

Dark Matter Searches at the FCC(-hh) : An Experimental Overview

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Northwestern University

2nd FCC Physics Workshop
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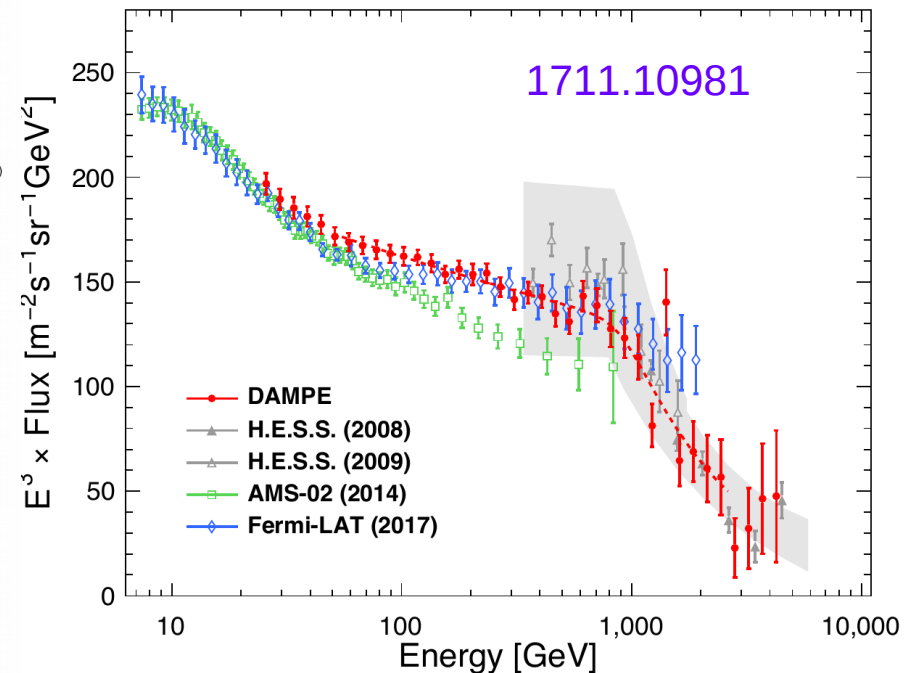
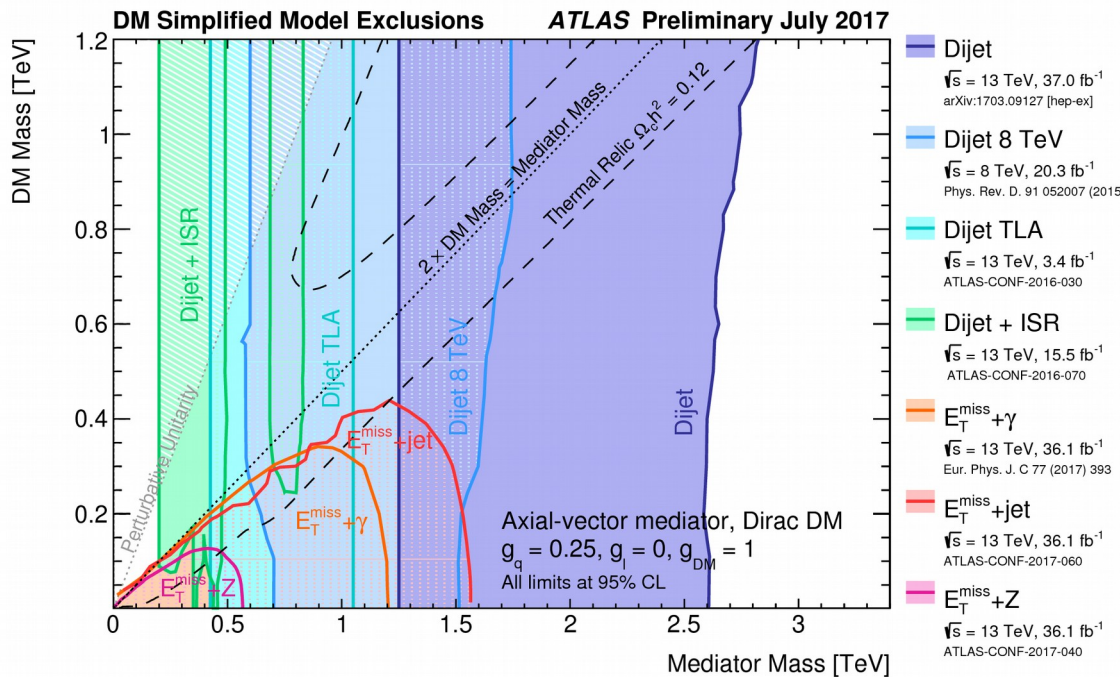
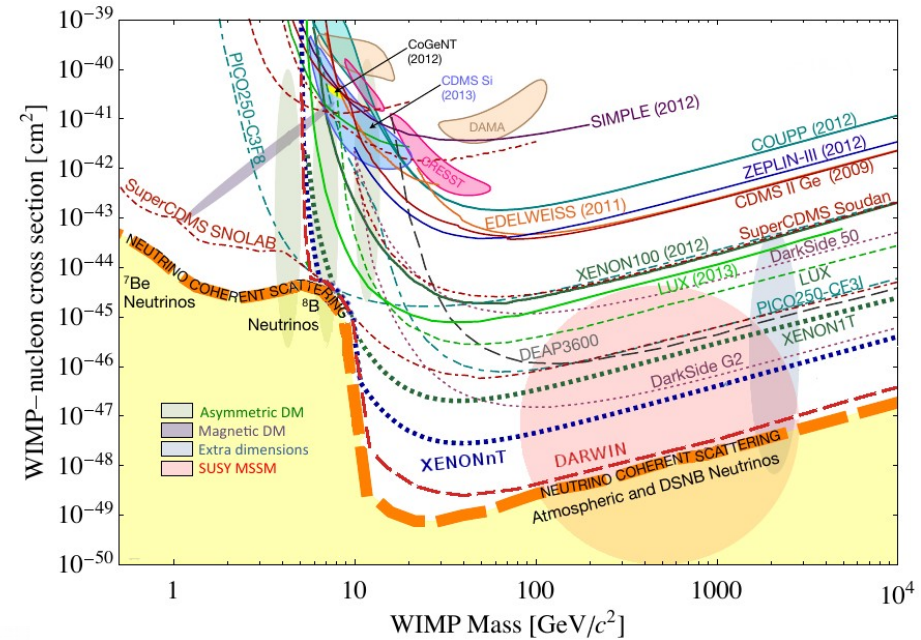


(wimp) DM Today

Direct detection: nearing unprecedented sensitivity

Indirect detection: now probing TeV-scale DM

Collider: mature & multifaceted DM search programs

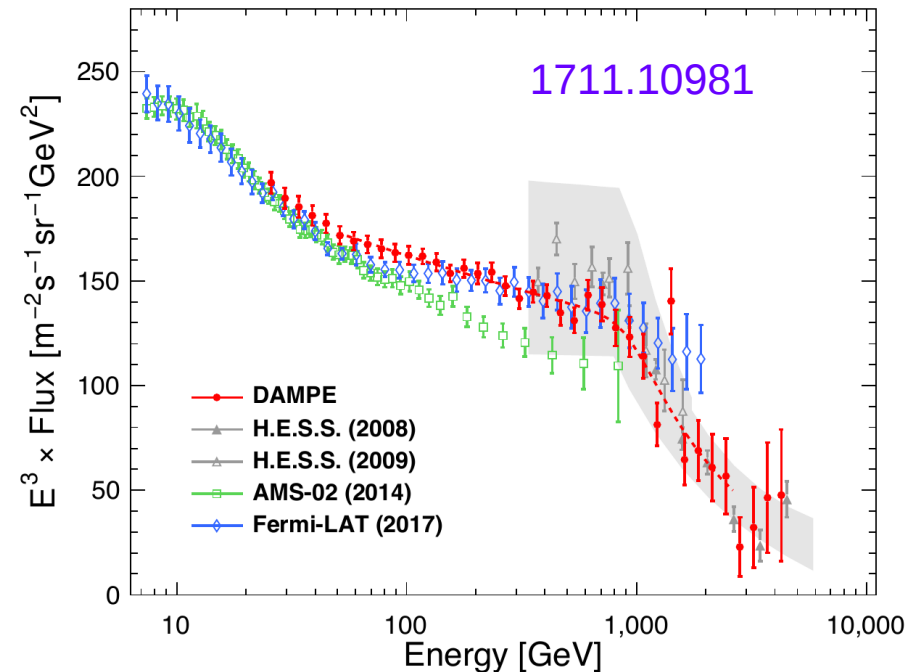
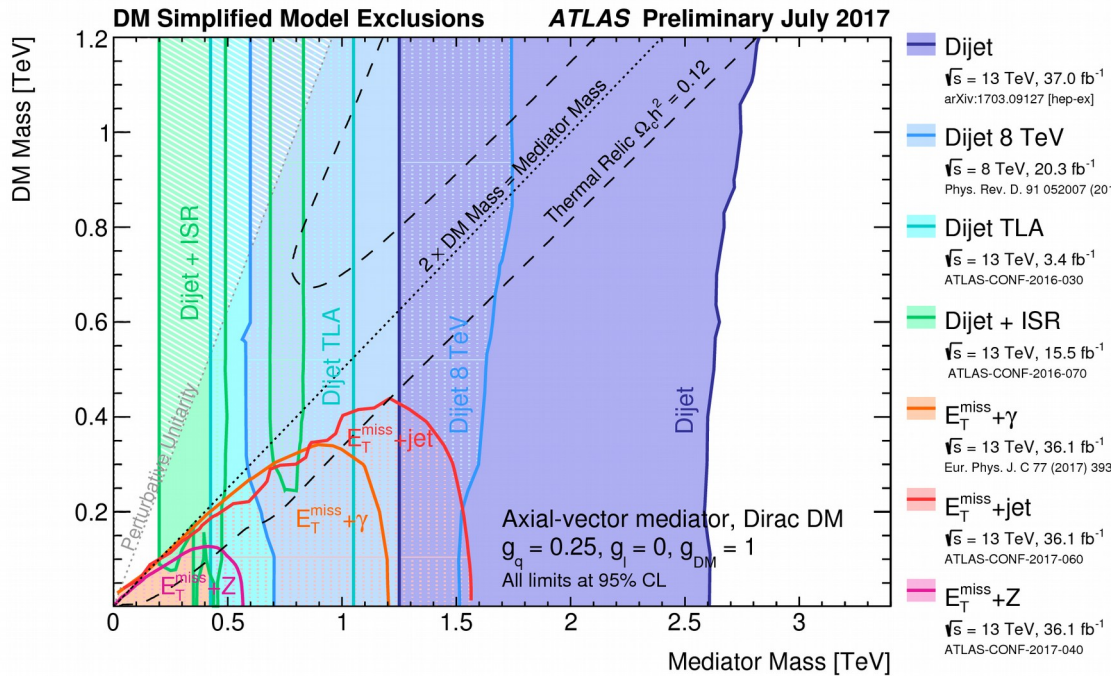
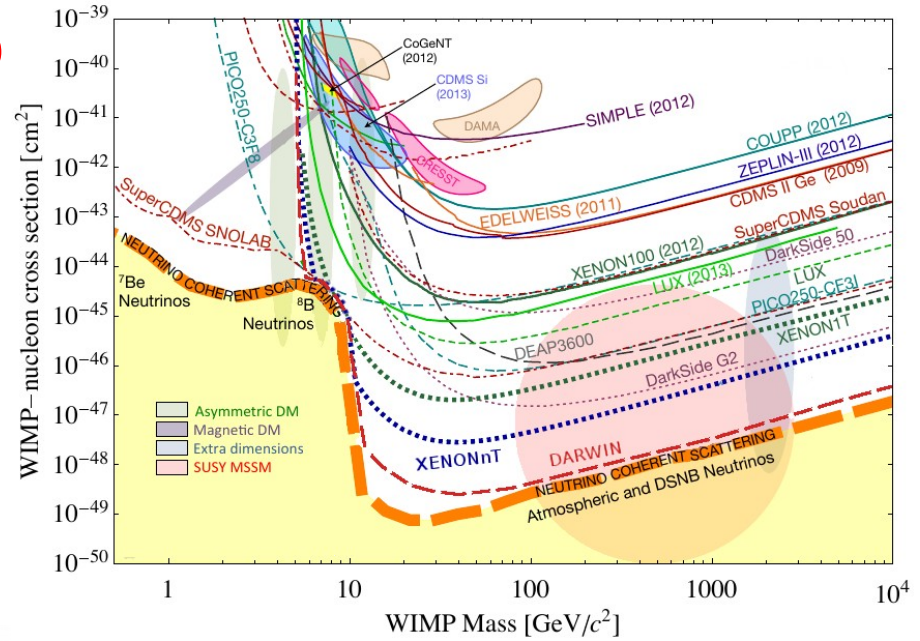


(wimp) DM Today

Direct detection: approaching neutrino floor, sensitivity limitations nigh?

Indirect detection: persistent & difficult to quantify astro uncertainties ...

Collider: DM & mediator mass reach beginning to plateau



Collider Dark Matter

Complementarity *crucial* for an unambiguous DM discovery

For colliders to continue to aid the effort, we must:

- Extend mass reach, cover the TeV-scale
- Push lower in cross section, gain sensitivity to rare processes
- Capitalize on detector advances, support a rich exp program

➡ Need future collider program to continue DM dialogue!

LHC program provides perspective for FCC DM searches

- Traditional MET-based searches
- More complex signatures searches

Focus of this talk : what can the next generation of DM collider searches learn from the LHC DM effort (& LHC-inspired studies)?



MET + X

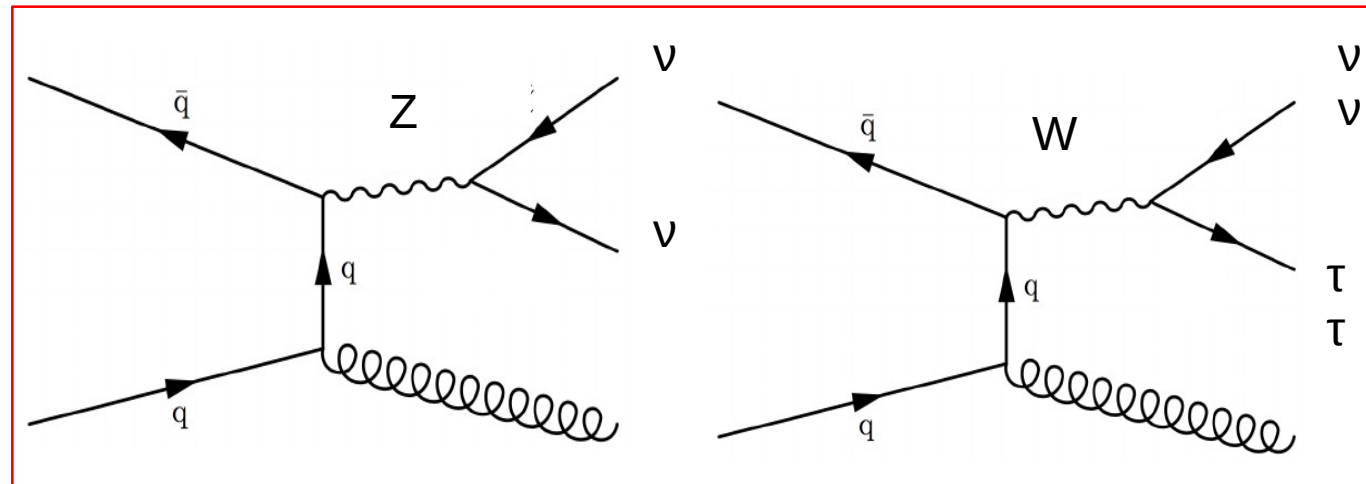
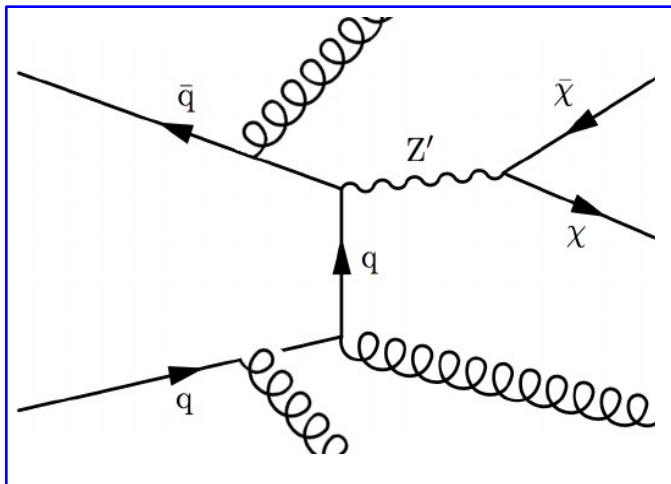
Focus of much of Run-2 experimental DM program

Select large pT_{miss} & prompt, reconstructed objects:

- $X = \text{jets, leptons, photons, heavy flavor, Higgs}$

Most general MET+X final state : monojet

- Assumes only that DM couples to quarks
- These days: multijet+MET, boosted category for mono-hadronic W/Z
- Primary background from MET tails of **SM $Z \rightarrow \nu\nu, W \rightarrow \nu\tau$**



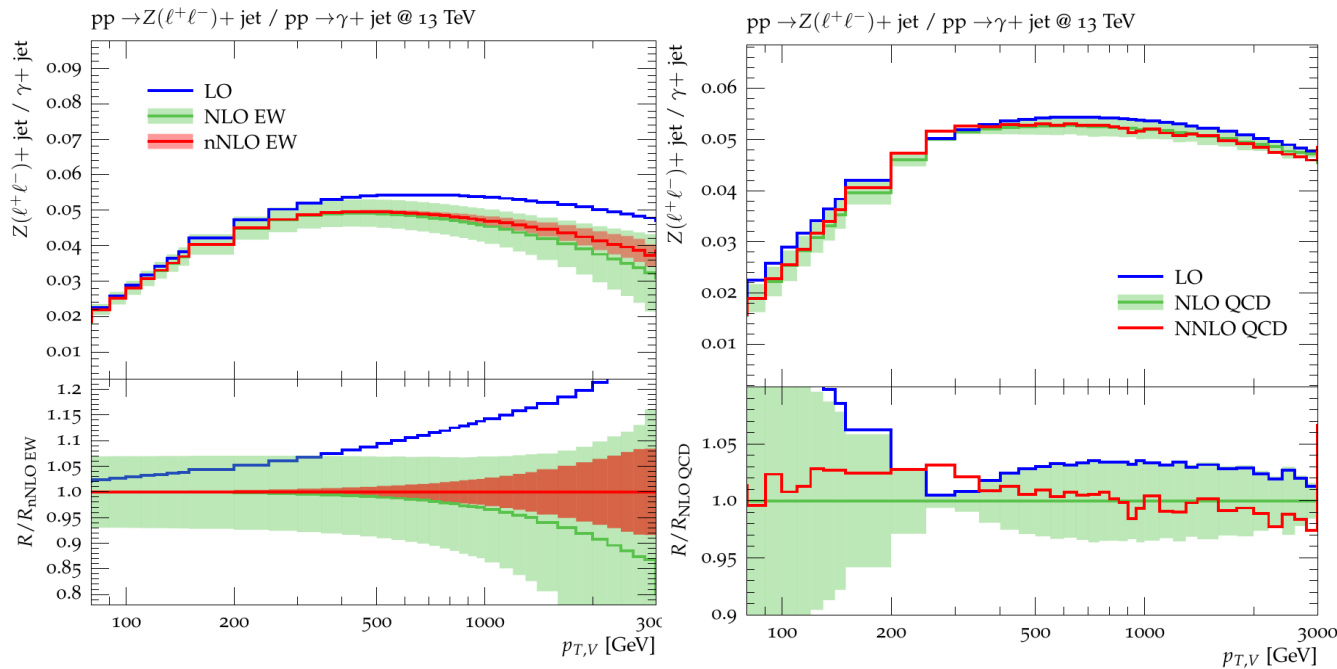
Monojet

Self-calibrating via simultaneous fit of signal & control regions

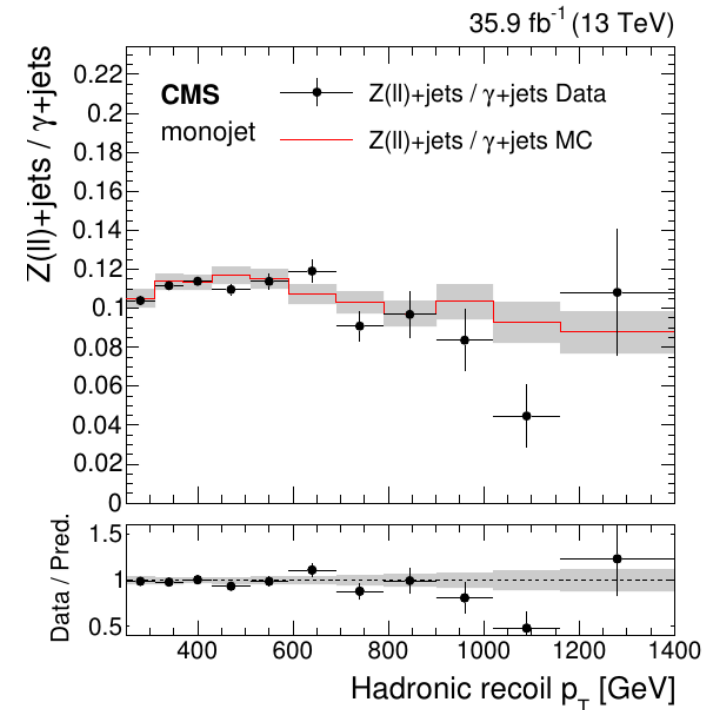
- Signal: high-MET, min $\Delta R(\text{jet}, \text{MET})$ to avoid instrumental backgrounds
- Control: leptonic W/Z, high-stat γ +jet

Relies on precision QCD+EWK predictions for SM bkg, sophisticated treatment of uncertainties, constrained via the fit

- Scheme ensures that search is always statistically limited ($\sim 1\%$ syst.)



1705.04664 : J. Lindert, et al



1712.02345

Monojet

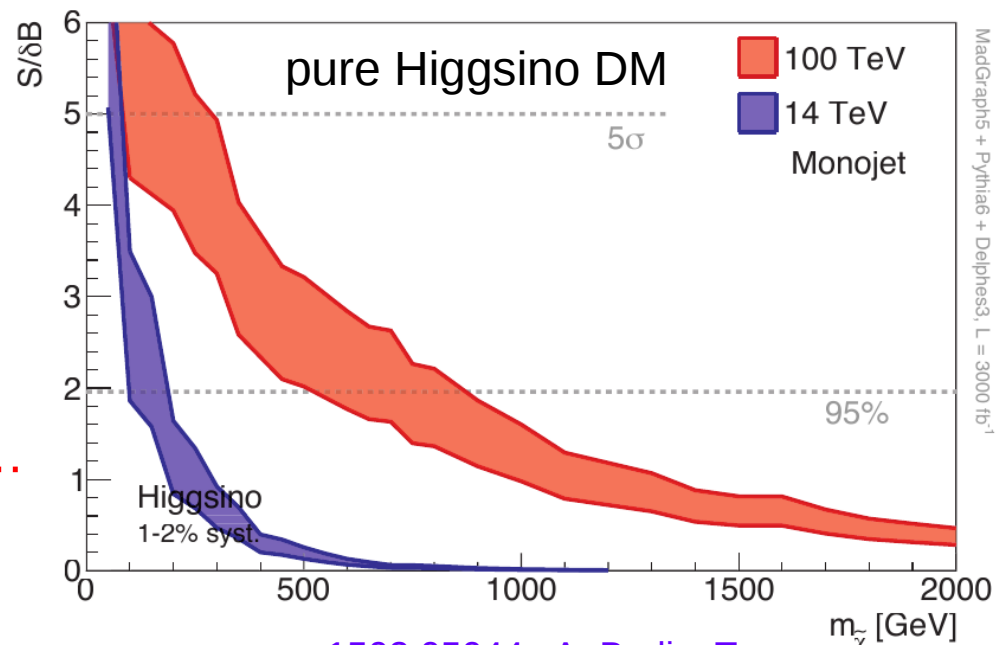
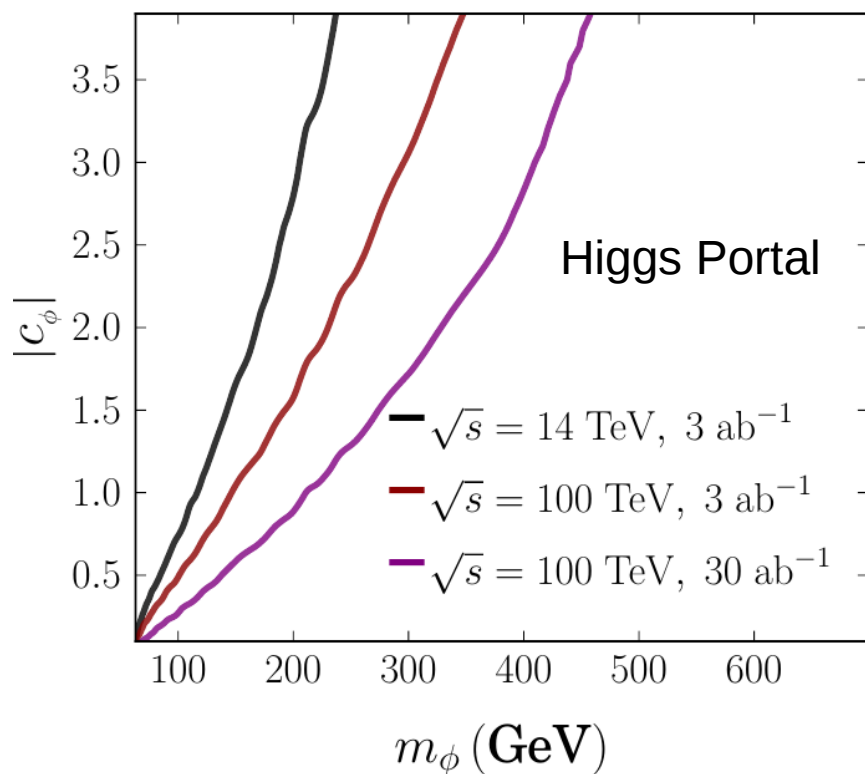
Probes a rich set of DM models

- SM mediators: Higgsino/Wino/Bino DM, Higgs portal ...

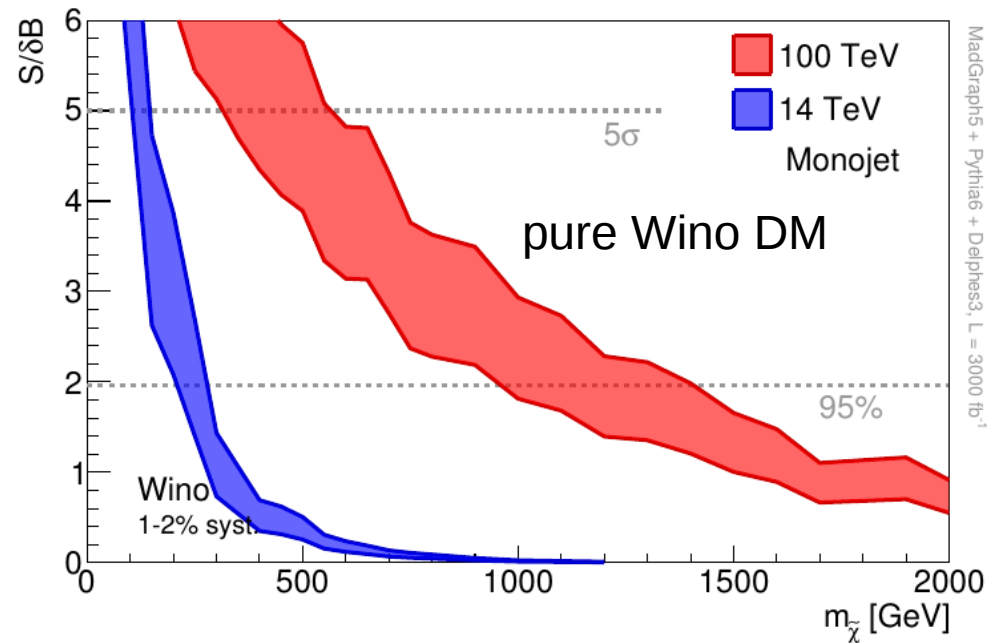
Mass reach and coupling sensitivity significantly improve @ FCC!

- Assuming bkg precision kept at %-level ...

1412.0258: N. Craig, H. K. Lou, M. McCullough, A. Thalapillild
95% Combined Exclusion



1502.05044 : A. Berlin, T. Lin, M. Low, L-T Wang



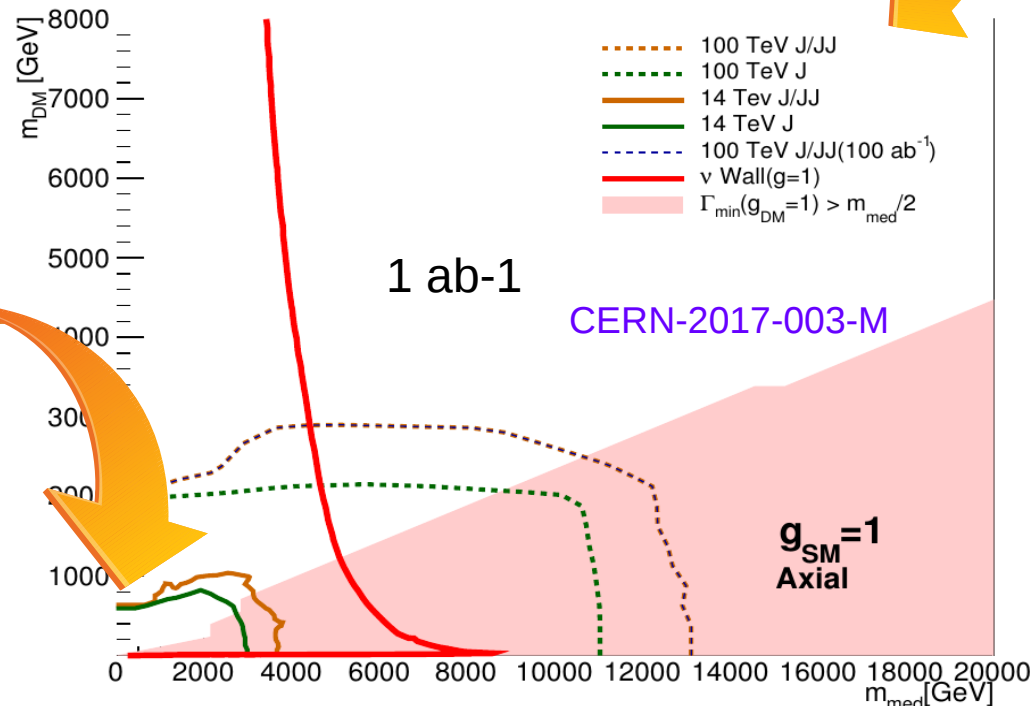
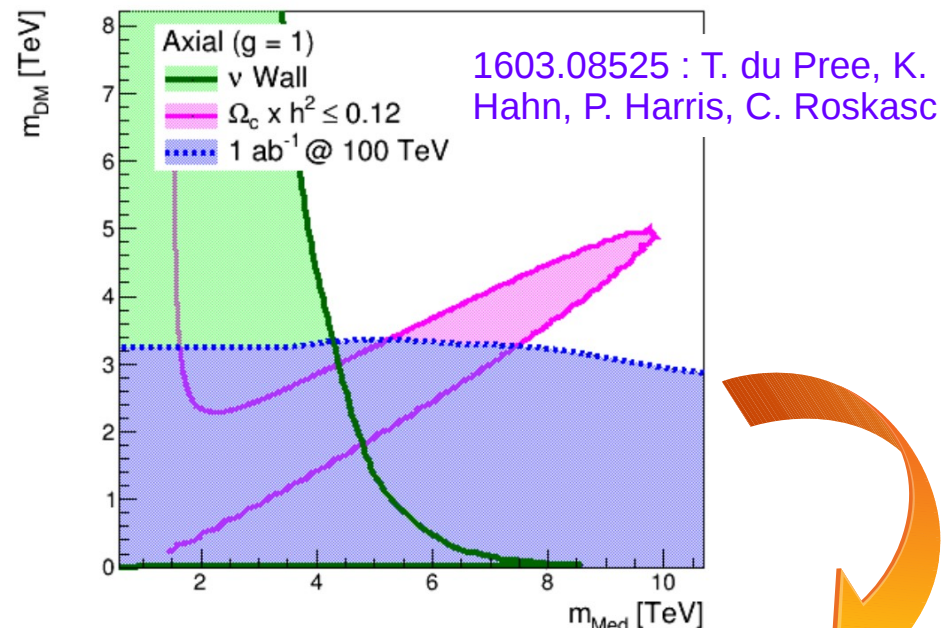
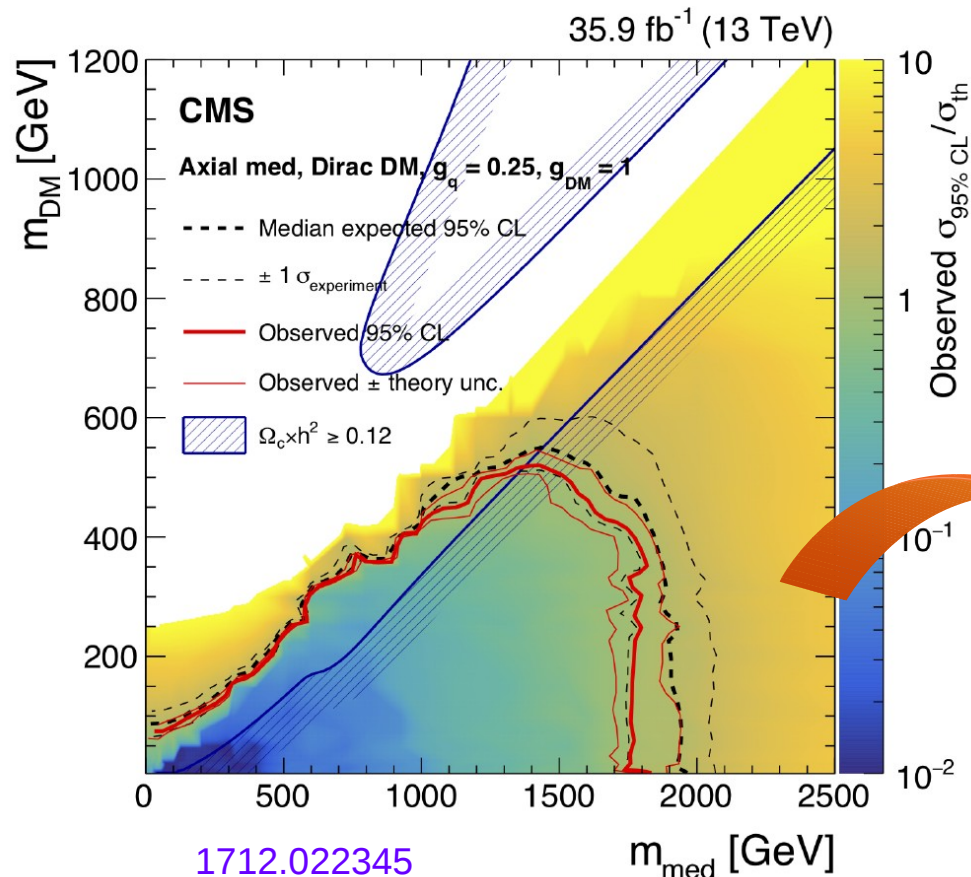
Monojet

New BSM mediators

- Vector/Axial-Vector, Scalar/Pseudoscalar
- Cf. simplified DM models (1507.00966)

FCC can probe large regions of parameter space inaccessible to DD/ID

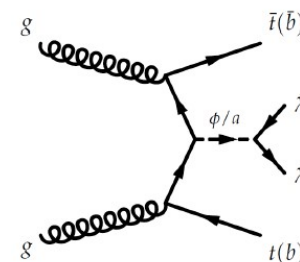
- Assuming bkg precision kept at %-level ...



Beyond Monojet: MET+X

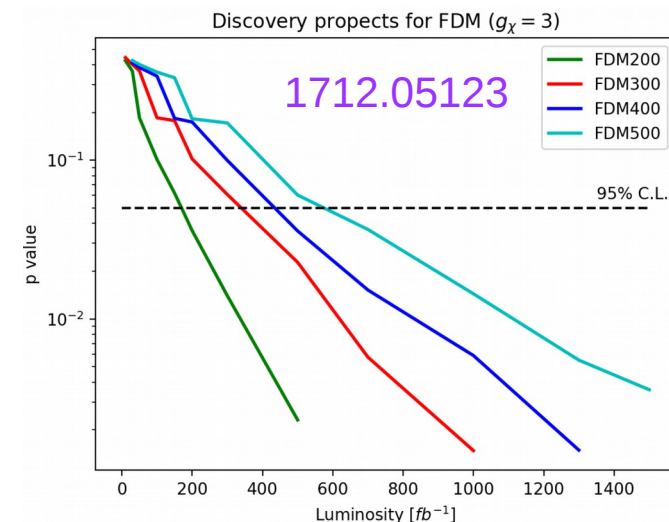
Other channels probe regions less accessible for monojet

- Eg: $tt + DM \rightarrow$ low-mass spin-0 mediators
- Backgrounds (SM tt , single- t , ttV) will eventually require
- monojet-level precision



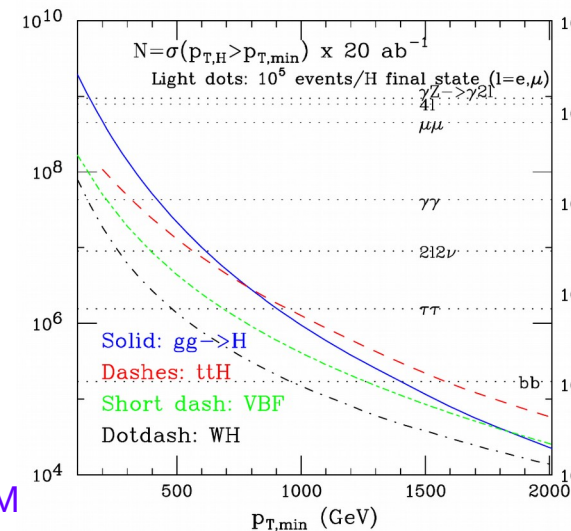
FCC studies of tt for Higgs portal underway ...

- tt dilepton : (1712.05123) B. Dutta, T. Kamon, P. Ko, J. Li
- tt all-channels : (in-progress) K. Hahn, P. Harris, MLM



Updates from the latter?

- CMS $tt+DM$ search (1706.02581) reimplemented as an FCC delphes analysis
- 13 TeV delphes analysis validated (to $\sim 10\%$) against public CMS results
- Finishing MC generation for 100 TeV
- Exploring boosted extensions relevant for FCC



CERN-2017-003-M

Beyond Monojet: MET+X

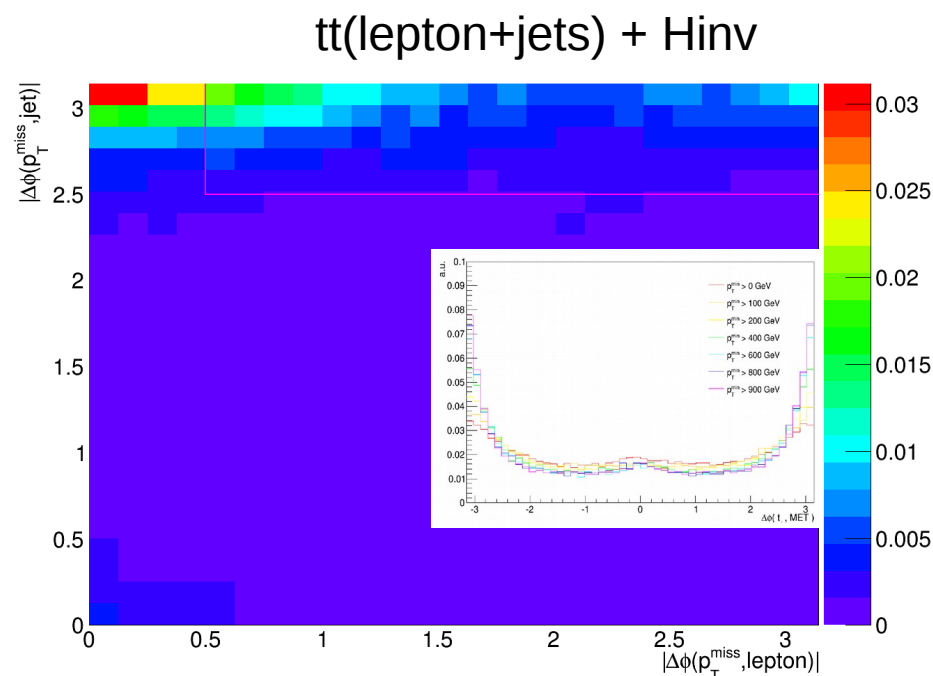
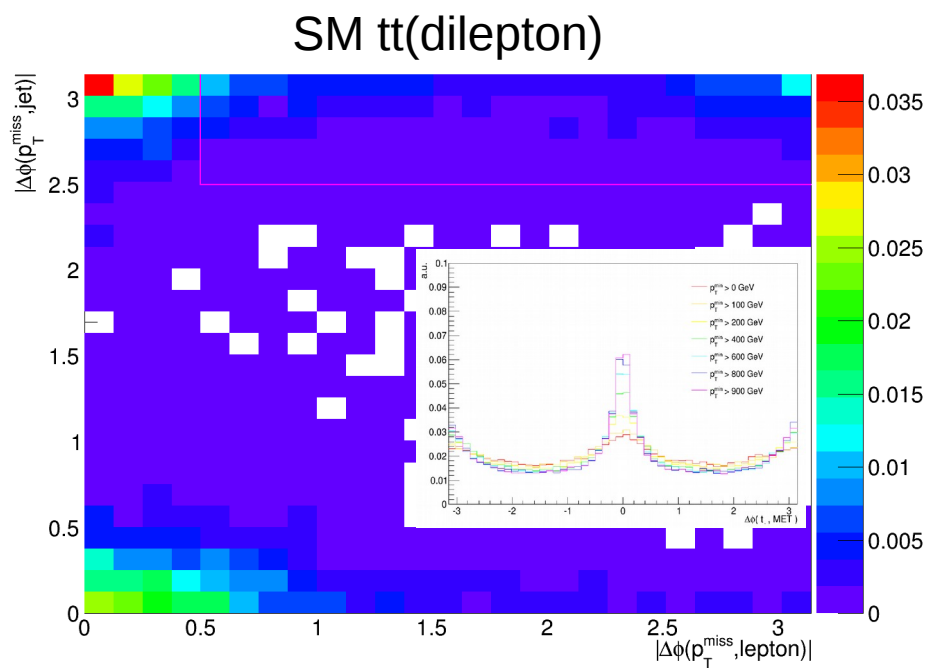
Main background from SM channels with one less lepton

- Eg: dilepton a background in lepton+jets signal region if 2nd lepton is lost
- In 1706.02581, tt background suppressed by tagging hadronic tops
 - At LHC jets from hadronic tops are *resolved* for accessible signals

At FCC, *boosted* top tagging could improve signal purity at large $p_T(H)$

- Large $\Delta\Phi(\text{MET}, \text{jet})$ & $\Delta\Phi(\text{MET}, \text{lepton})$ → tops recoiling against the Higgs

In-preparation : K. Hahn, P. Harris, MLM

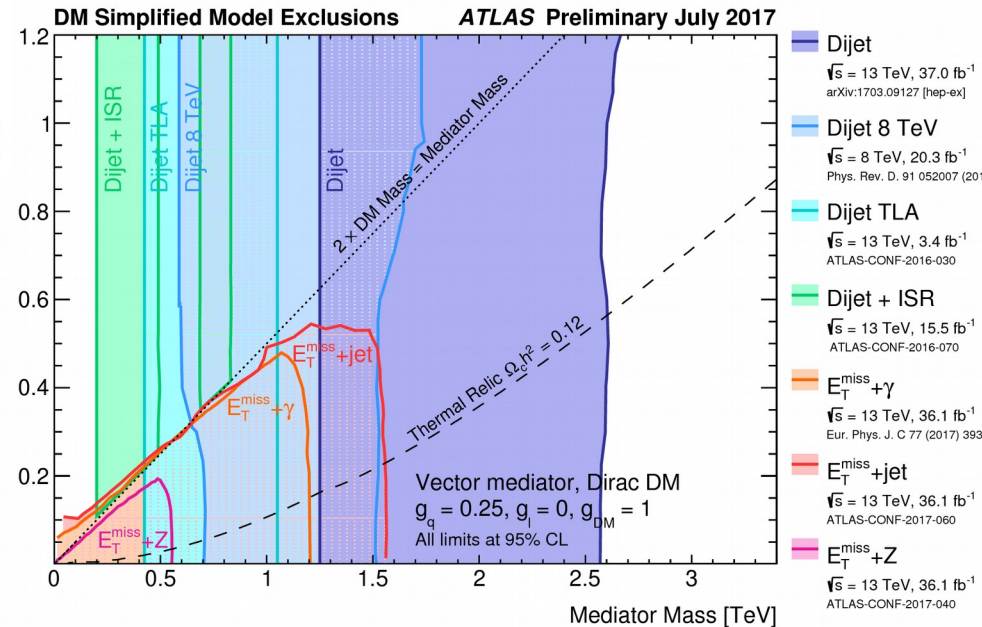
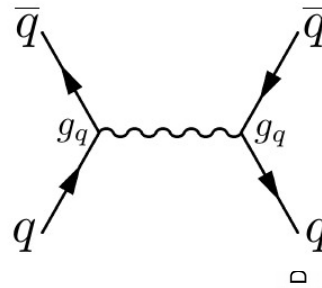


Beyond Monojet : Mediator Searches

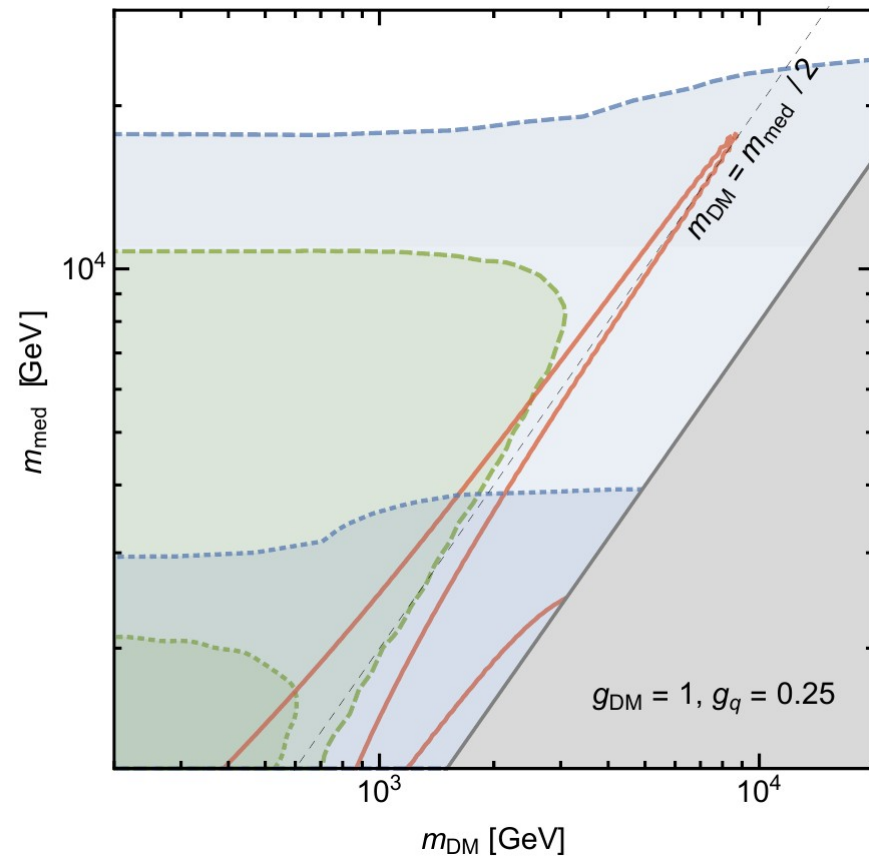
Via bump hunts in dijet, diphoton, etc. spectra

Special triggering & analysis techniques needed at low mediator mass

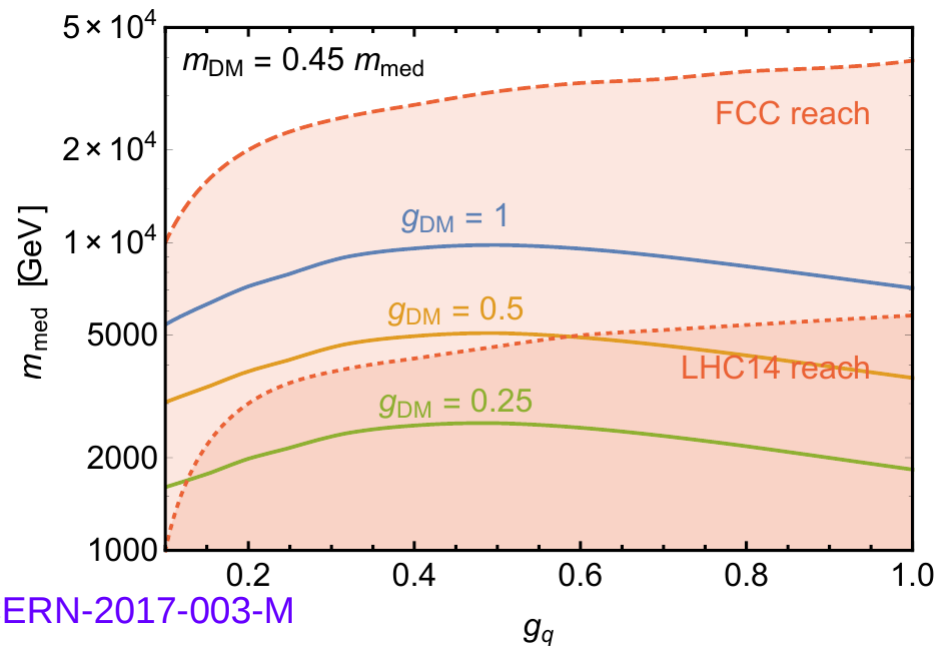
- TLA, scouting, substructure ...



CERN-2017-003-M



CERN-2017-003-M





LHC already roughly probing TeV-scale, no sign of DM ...

Need to look beyond the simple MET-X topology

1510.03460 : J. Bramante, P.J. Fox, A. Martin, B. Ostdiek, T. Plehn, T. Schell, M. Takeuchi

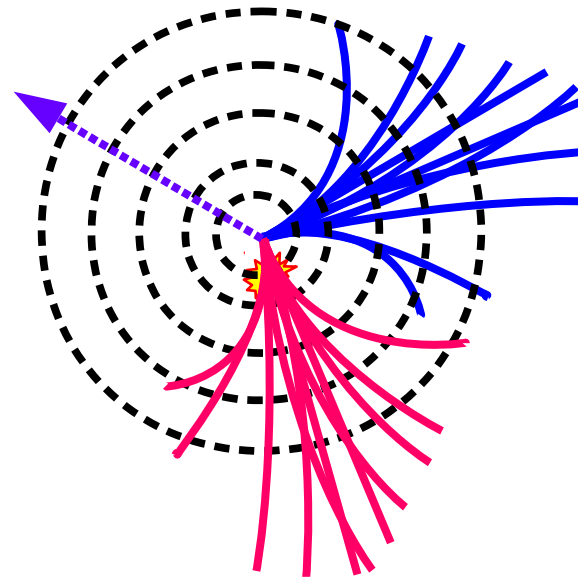
- Eg: access to bino-wino via soft leptons & photons

In many theories, DM connected with long-lived New Physics, eg:

- Simple models : SUSY-ish extra EWK multiplets, SM mediators
- ADM, SIDM, Dark Sectors, Dark Photons, Neutral Naturalness ...

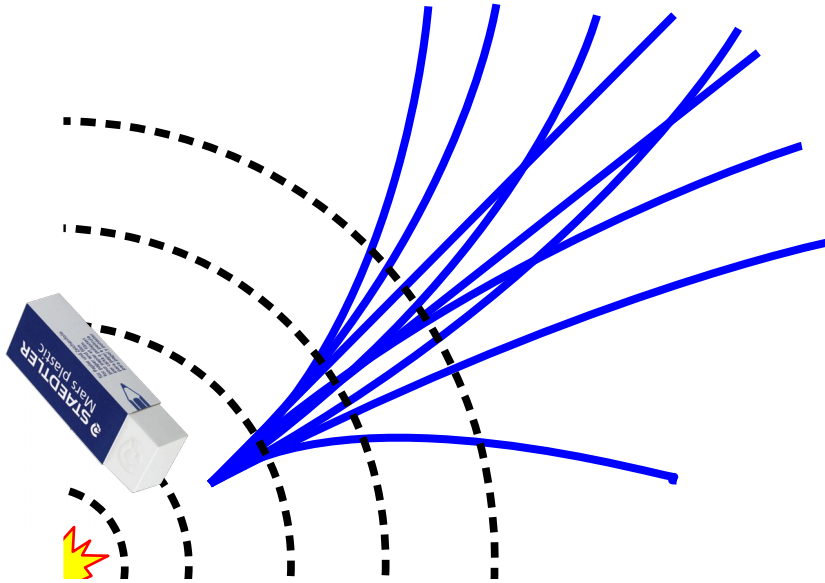
Additional signatures are powerful, but experimentally challenging

- Disappearing tracks
- Displaced vertices
- “Emerging jets”
- Semi-visible jets
- ...



Such searches stretch capabilities of present-day tracking & triggering!

Displaced Objects + MET



DM produced together with neutral long-lived particles decaying back to SM

NLLPs can be, for eg:

- New scalars that mix with Higgs
- Glueballs (Twin Higgs) decaying to hadrons
- ν -hadrons from Hidden Valley decaying to hadronic or leptonic jets
- ...

Extend typical MET+X searches, capitalize on this distinctive signature

- A topic of recent experimental interest, eg :

Discussions at LHC DMWG, <https://indico.cern.ch/event/682235/>

Some experimental differences wrt traditional MET+X searches

- Energy sharing in secondary decays \rightarrow MET selection less effective
- $\min \Delta R(\text{jet}, \text{MET})$ can hurt for some mass splittings
- Displaced jets can fail various b-vetos

Displaced Objects + MET

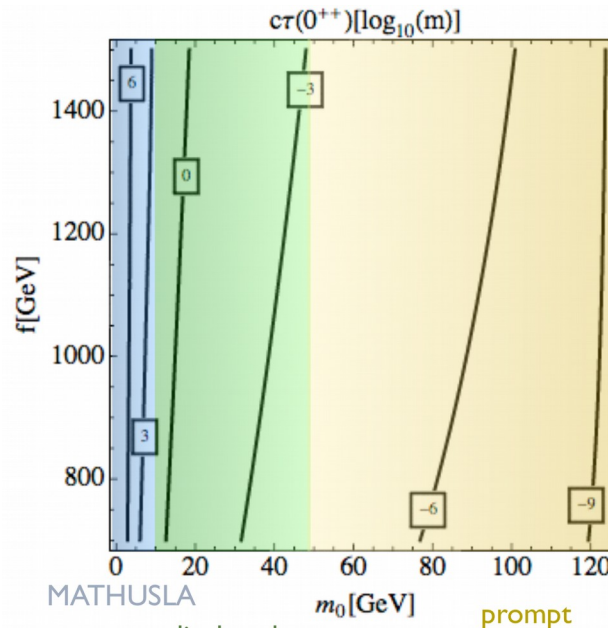
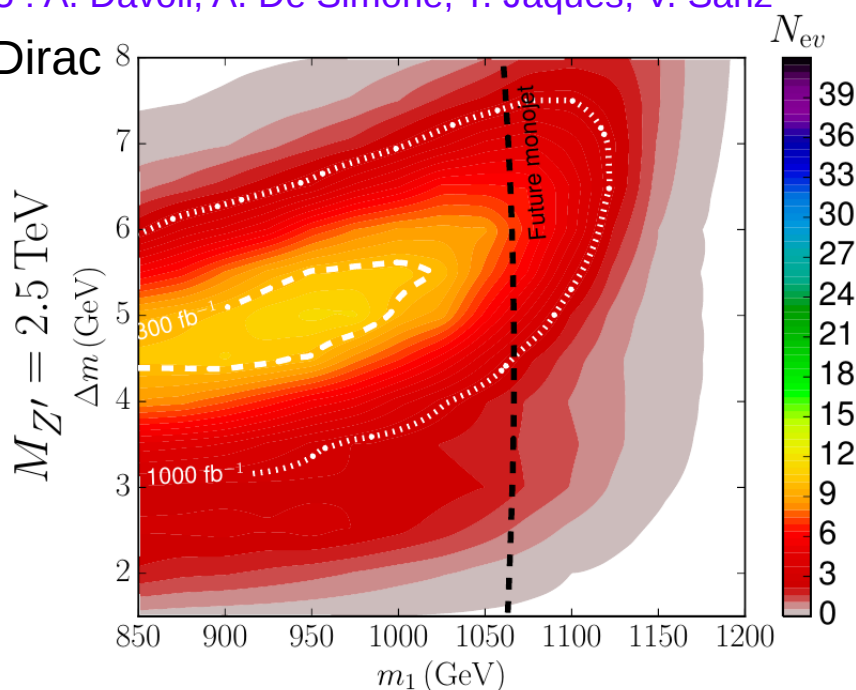
Many DM models give displaced (visible) + MET signatures at LHC & FCC

Experimental efforts using (extended) simplified models in development ...

- Simple recasts of MET+X searches
- Dedicated MET + displacedX analyses

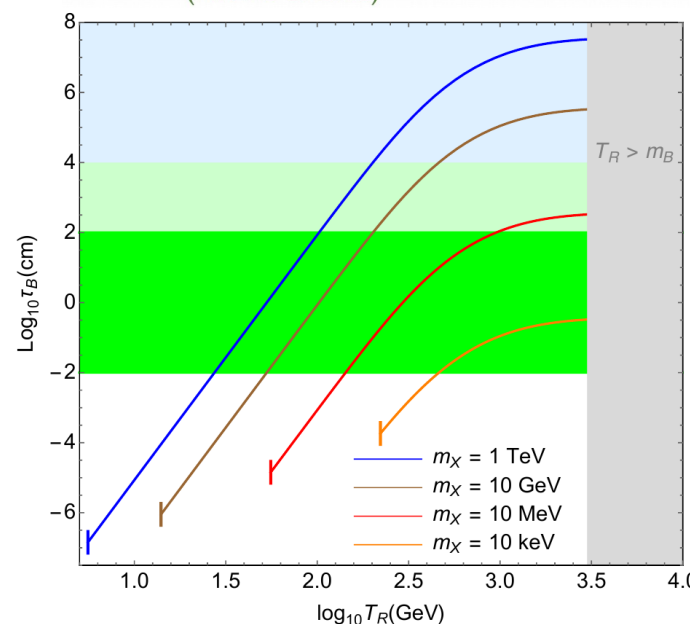
1706.08985 : A. Davoli, A. De Simone, T. Jaques, V. Sanz

PseudoDirac DM



1501.05310:
N. Craig,
A. Katz,
M. Strassler,
R. Sundrum

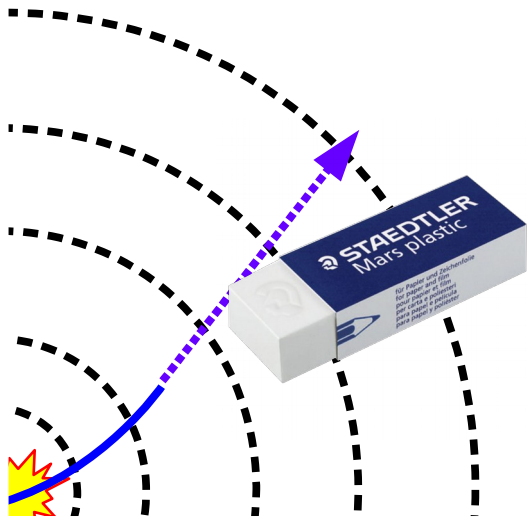
Glueballs



1506.07532 :
R. Co,
F. D'Eramo,
L. Hall,
D. Pappadopulo

FIMPs

Disappearing Track



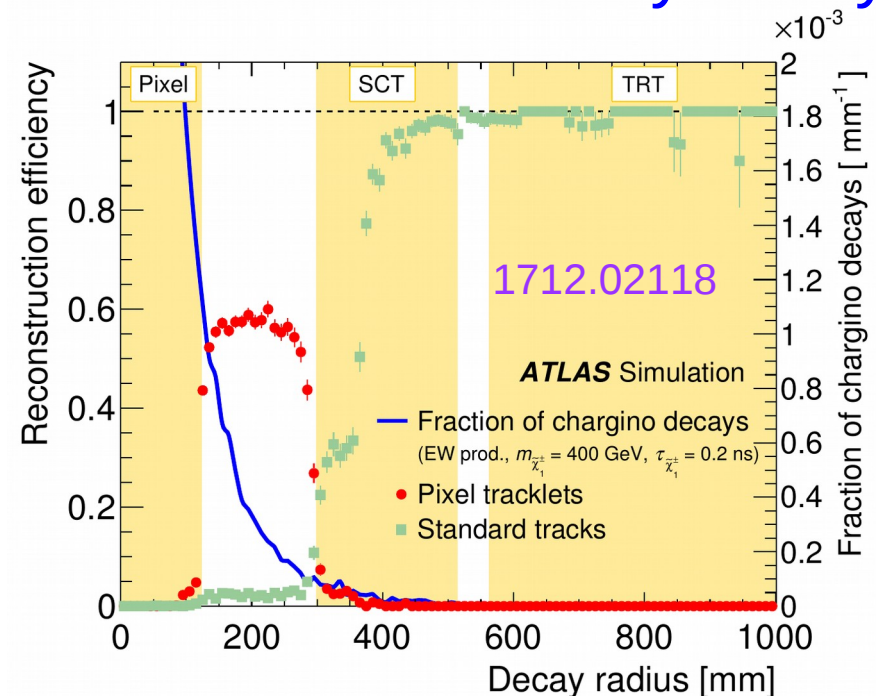
Charged particles with significant lifetimes decaying to DM (sometimes + soft 'X')

These appear in, for eg:

- Compressed “SUSY”, EWKino-DM
- Models w/ long-lived coannihilation partners

Present exp. strategies target large MET from secondary decay

- Backgrounds from multiple-scattering, brems, combinatorics
- **No current capabilities for triggering on short tracks**
- Even if selected by trigger, short track reconstruction is challenging



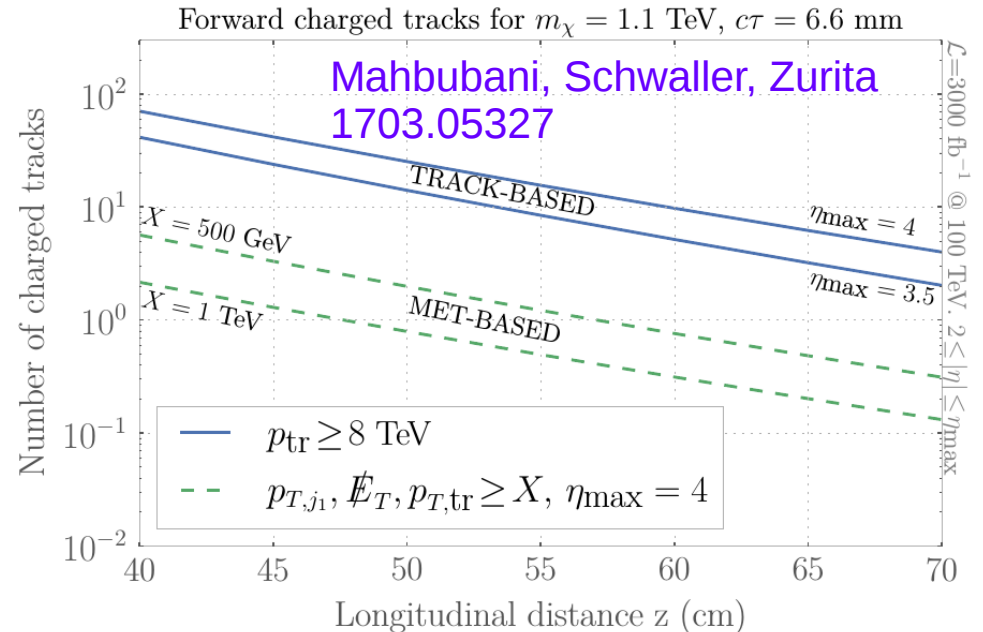
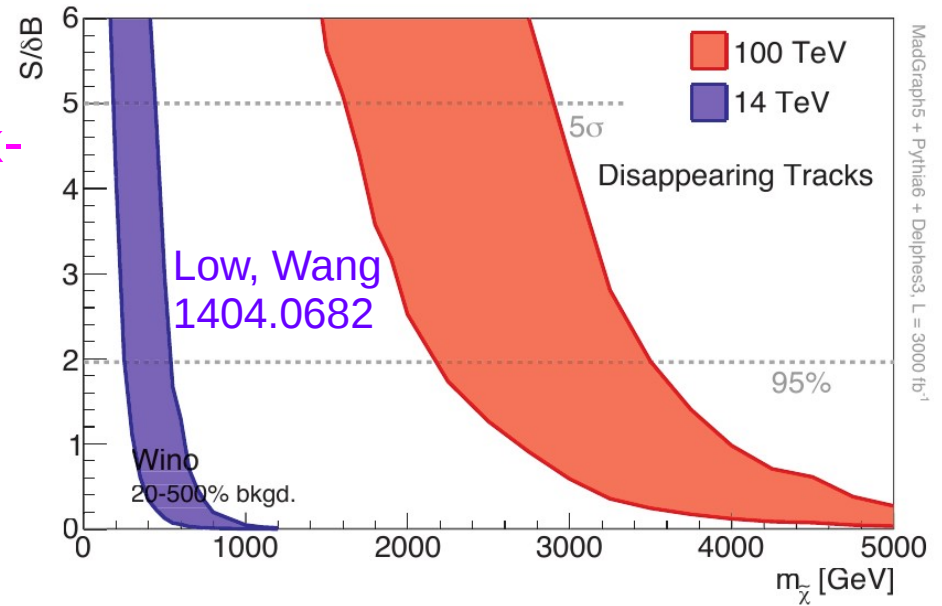
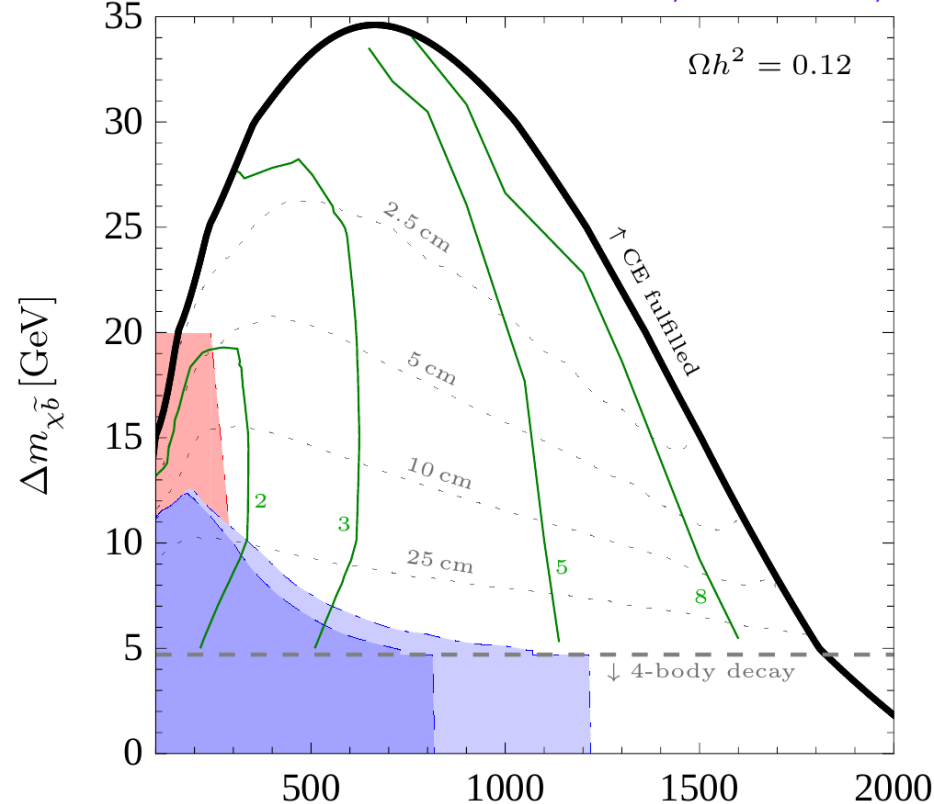
Disappearing Track

FCC can cover full range of thermal Wino DM masses!

Pure Higgsino also accessible with track-based search that includes fwd region

Coannihilation processes can require charged partners w/ significant lifetimes

1705.09292 : Garny, Heisig, Lulf, Vogl
see also 1702.00750 : Khoze, Plascencia, Sakurai



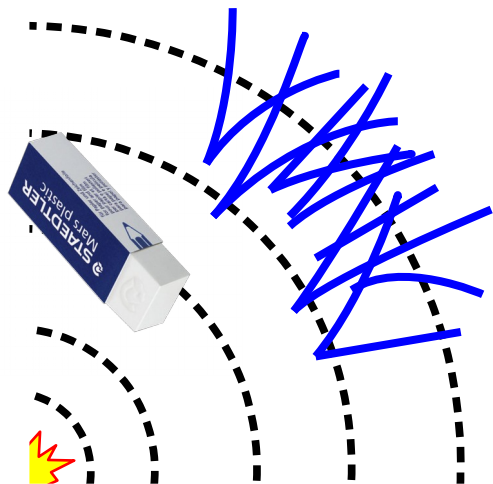
Other experimental signatures

Motivated by models w/ expanded particle content (Hidden Valley)

Emerging jets : showering within dark sector, appearing via decays back to visible SM particles

1502.05409 : P. Schwaller, D. Stolarski, A. Weiler

- ADM models with TeV-scale mediators connecting QCD w/ dark-QCD
- Produces clusters of displaced vertices

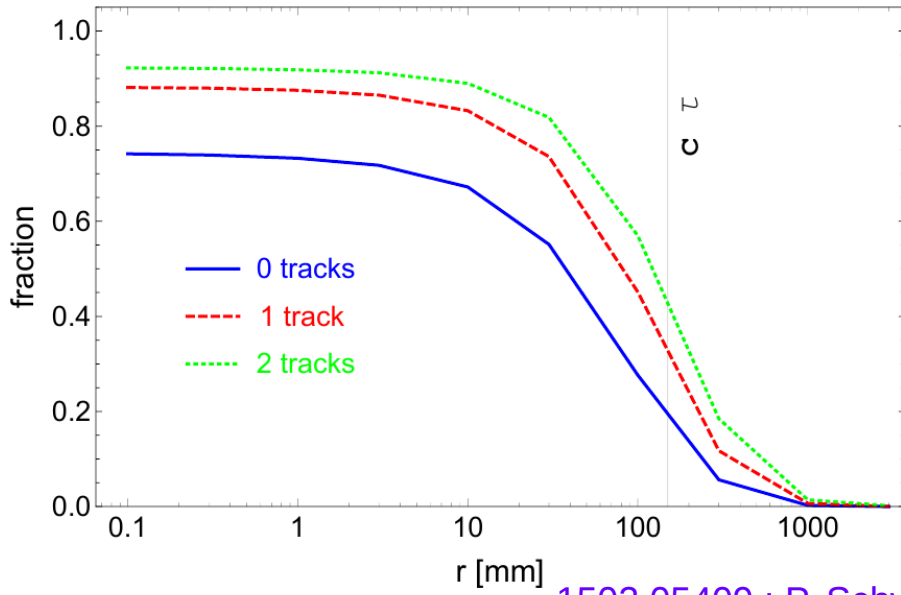


Nice example of a potentially pathological signal :

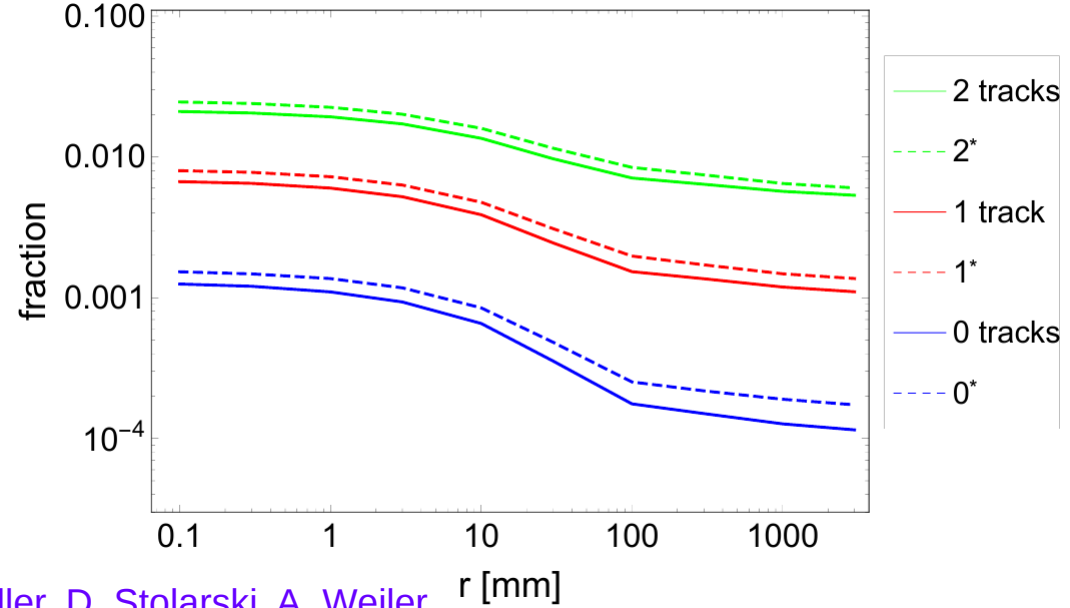
- Depending on dark-pion lifetime, **displaced tracks/vertices may not be reconstructed**
- Emerging jet can be reconstructed as a calorimetric jet with large neutral energy fraction
 - But experiments often **limit neutral fraction to filter instrumental effects!**
- **Vertex association? Need a recoiling visible jet to find PV?**

Emerging Jets

E(1 GeV, n, r) ≥ 1, Model A



E(1 GeV, n, r) ≥ 1, QCD



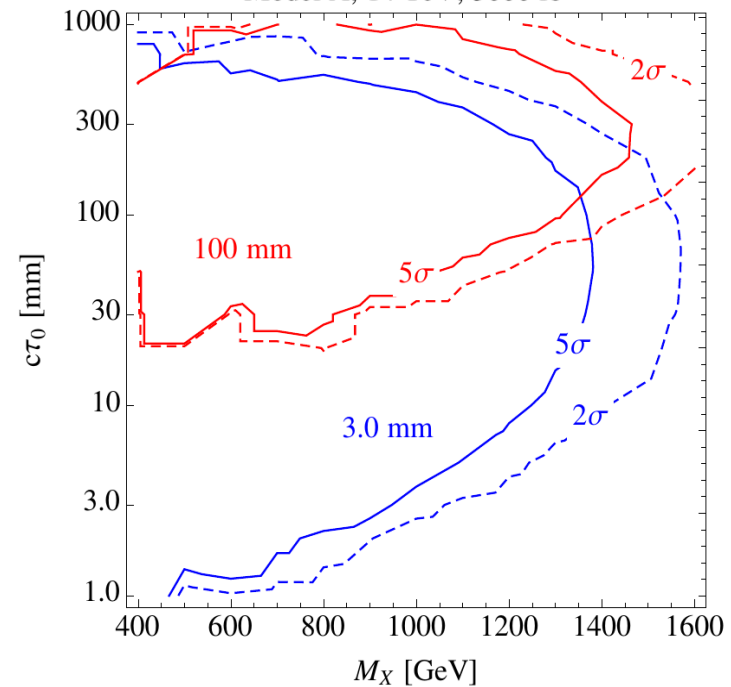
1502.05409 : P. Schwaller, D. Stolarski, A. Weiler

Classify jets in # prompt tracks

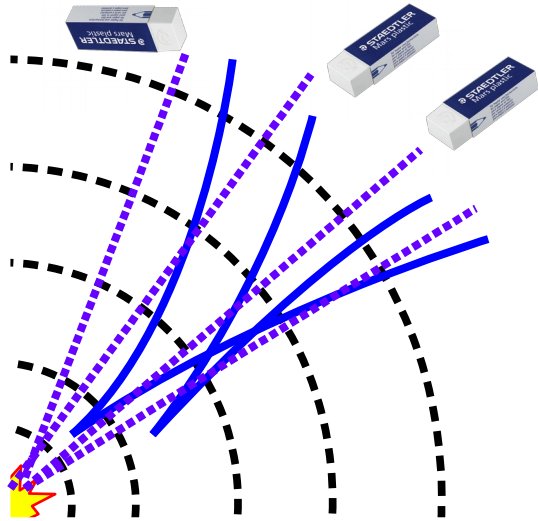
- Assume secondary vertex reconstructed with resolution of O(mm)
- Small QCD background after cut on prompt tracks
- LHC mediator exclusions projected to ~1.5 TeV

Dedicated FCC studies?

Model A, 14 TeV, 3000 fb⁻¹



Other experimental signatures

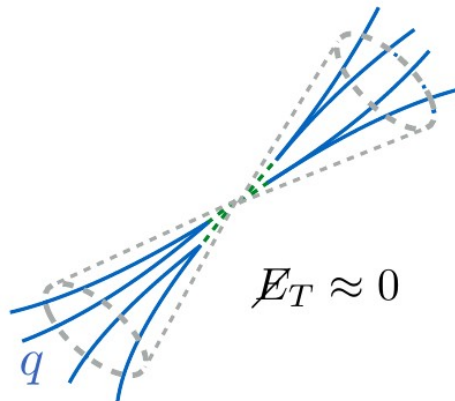


Semi-visible jets : some (not all) dark sector particles stable on detector scales

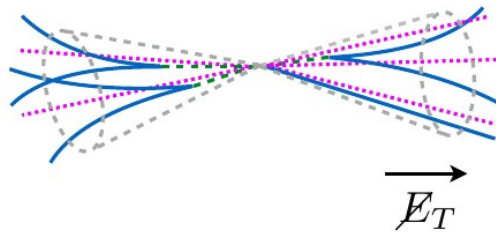
1707.05326 : T. Cohen, M. Lisanti, H.K. Lou, S. Mishra-Sharma

- Stable dark hadrons: MET aligns w/ jet direction
- **Typical present-day DM searches require a minimum $\Delta R(\text{jet}, \text{MET})$ to ensure good MET reco**
- Depending on fraction of stable hadrons (r_{inv}), topology can map to completely visible or monojet topologies

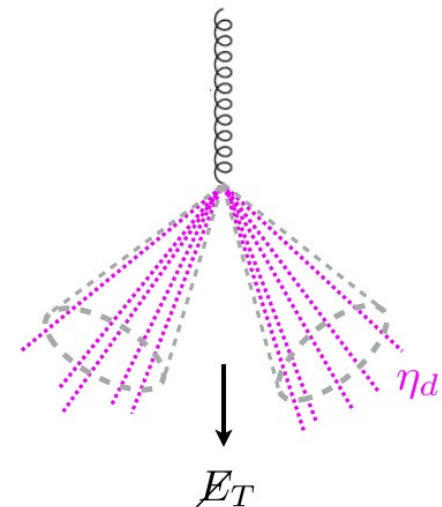
$$r_{\text{inv}} = 0$$



$$0 < r_{\text{inv}} < 1$$



$$r_{\text{inv}} = 1$$



Semi-visible Jets

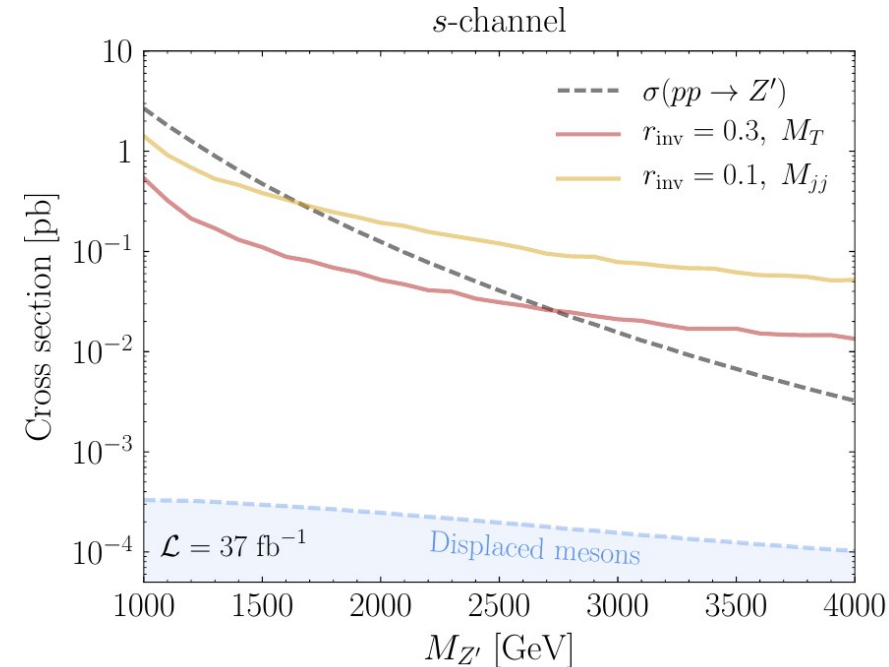
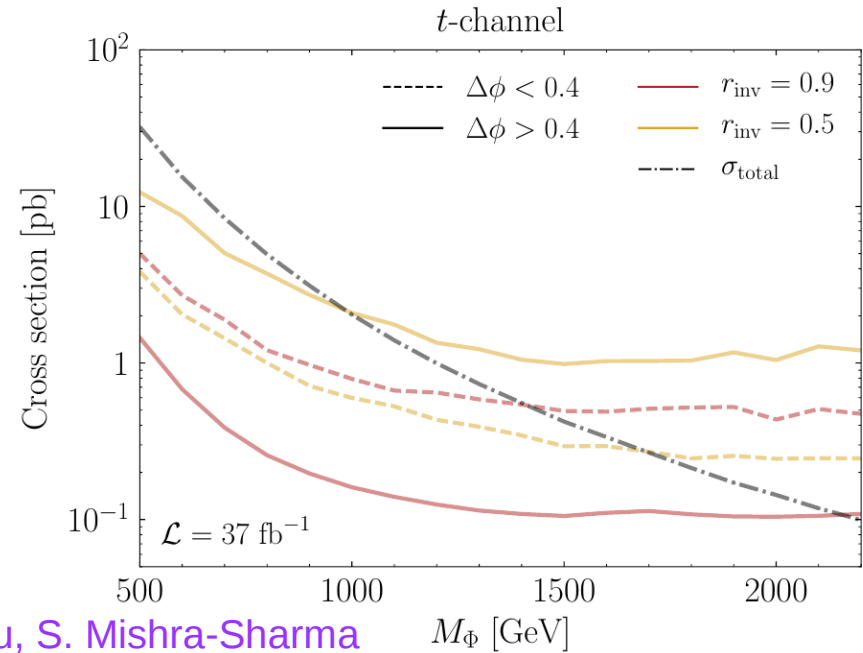
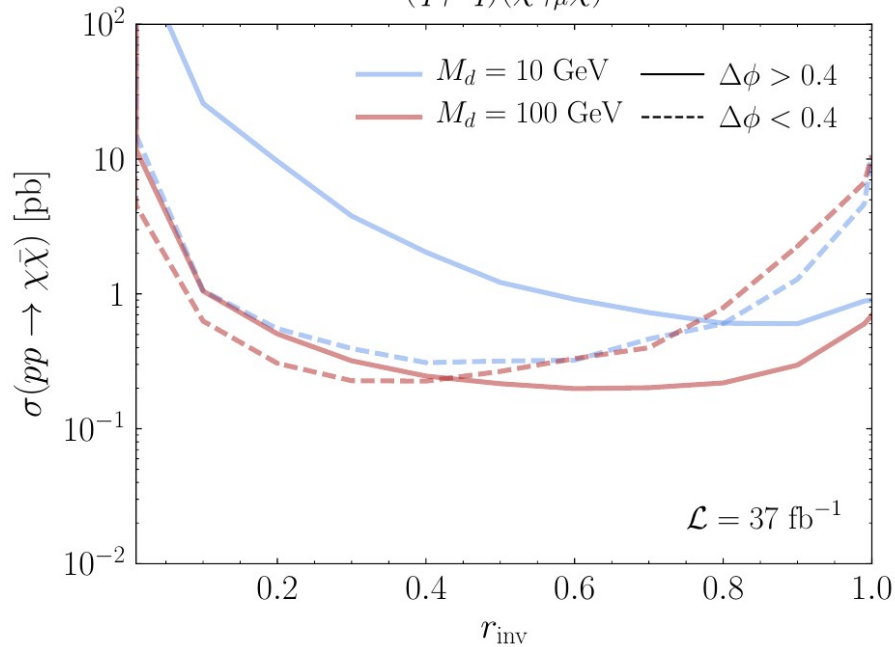
Semi-visible jets : some (not all) dark sector particles stable on detector scales

- Monojet best for $r_{\text{inv}} \rightarrow 1$, large $\Delta\Phi$
- Need small $\Delta\Phi$ for intermediate r_{inv}
- Presumably dijet for $r_{\text{inv}} \rightarrow 0$

Dedicated FCC studies?

1707.05326 : T. Cohen, M. Lisanti, H.K. Lou, S. Mishra-Sharma

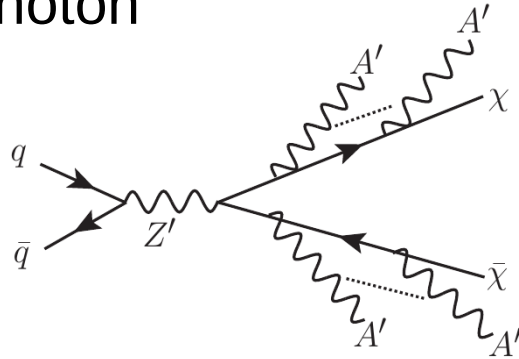
$$(\bar{q}\gamma^\mu q)(\bar{\chi}\gamma_\mu\chi)$$



Other experimental signatures

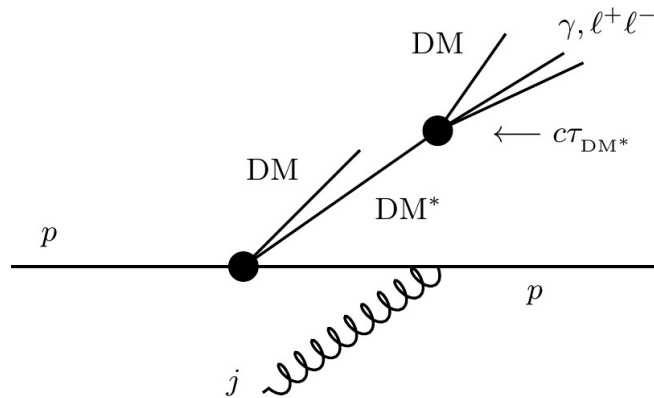
(Displaced) “lepton-jets”

- Low-mass DM can radiate dark photons that mix with SM photon

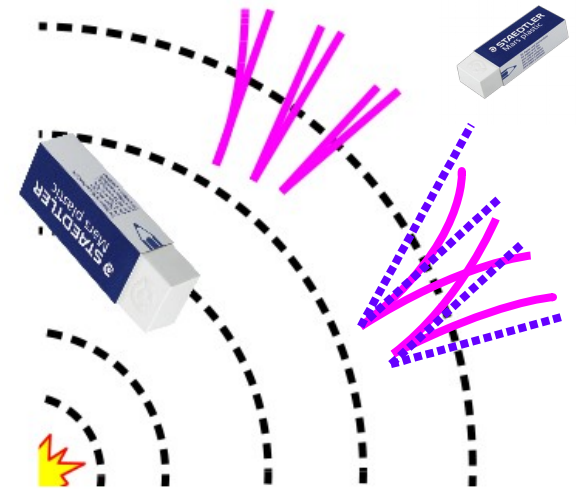


1505.07459 : Buschmann, Kopp, Liu, Machado

- Inelastic DM: long-lived, excited DM states. DM can be colinear with DM^* decays



1508.03050 : Izaguirre, Knrjaic, Shuve



Experimental Issues:

- Signals from narrow electron/tau/pion jets can be difficult to reconstruct
- $\Delta\phi(\text{lepton}, \text{MET})?$

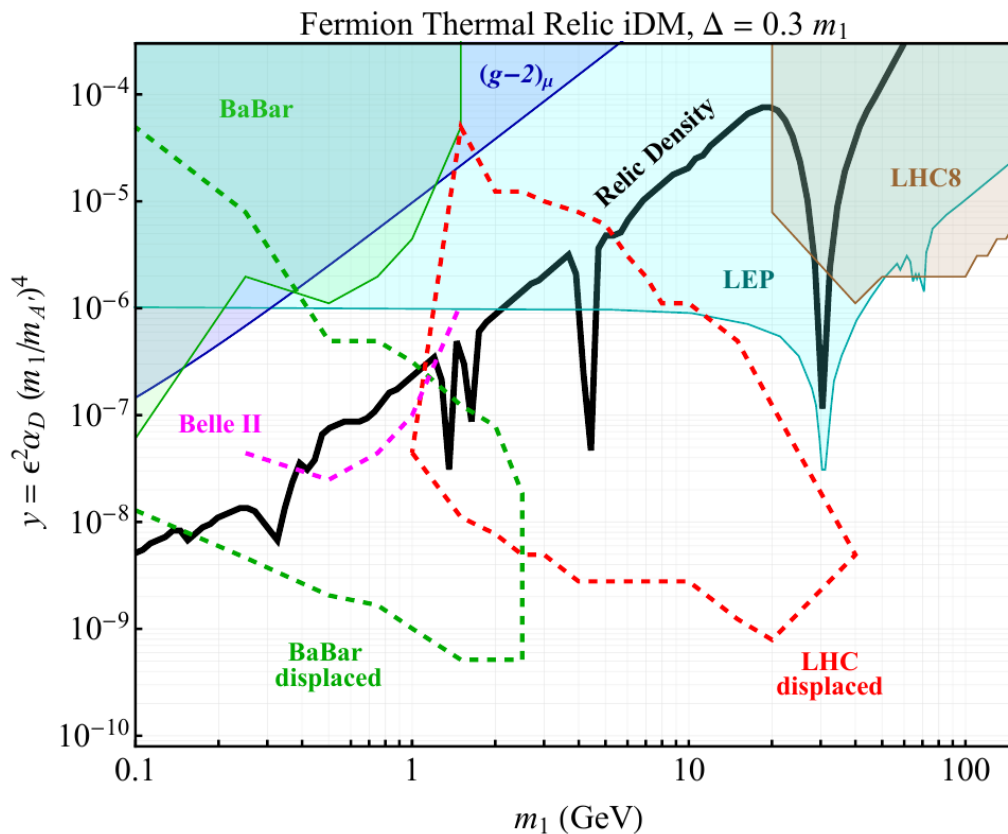
(displaced) Lepton Jets

LHC projections from displaced lepton jets:

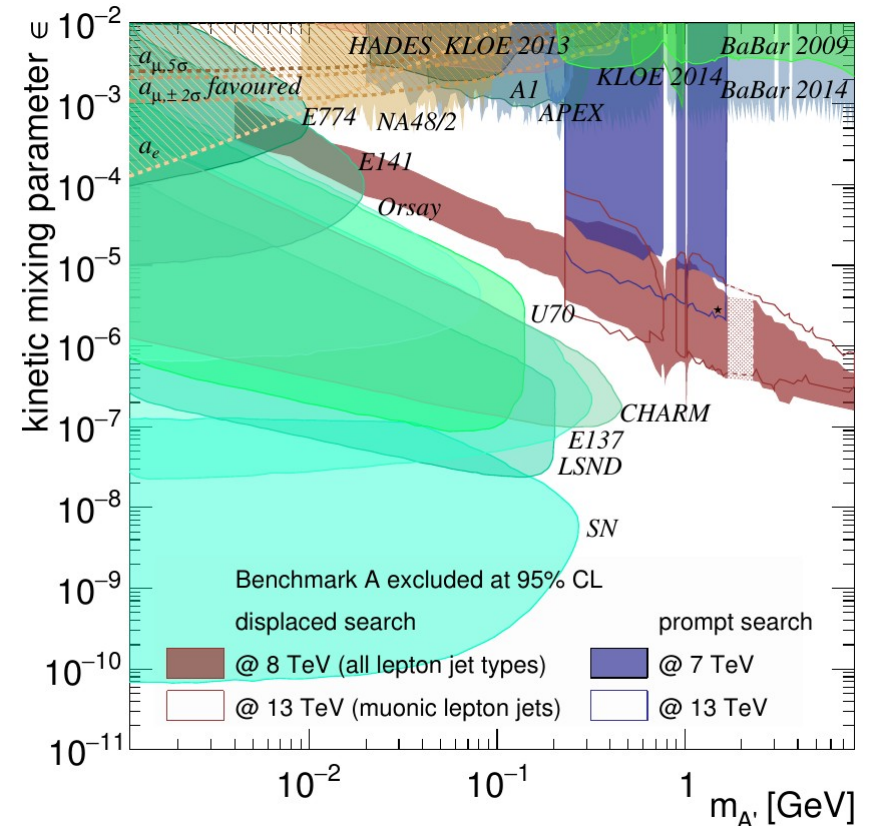
- Limits on DM / massive dark photon from iDM
- Limits on DM radiating dark photons

Dedicated FCC studies?

1508.03050 : Izaguirre, Knrjaic, Shuve



1505.07459 : Buschmann, Kopp, Liu, Machado



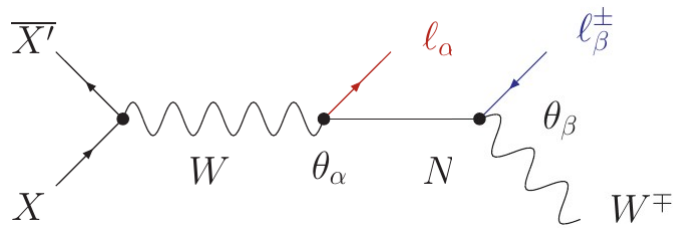
Lepton Jets & FCC-ee

Massive sterile neutrinos could serve as DM or a DM portal

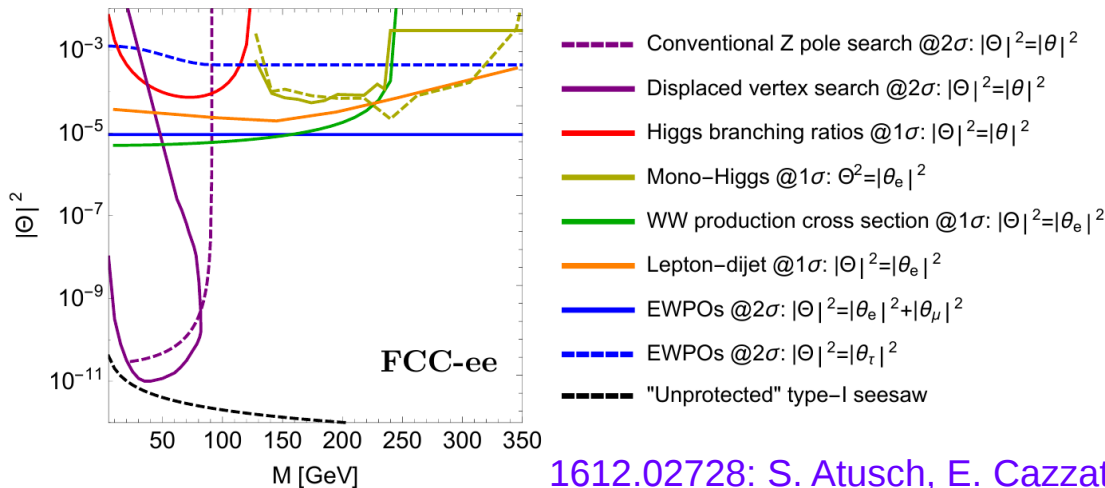
1606.01258, 1607.02373 : M. Escudero, N. Riusa, V. Sanz

Multilepton & (displaced) Lepton Jets powerful signatures at colliders

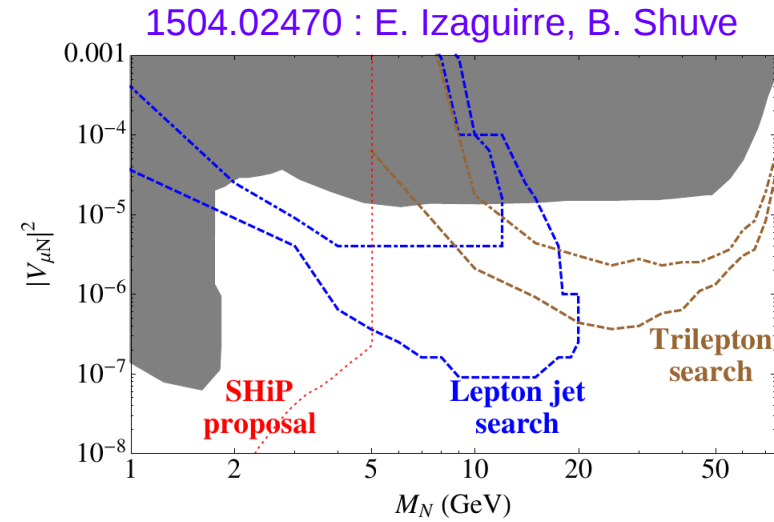
- Lepton Jets a useful probe for $M_N \ll M_W$



FCC-ee covers large parameter space!

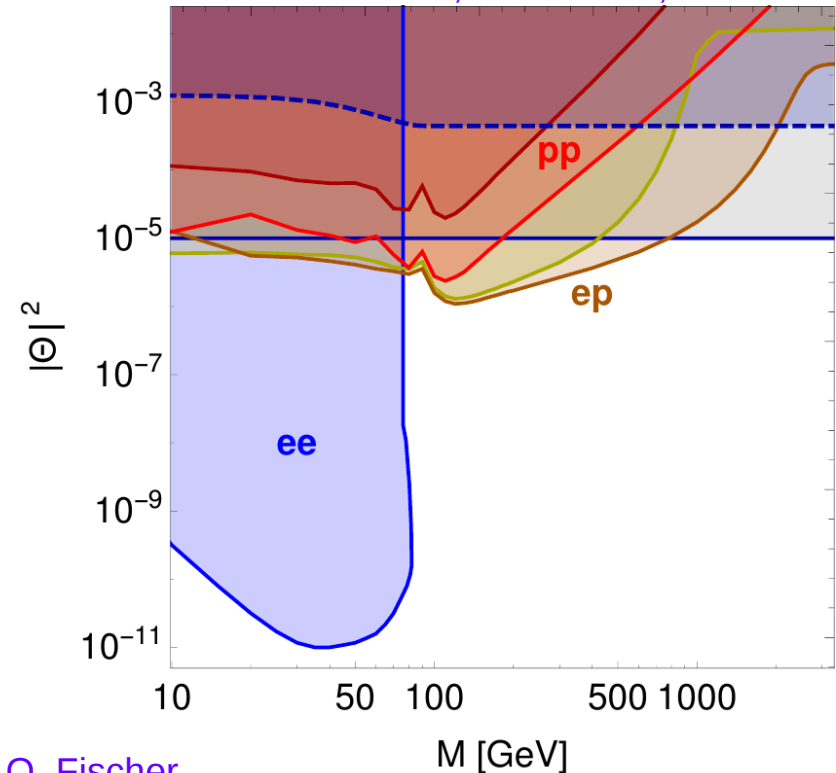


1612.02728: S. Atusch, E. Cazzato, O. Fischer



1504.02470 : E. Izaguirre, B. Shuve

1612.02728: S. Atusch, E. Cazzato, O. Fischer



New Territory

FCC-hh would *significantly* extend reach of DM searches

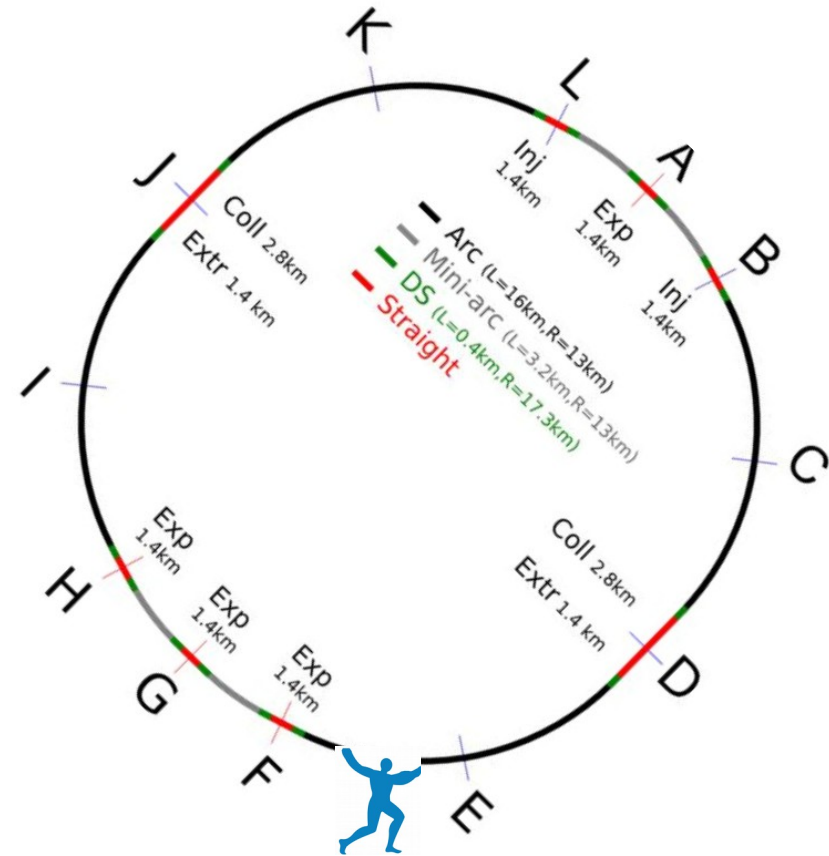
- Parameter space of some models would be *completely* covered

Physics requirements & operating environment make this a heavy lift ...

- MET+X : MET resolution @ PU 1000?
- Non-minimal models: aggressive demands placed on tracking

Yet time does not stand still ...

- Many new experimental (*) capabilities being developed for the HL-LHC
 - Especially wrt tracking & triggering
- These are also investments in foundational R&D for FCC detectors



(*) expect theory advances from EWK/Higgs/top precision measurements @ HL-LHC as well

New Capabilities : 3D pixels

FCC-hh innermost tracker @ $r=2.5$ cm

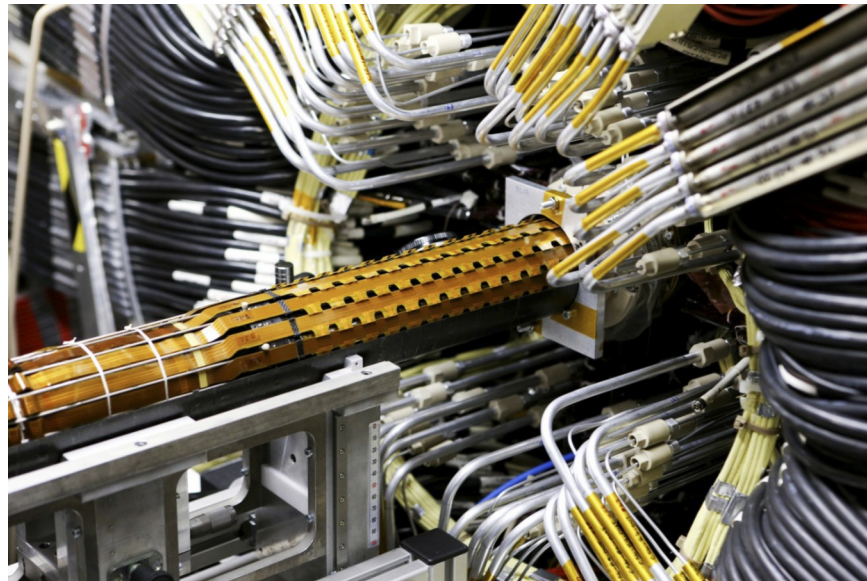
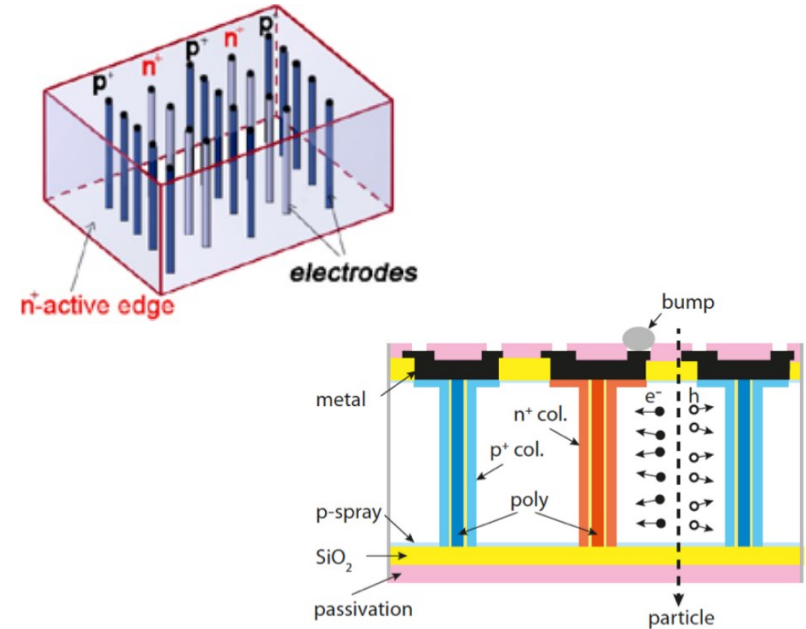
- TID $\sim 30\times$ HL-LHC!

3D pixels : highly-granular & extremely rad-hard

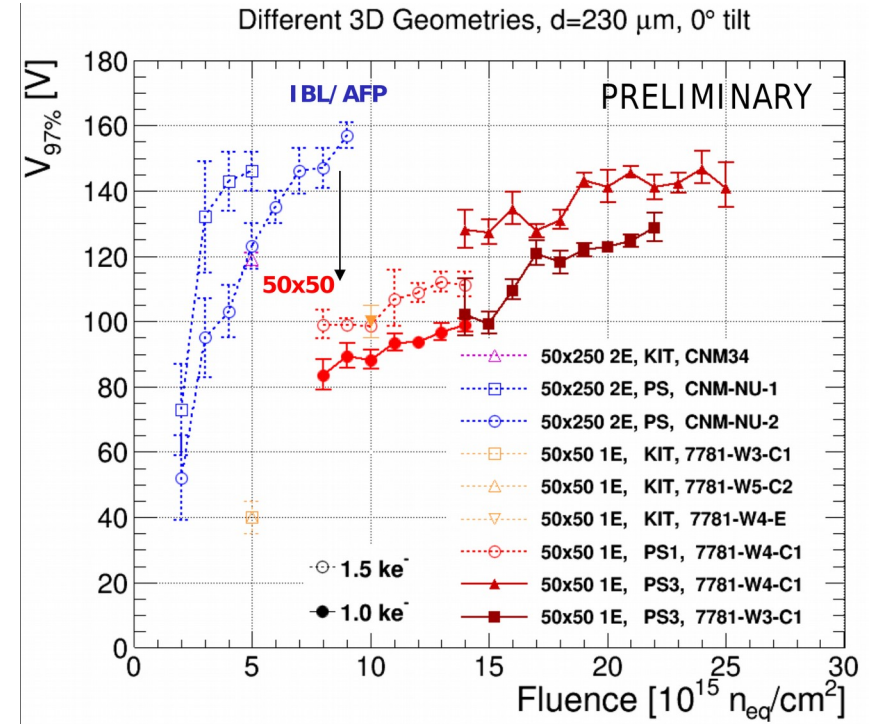
- Smaller electrode distances \rightarrow lower $V_{\text{depletion}}$
- Small drift distance \rightarrow fast charge collection

Extensive R&D programs in place

- First successful use of 3D pix in ATLAS IBL
- Groups developing next-gen tech (cf: RD50)



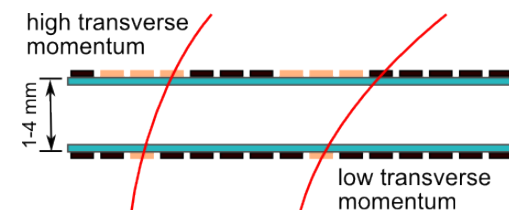
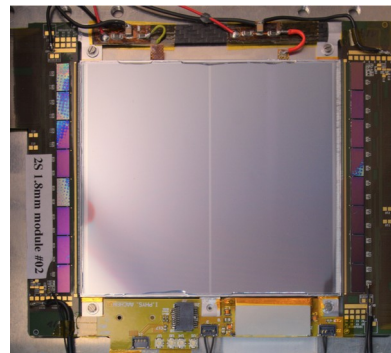
CERN-LHCC-2010-013 ; ATLAS-TDR-19



New Capabilities : Track Trigger

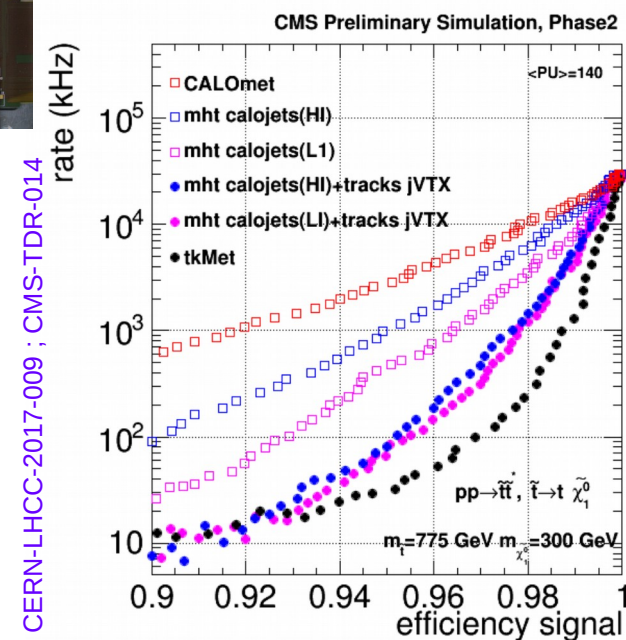
L1 Track Triggering for the HL-LHC

- CMS: self-seeded **OT** tracking
- **no ROI**, can trigger on tracks alone!



Primary motivation: fighting pile-up

- Reject soft tracks from high- z_0 interactions
→ contain trigger rates and lower thresholds
- **Combinatorics and data rates are major challenges**
 - I/O already limited @ detector front-ends ...
 - **Target tracks w/ $p_T > 2-3$ GeV**



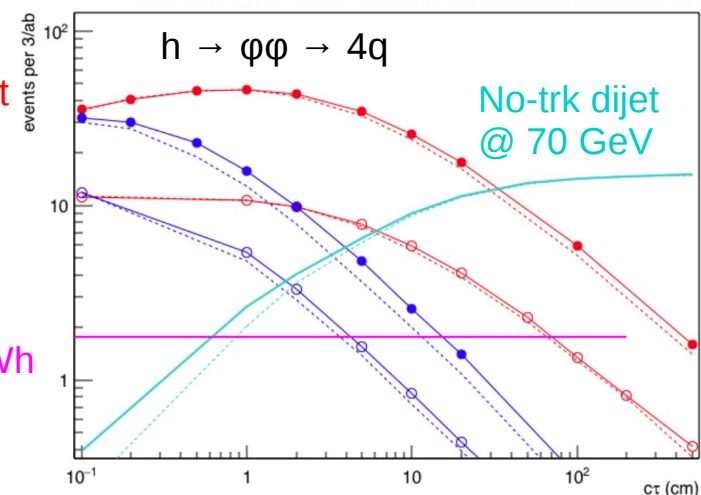
But other applications possible

- Baseline++, track-derived quants
 - Track MET/jets/isolation
 - **Could be exploited for BSM signals**
- **Displaced tracks?** Under study ...

Loose Quad-jet
@ 10,20 GeV

Tight Quad-jet
@ 10,20 GeV

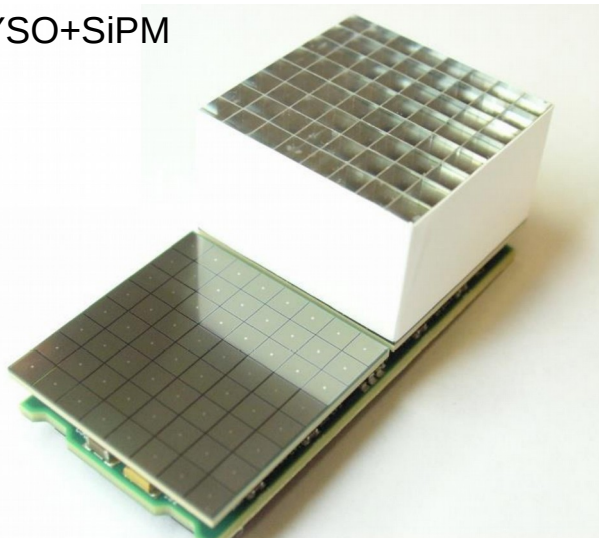
Lepton
triggered Wh



1705.04321 : Y. Gershtein

New Capabilities : Fast Timing

LYSO+SiPM



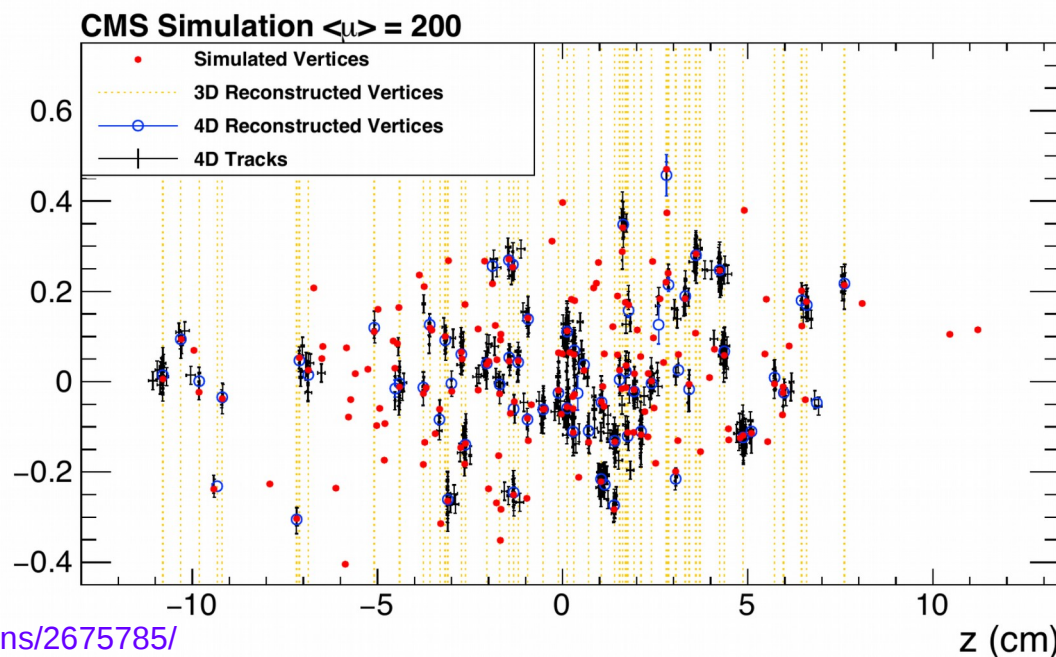
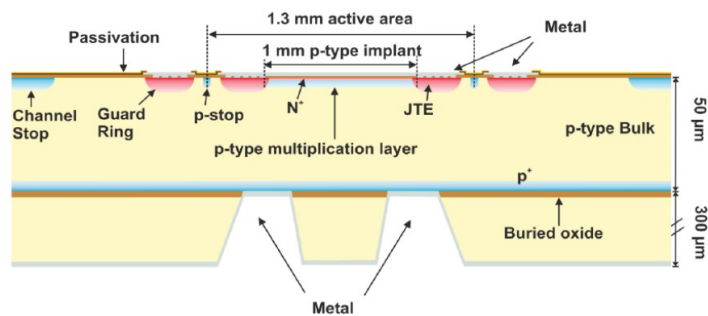
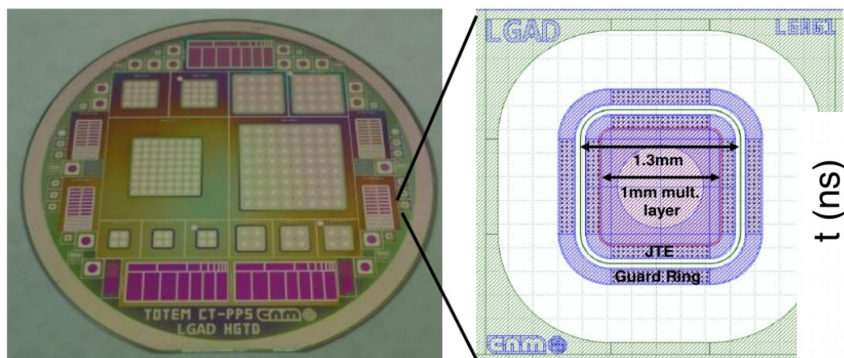
Precision timing layers for HL-LHC

- Various technologies under consideration
- 20-40 ps time resolution demonstrated!

Current thrust is pile-up mitigation ...

- z-coordinate from 4D tracking / vertexing

Applications for LLP?



VERTEX2017

R. Yohay (CMS): <https://indico.cern.ch/event/627245/contributions/2675785/>

G. Kramberger (ATLAS): <https://indico.cern.ch/event/627245/contributions/2676819/>

J. Bendavid
<https://indico.cern.ch/event/524795/ timetable/#65-cms-plans-performance>

Summary

DM searches @ FCC(-hh) will probe a huge parameter space, providing crucial complementary w/ DD/ID programs



Direct approaches: MET+X

- Big gains in DM & mediator masses @ FCC
- Sensitivity to much smaller couplings → displaced signatures become important



Less direct approaches: non-standard objects

- Eg: (displaced, semivisible, emerging, lepton) jets
- General searches can miss complex signals
- FCC searches can build on techniques & analyses being developed *now* @ LHC ... stay tuned!

Physics at 100 TeV poses many experimental challenges

- Eg: excellent & expanded tracking performance needed to move beyond traditional MET-based searches
- Technologies being deployed/designed today will bridge to the future