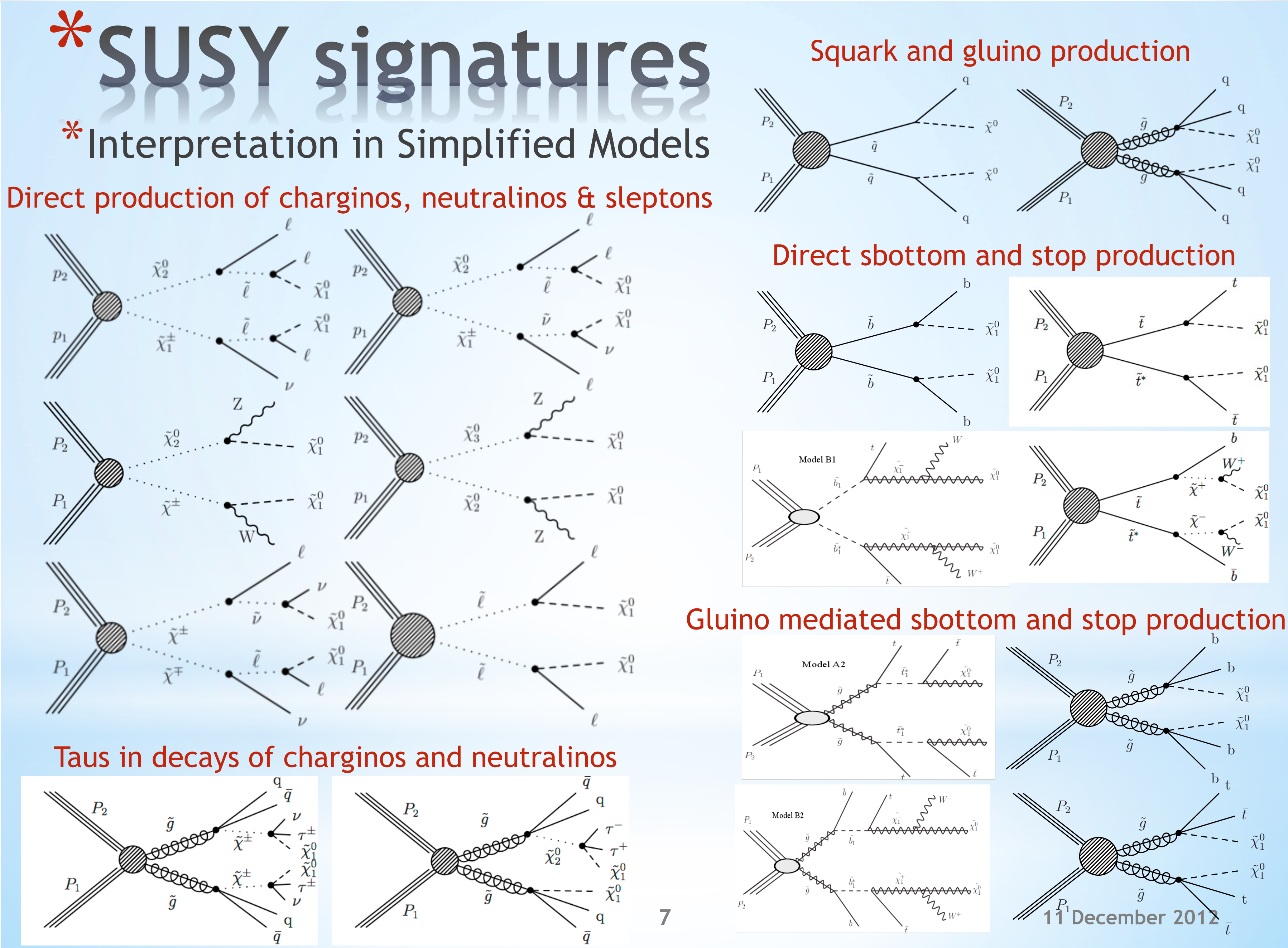
- Not relay on your favorite theorist to define signatures
  - Variety of creative models sometimes with very specific predictions
  - Fine tuning of search potentially counterproductive

- Experimental approach: final states predicted by different models for different corners of parameter space
  - MET + 1 jet
  - MET + > 1 jet
  - MET + 1 lepton
  - MET + 2 lepton
    - same sign
    - opposite sign
  - MET + multi-leptons
  - MET + high pt photon

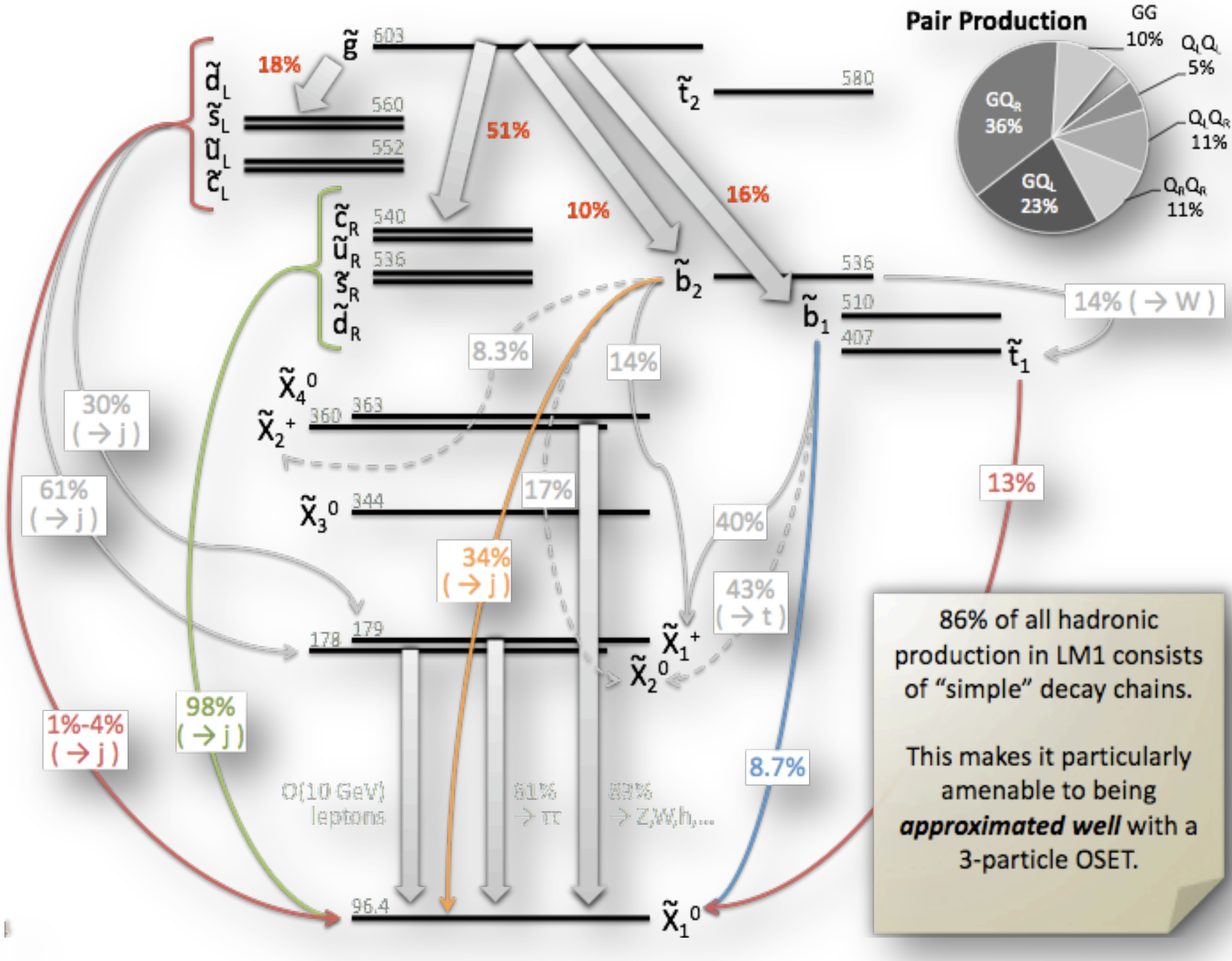


- Model-independent strategy to constrain classes of models

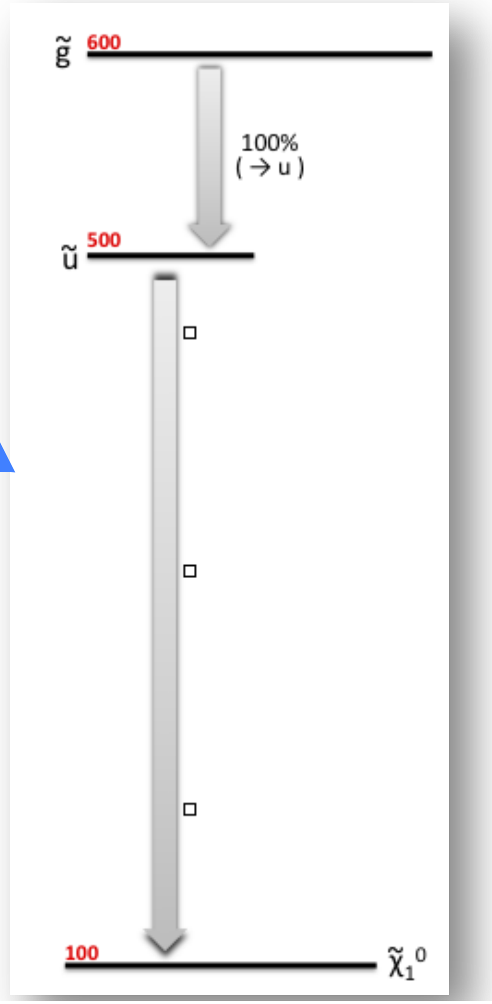
SUSY SIGNATURES



CMSSM



What the individual searches are sensitive to is much more simple…



Simplified model spectrum (SMS)
with 3 particles, 2 decay modes

INTERPRETATION OF SUSY SEARCHES

THE interpretation tool for SUSY searches @ LHC

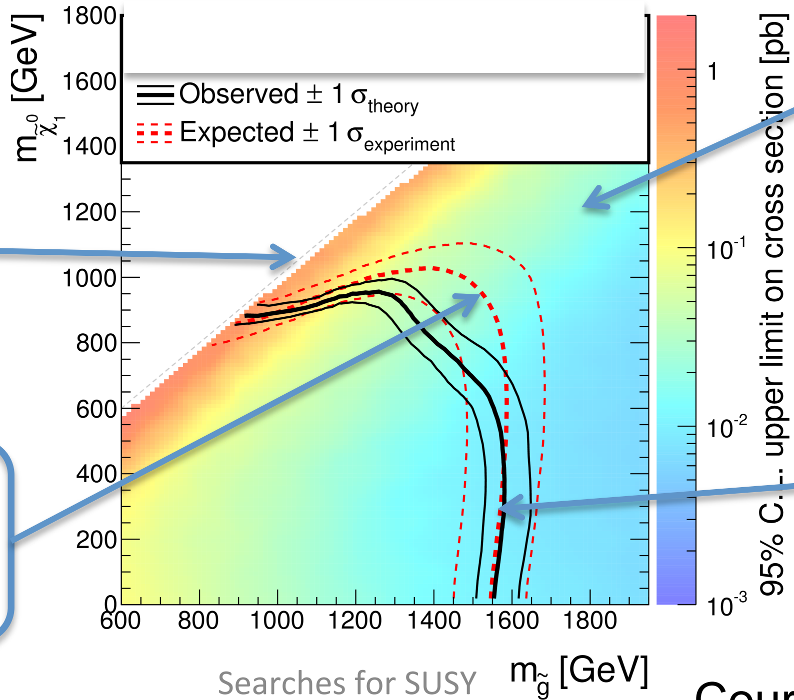
Pros

- closely related to exp. observables
  - understand features
- limited number of parameters
  - results as 2D scans
- "easy" reinterpretation (cross-section limit)

Cons

- no complete model
  - consistency, higher-order corrections?
- application to other (full) models
  - ignores details of production, spin structure, …

A short interpretation guide



Kinematic limit

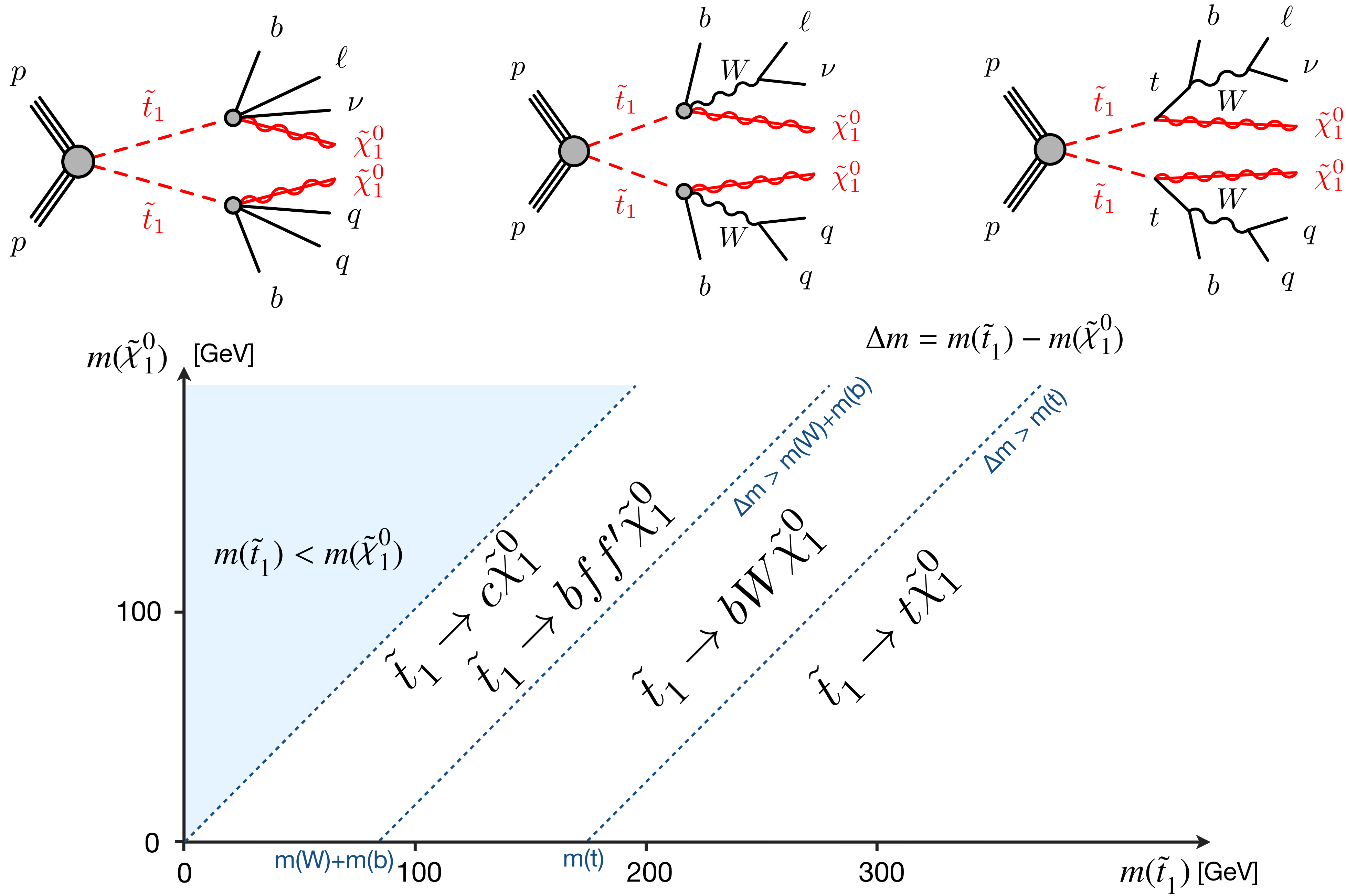
Map of observed cross section limits
- under assumption BR=1

Expected (median) mass limit
- at nominal production cross section
- 1σ variations due to stat+syst

Observed mass limit
- variations correspond to $\pm 1\sigma$ uncertainty on the total production cross section

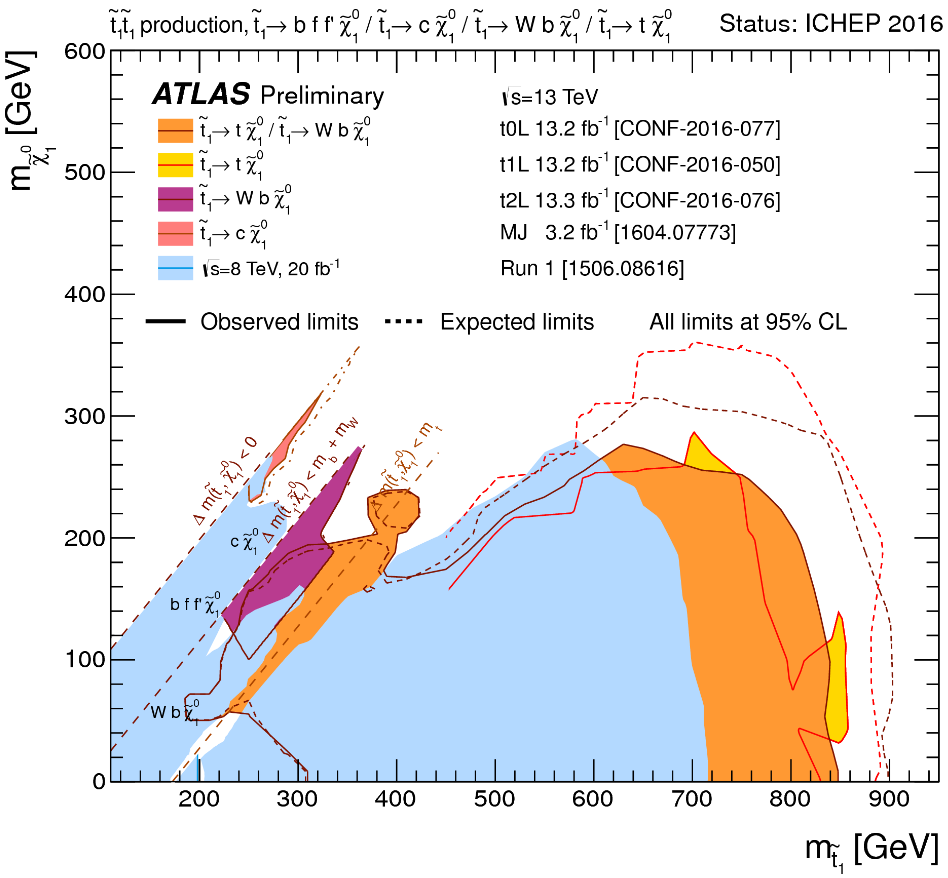
Courtesy of W. Adam ICHEP 2016

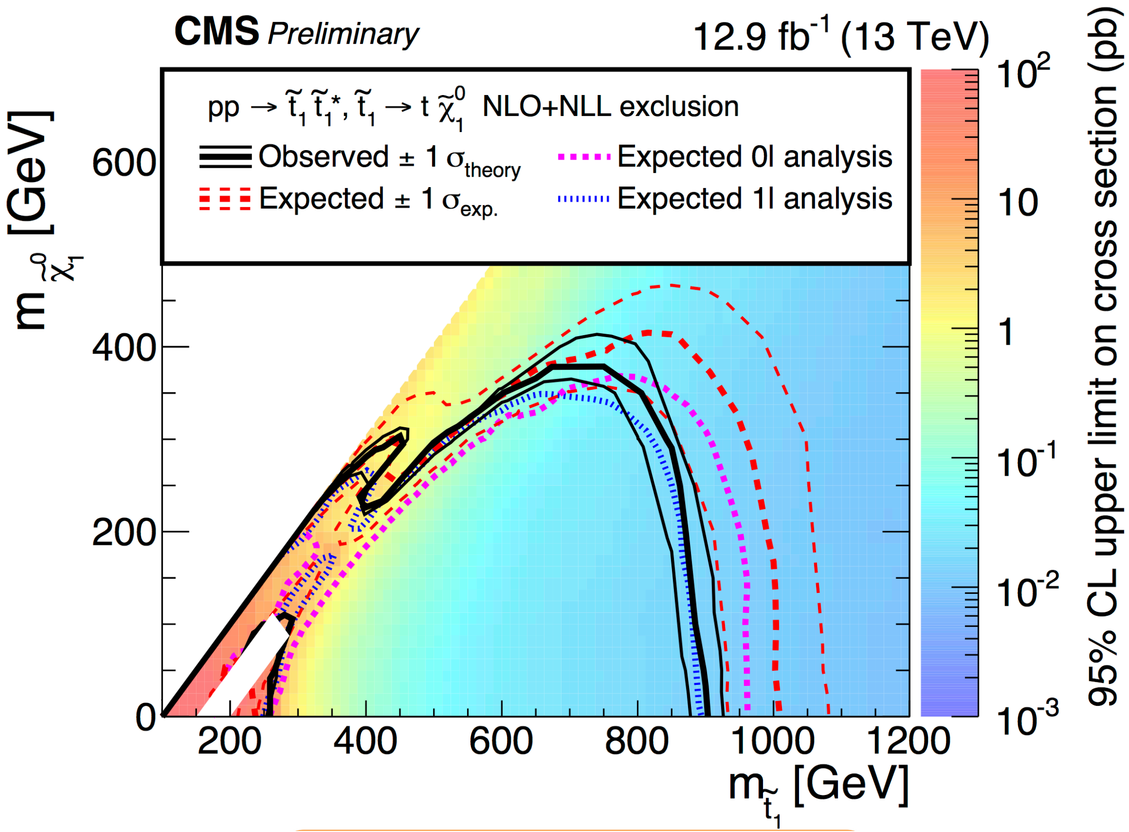
STOP DECAYS



p
p
$\tilde{t}_1$
b
ℓ
ν
q
W
t
$\tilde{\chi}_1^0$
$\Delta m = m(\tilde{t}_1) - m(\tilde{\chi}_1^0)$
$m(\tilde{\chi}_1^0)$ [GeV]
$m(\tilde{t}_1) < m(\tilde{\chi}_1^0)$
$\tilde{t}_1 \to c\tilde{\chi}_1^0$
$\tilde{t}_1 \to bff'\tilde{\chi}_1^0$
$\tilde{t}_1 \to bW\tilde{\chi}_1^0$
$\tilde{t}_1 \to t\tilde{\chi}_1^0$
Δm > m(W)+m(b)
Δm > m(t)
100
0
0
m(W)+m(b)
100
m(t)
200
300
$m(\tilde{t}_1)$ [GeV]

CONSTRAINTS ON STOP





Future Prospects

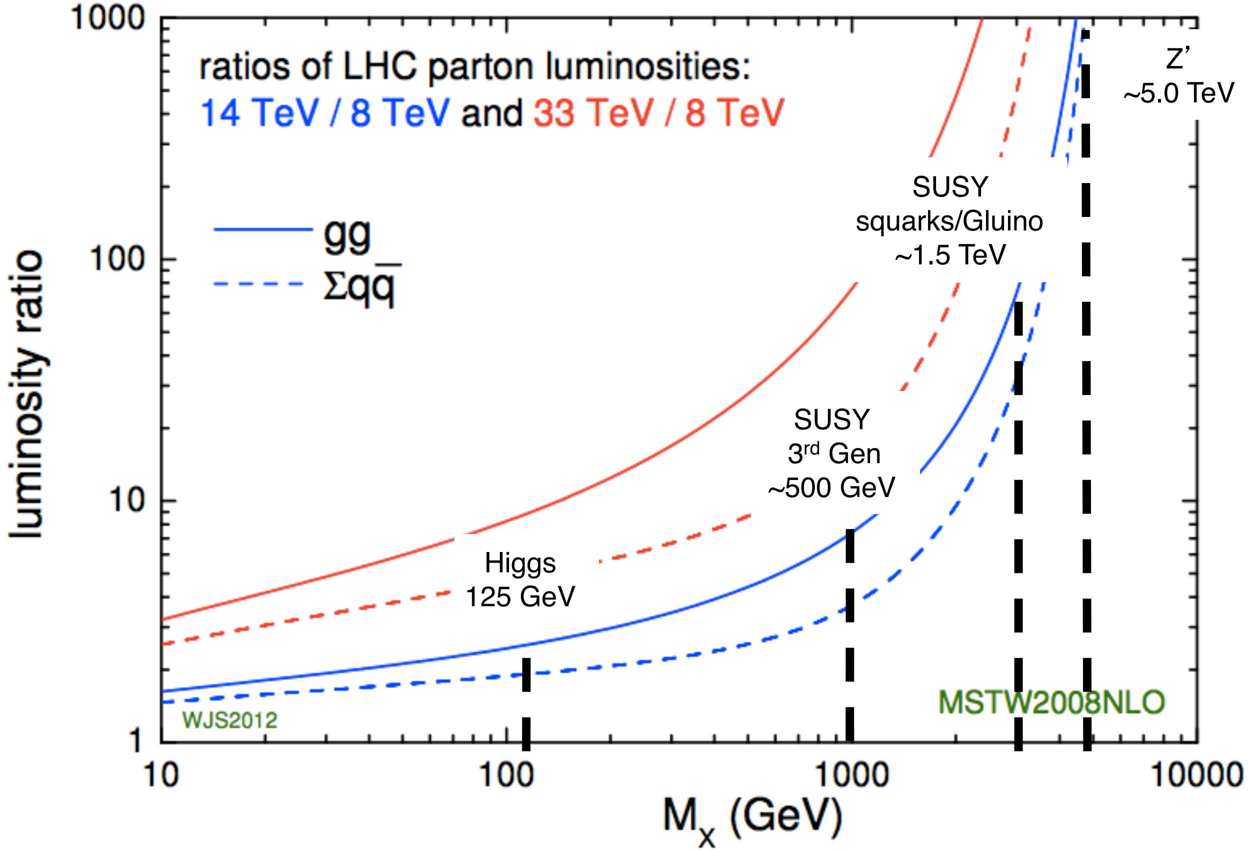
BENEFITS OF HIGHER ENERGY

Higgs:
pp → H, H→WW, ZZ and γγ
mainly gg: factor ~2

SUSY – 3rd Generation:
Mass scale ~ 500 GeV
qq and gg: factor ~3 to 6

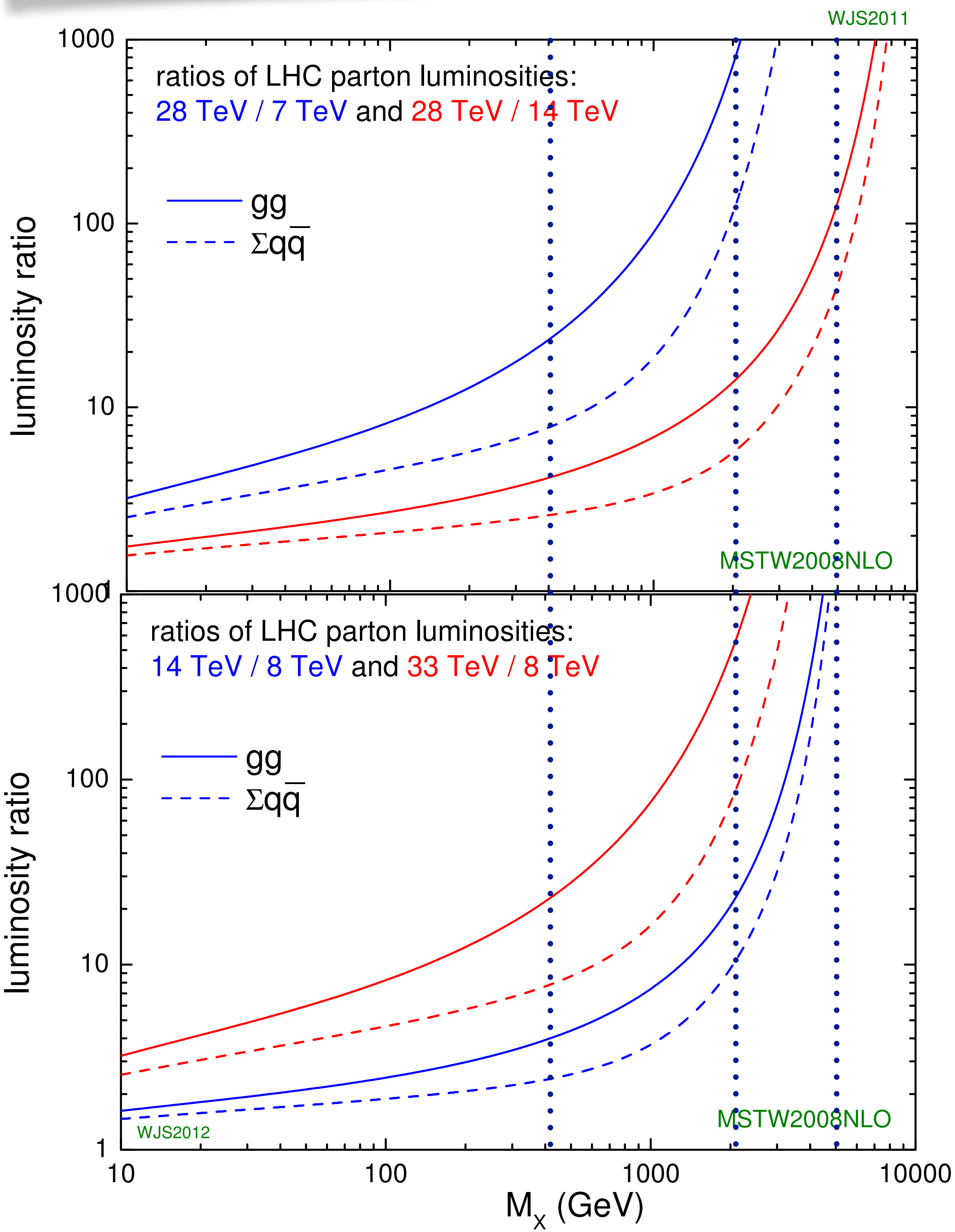
SUSY – Squarks/Gluino:
Mass scale ~ 1.5 TeV
qq,gg,qg: factor ~40 to 80

Z' :
Mass scale ~ 5 TeV
qq: factor ~1000

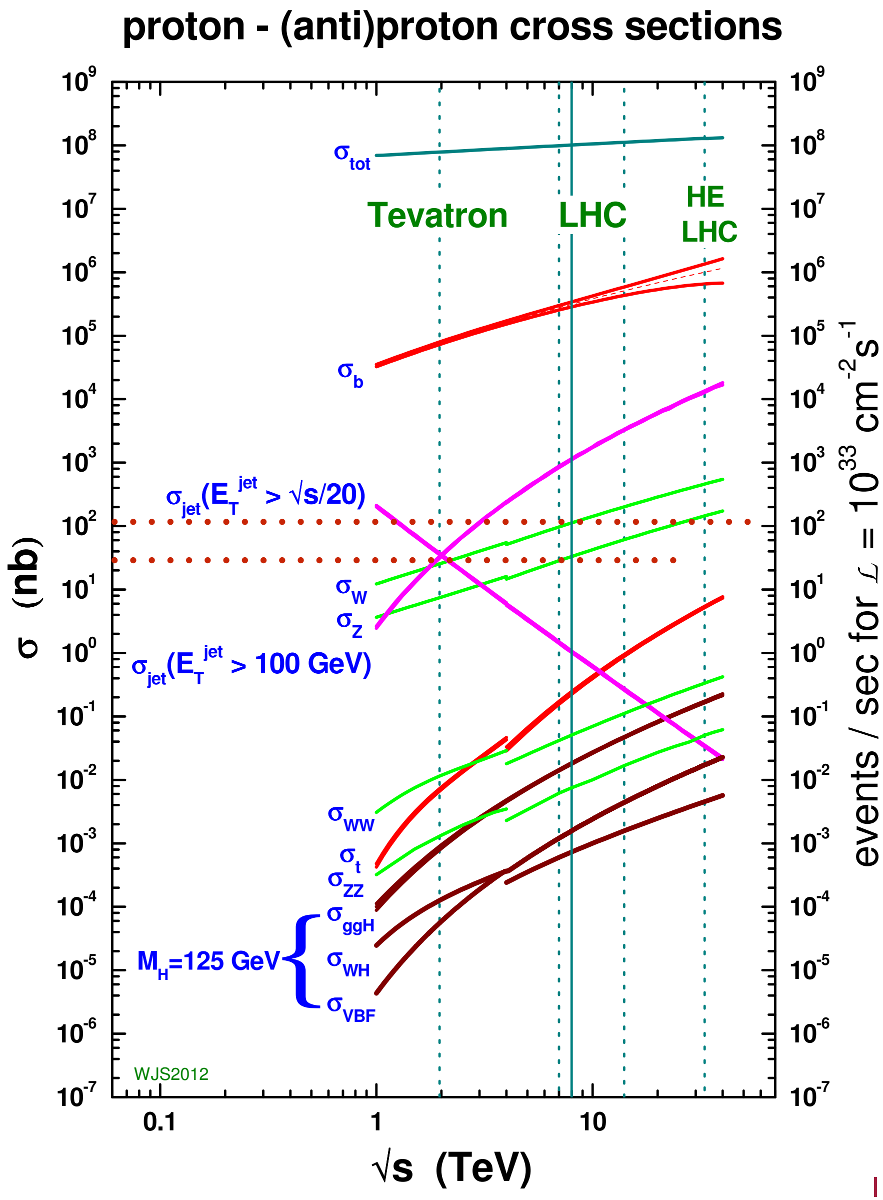


Increase in energy will help a lot!
Not just for SUSY...

IMPORTANCE OF INCREASE IN ENERGY



Even Rare Standard Model processes background for searches



What Have We Learned?

What Have We Learned?

- Largest scientific machine ever built performed beyond expectations
  - First particle discovered in 20 years
- First ever spin-0 elementary particle
- Investigations so far support Standard Model predictions
  - but do not exclude yet new theories at higher energy
- *Relatively small mass of new boson leaves theoretical puzzles to be addressed*
  - Physics at electroweak scale (100 GeV) regulated at Planck scale (10^{19} GeV)

OUTLOOK

Outlook

- Extensive search program just starting to probe new territories beyond Standard Model
  - Only most basic and simplistic theories probed at this point
- New gauge bosons excluded up to ~4 TeV of mass
- New fermions excluded up to ~0.7 TeV of mass
- But these searches assume strong coupling

OUTLOOK

- Extensive search program just starting to probe new territories beyond Standard Model
  - Only most basic and simplistic theories probed at this point
- New gauge bosons excluded up to ~4 TeV of mass
- New fermions excluded up to ~0.7 TeV of mass
- But these searches assume strong coupling
- Probability of producing new particles increased up to 50 times wrt Run 1
- *Exploration of a new territory just begun*

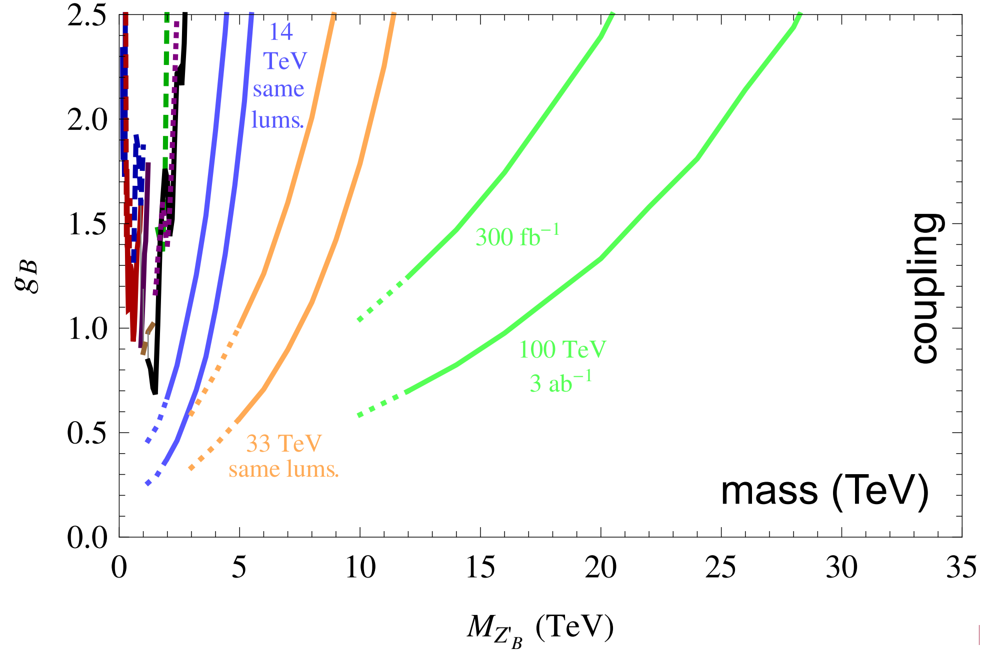
Only Higgs ?

.. also New Exotic Particles

PERSONAL PERSPECTIVE

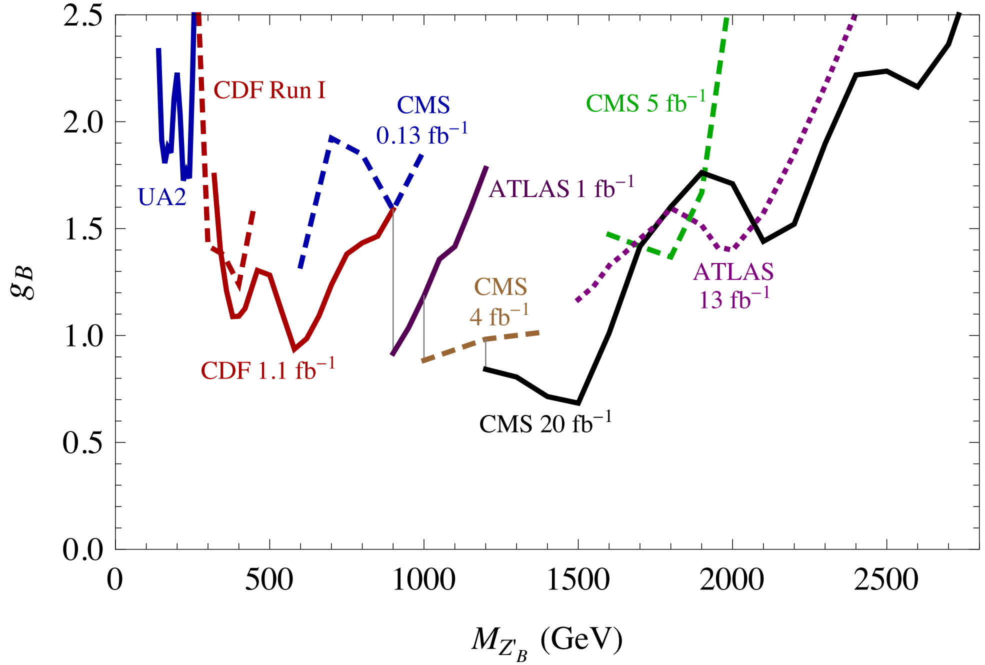
PERSONAL PERSPECTIVE

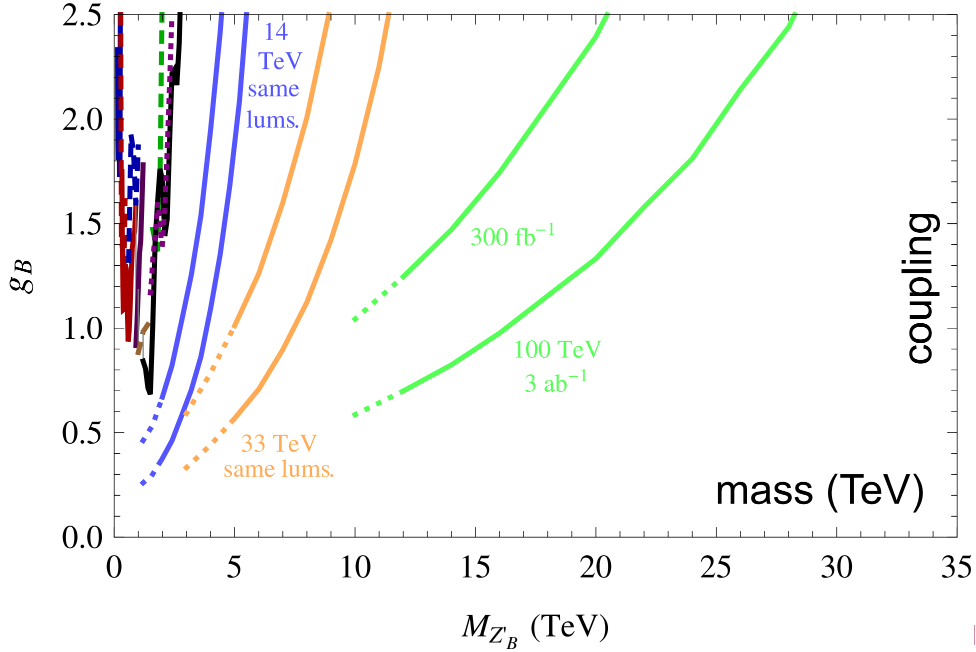
- Next two years critical for future of searches
  - Happy Ending: New particles discovered
    - if mass not too large, accumulate data with high-luminosity LHC to study properties and define next step
    - if heavy, aim at upgrade of energy



Personal Perspective

- Next two years critical for future of searches
  - Happy Ending: New particles discovered
    - if mass not too large, accumulate data with high-luminosity LHC to study properties and define next step
    - if heavy, aim at upgrade of energy
  - No particles found
    - Indirect search through Higgs couplings becomes critical
    - Maybe new particles weakly coupled to known particles
    - Use high-luminosity LHC to probe weakly coupled scenario





PERSONAL PERSPECTIVE

- Next two years critical for future of searches
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- Dark Matter
  - Potential of search at LHC highly dependent on center-of-mass energy
    - Does not require very large data samples
  - Several direct detection experiments underway for large mass candidates
    - Xenon 1T just started. DarkSide (Liquid Argon) 20k underway
  - Interesting and model-independent claim at low mass deserves verification by new experiments

End Lecture 2