Searches for New Long-lived Particles with the ATLAS detector

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on behalf of the ATLAS Collaboration

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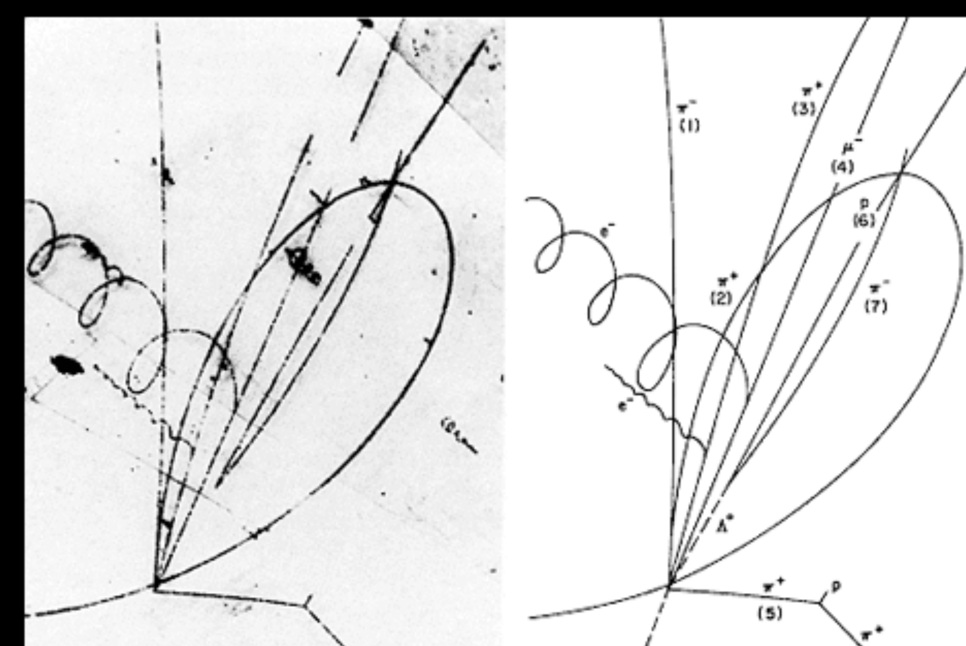
Long-lived particles

- ★ New particle search is not a guaranteed science anymore, but it is not the end.
  - ★ It's the era to ask **how** we could discover a new one.
- ★ LLP is one direction to expand the new particle search capability, and it sounds like a sense!
  - ★ Very distinctive **signatures** — low BGs.
    → Sensitivity increases linearly wrt. integrated luminosity.
    → Can **profit** future lumi increase much.
  - ★ Despite experimentally feasible with or without existing facilities, it's not very matured field yet.
    → Room of **creativity**.
  - ★ Theoretically **motivated** models.
  - ★ **History**: experimental particle physics dawn has started from finding LLPs!



Mechanisms of long lifetime

Analogous situations may be found in SM…

- ★ Scale hierarchy
- ★ Degeneracy
- ★ Rules
- ★ Coupling
- ★ Phase space

Charged Pion

$$\Gamma \sim g_W^2 \left(\frac{m_\pi}{M_W} \right)^4 m_\pi$$

Neutron

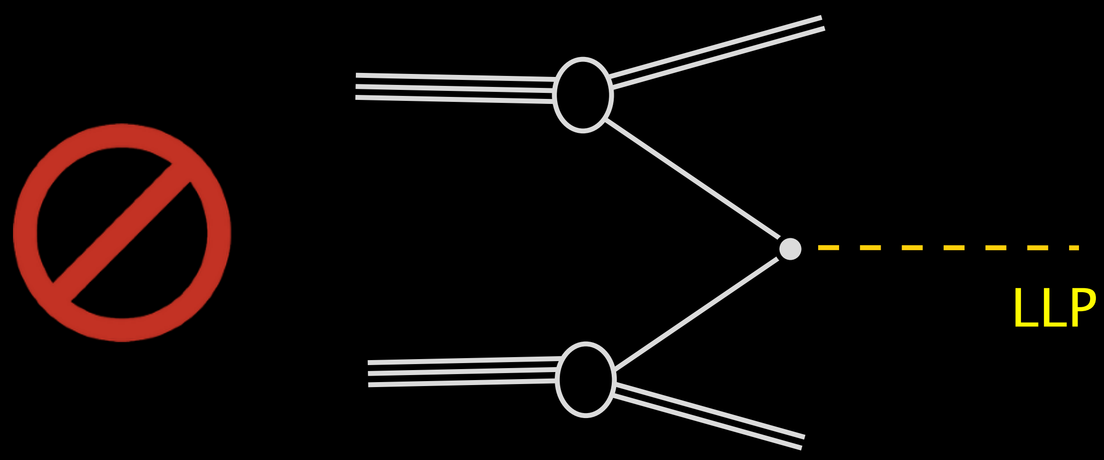
$$\Gamma \sim g_W^2 \left(\frac{m_n - m_p}{M_W} \right)^4 (m_n - m_p)$$

Why not BSM may have similar features?

LLP General: on the LLP Production

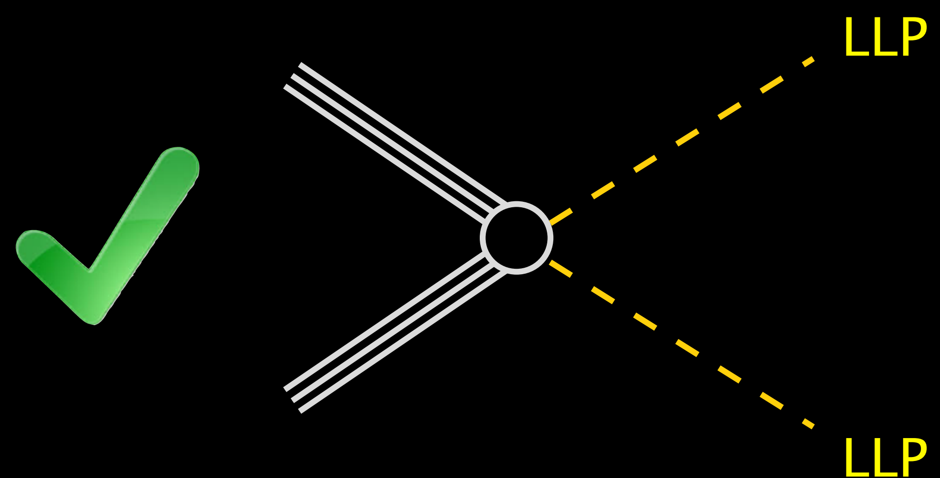
Quite many LLP models exist, but…

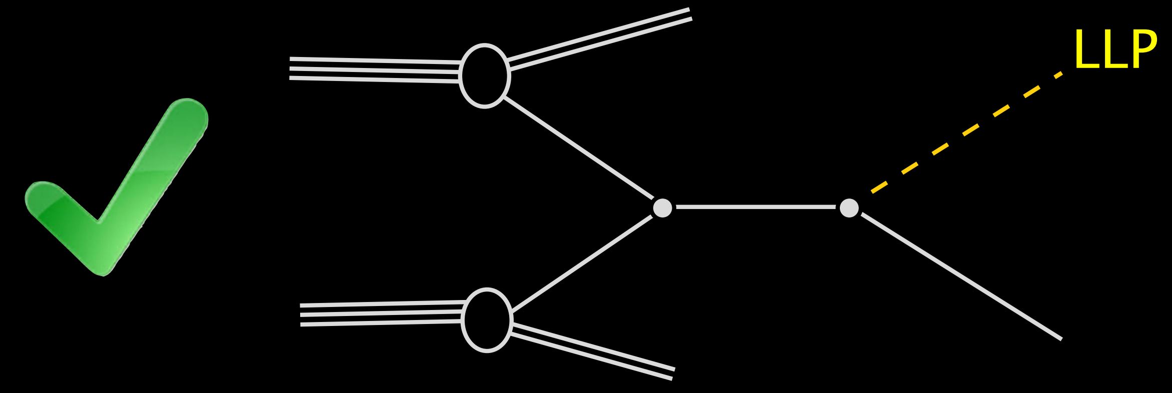
An LLP has a very narrow decay width.
→ Production with the same vertex as the decay should be suppressed.



Drell-Yan LLP production isn't good!

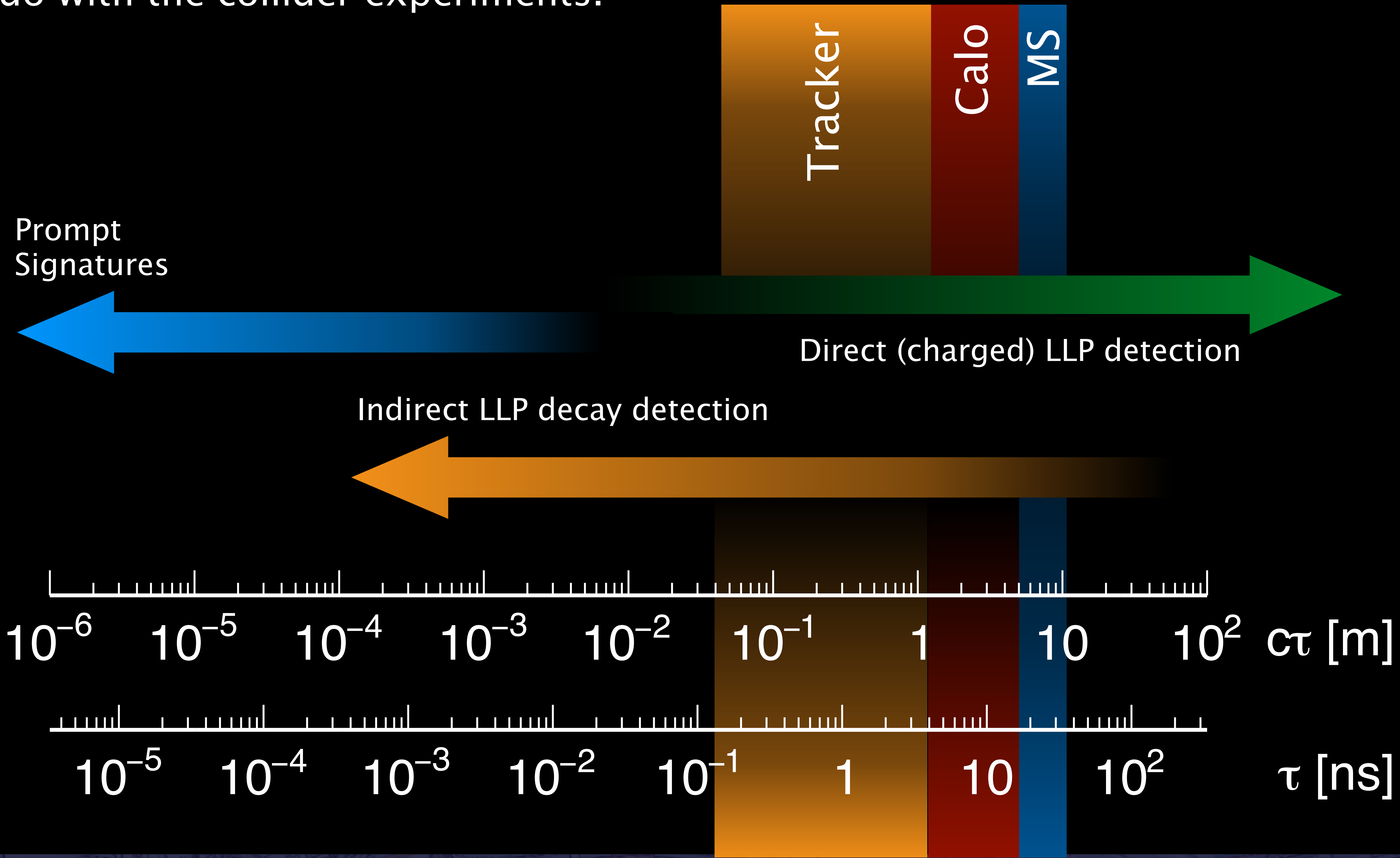
Meanwhile pair-production or cascade decay production are feasible.





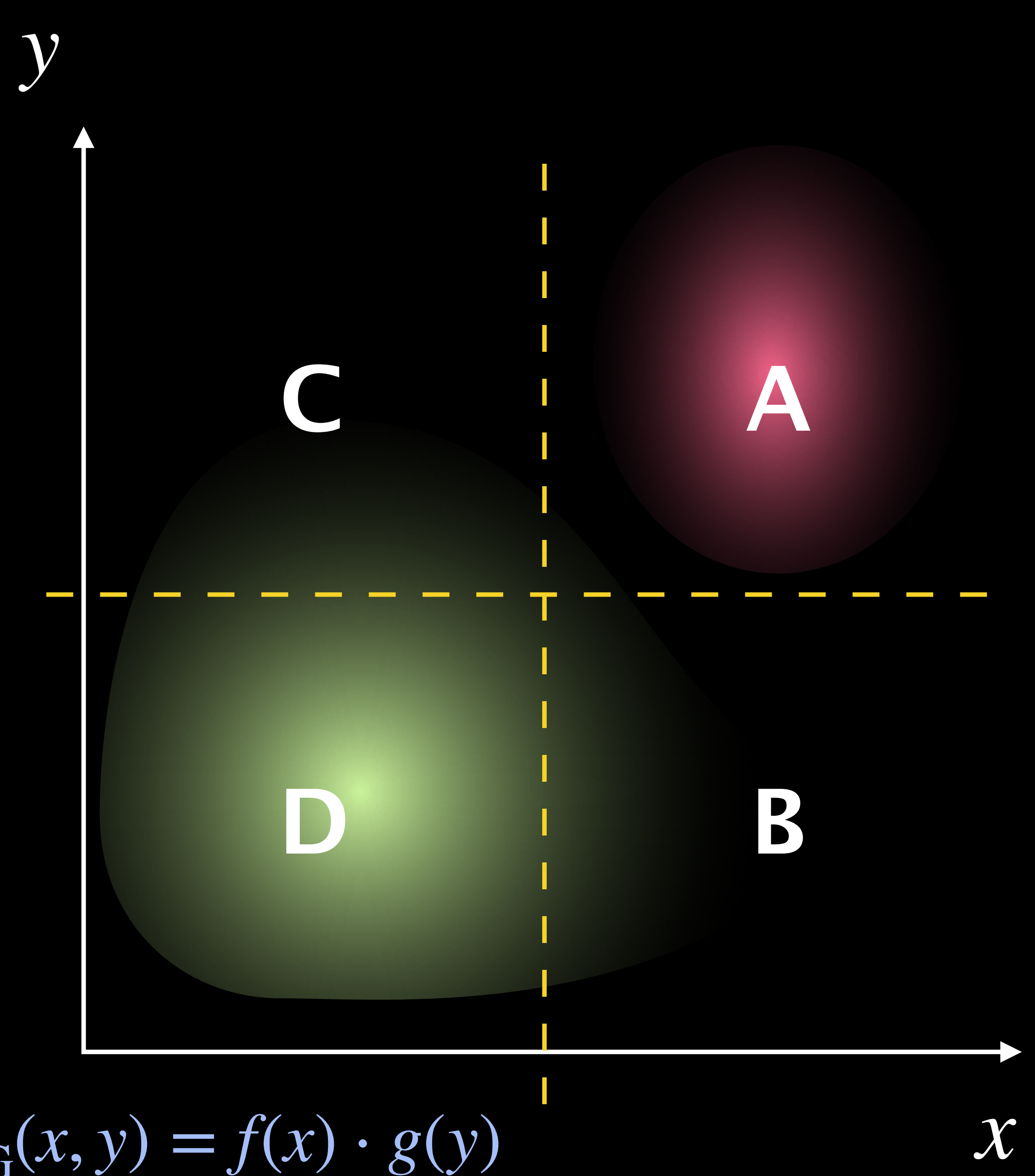
LLP General: Geometry and lifetime

LLP searches complete what we can do with the collider experiments.



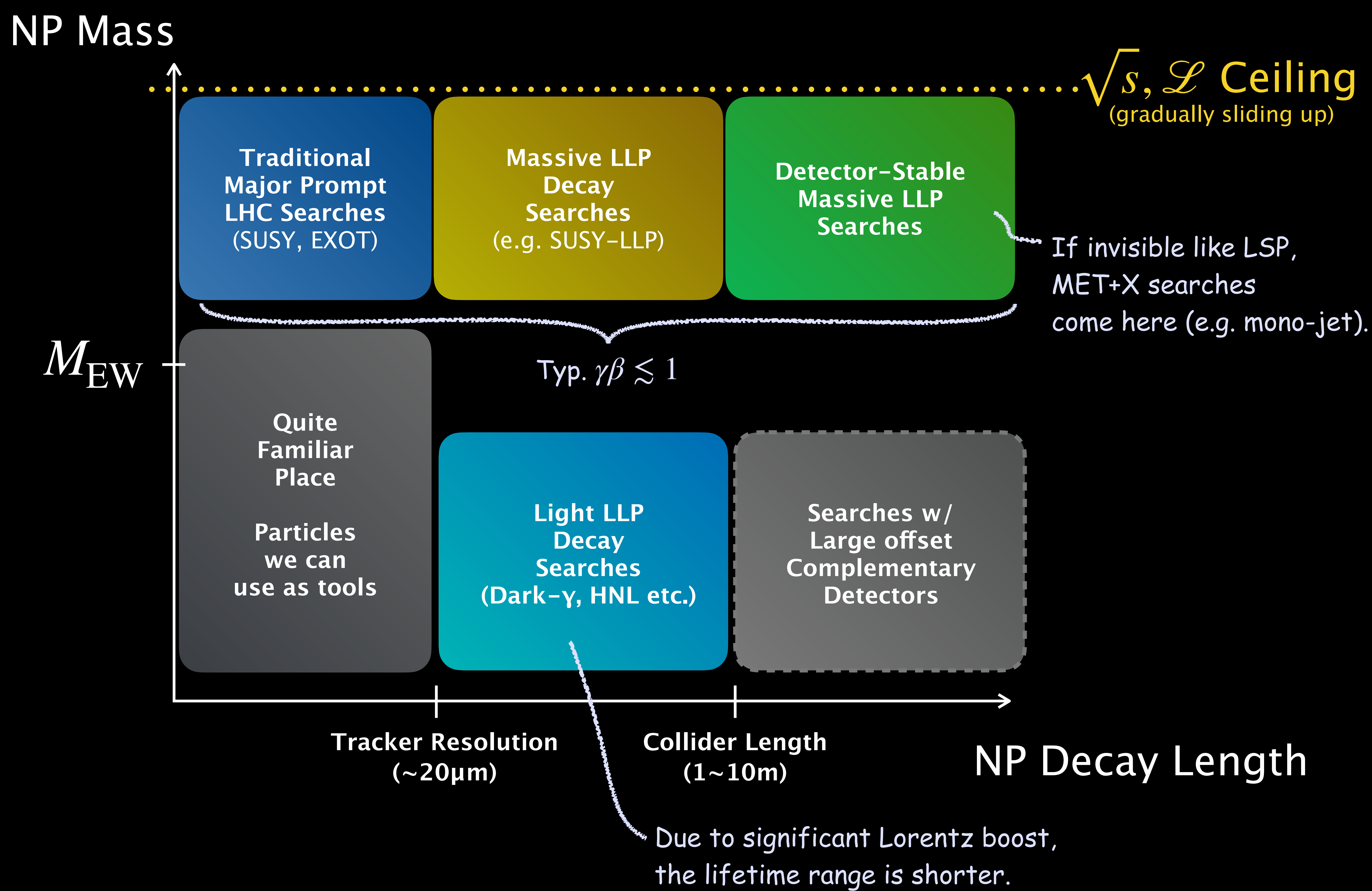
- Background events are mostly instrumental.
  - Cosmic rays, beam-induced backgrounds or fake objects.
- MC isn't reliable / unavailable. Data-driven estimation is necessary.
- Many analyses use "ABCD method" in the background estimation.
  - Allocate two orthogonal variables classifying signal and background.
  - As long as orthogonality of the two variables is secured:

$$N_A = N_B \times \frac{N_C}{N_D}$$



$$F_{\mathrm{BG}}(x, y) = f(x) \cdot g(y)$$

Accelerator LLP searches landscape



Mid Run2

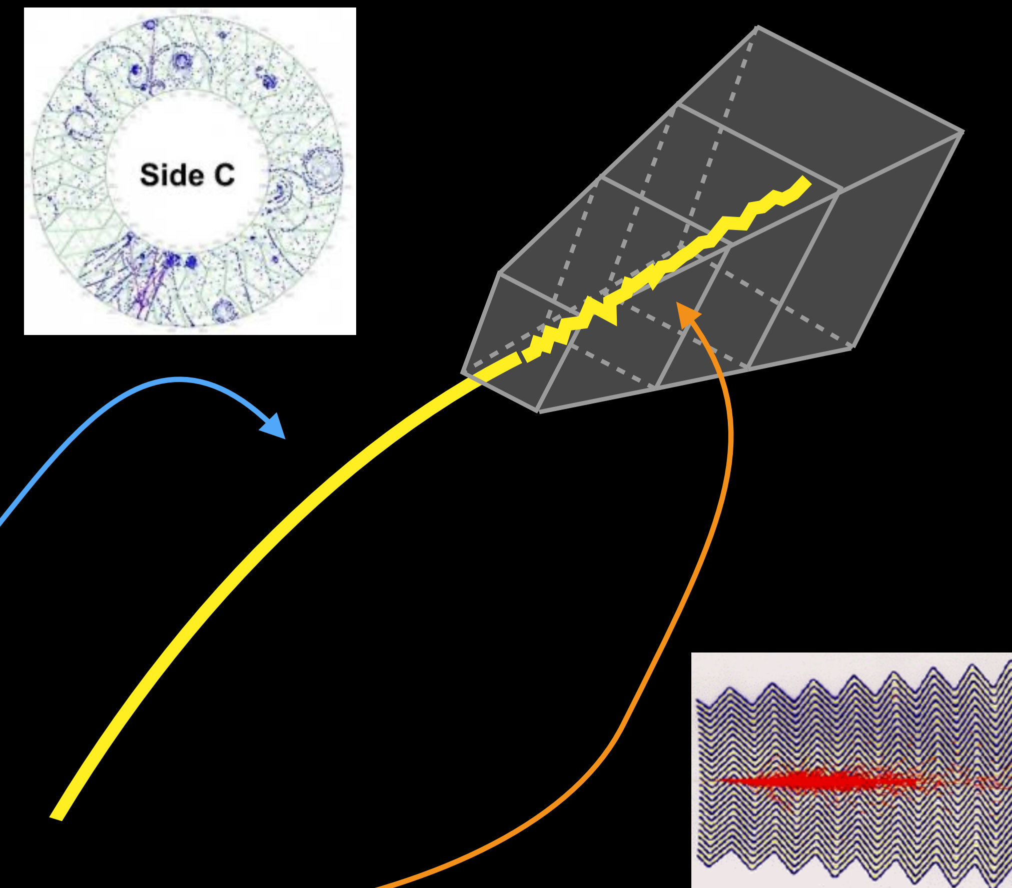
Magnetic monopole search

EXOT-2017-20 / PRL 124 (2020) 031802

Aim: test for Dirac's description of magnetic monopole.

$$q_m = N g_D e c \quad \text{where} \quad g_D = (2\alpha_e)^{-1} \simeq 68.5$$

→ Stable monopoles produced in LHC has $\sim 5{,}000\times$ more ionization loss than MIP!!



Striking Signature:

- Many of TRT (straw tube) high-threshold hits
- Non-showering sharp EM calo cluster

Trigger:

- Dedicated HLT seeded from $E_\mathrm{T} > 22$ GeV L1 electron trigger.
- Presence of many $\gtrsim 6$ keV TRT$_{\mathrm{(Xe)}}$ hits in a narrow 10 mrad wedge.

For monopole $|g| = g_D$:
- L1 eff. 55%
- HLT eff: 25–60% (after L1)

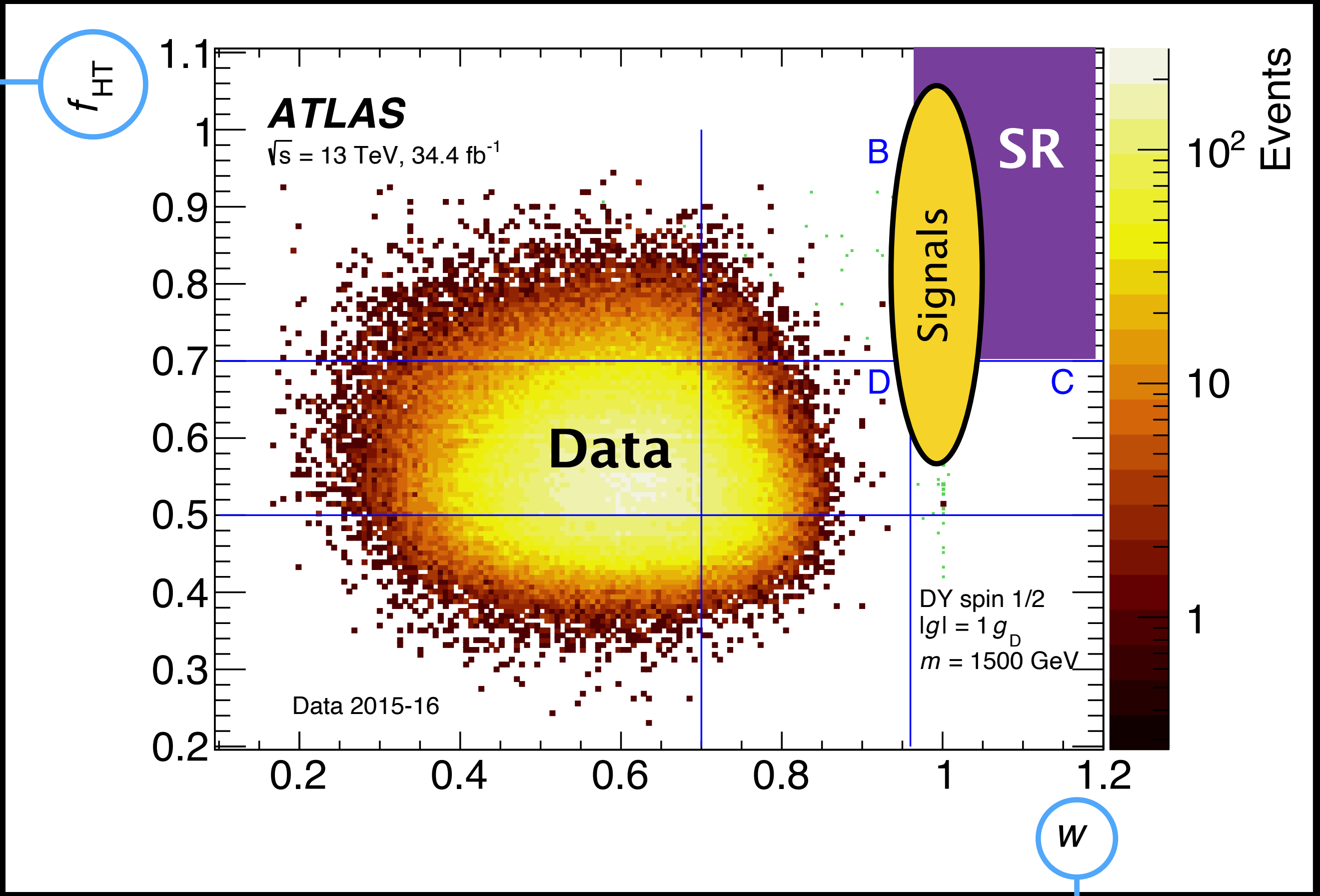
Also side note: Monopole MC simulation is peculiar:

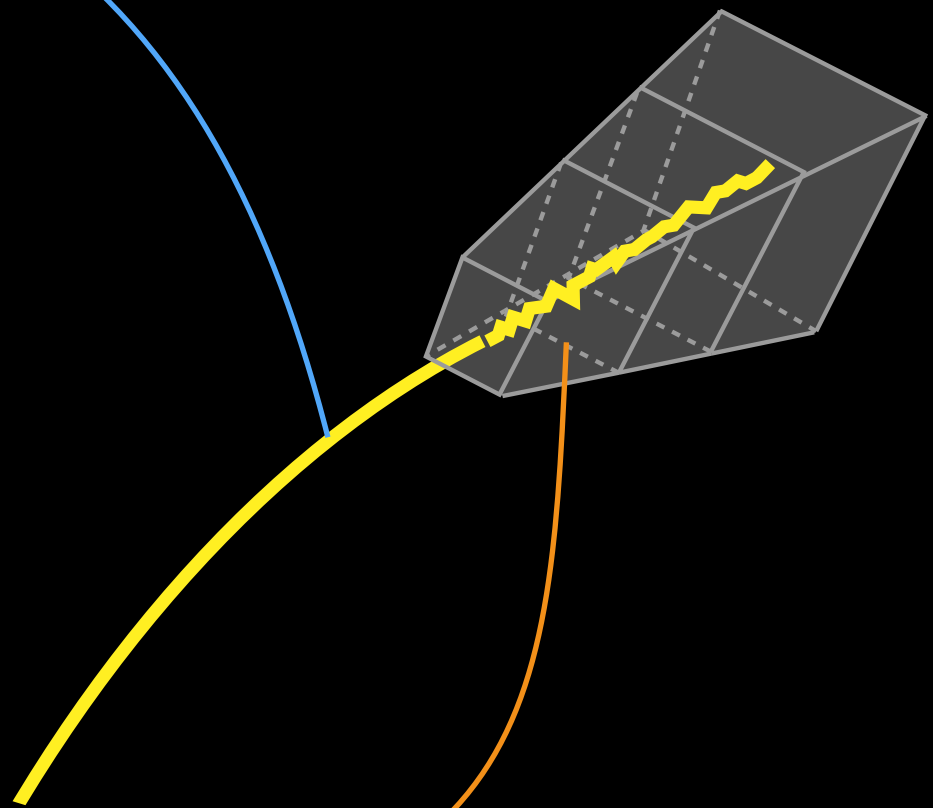
- Acceleration inside solenoid.
- Enormous ionization and δ–ray productions along track
- Deceleration of monopole in EM calo (and many stop inside it)
- Instead of $1/\beta^2$ "Bethe–Bloch" formula, $\log\beta^2$

Magnetic monopole search

EXOT-2017-20 / PRL 124 (2020) 031802

Fraction of high-threshold TRT hits along the road





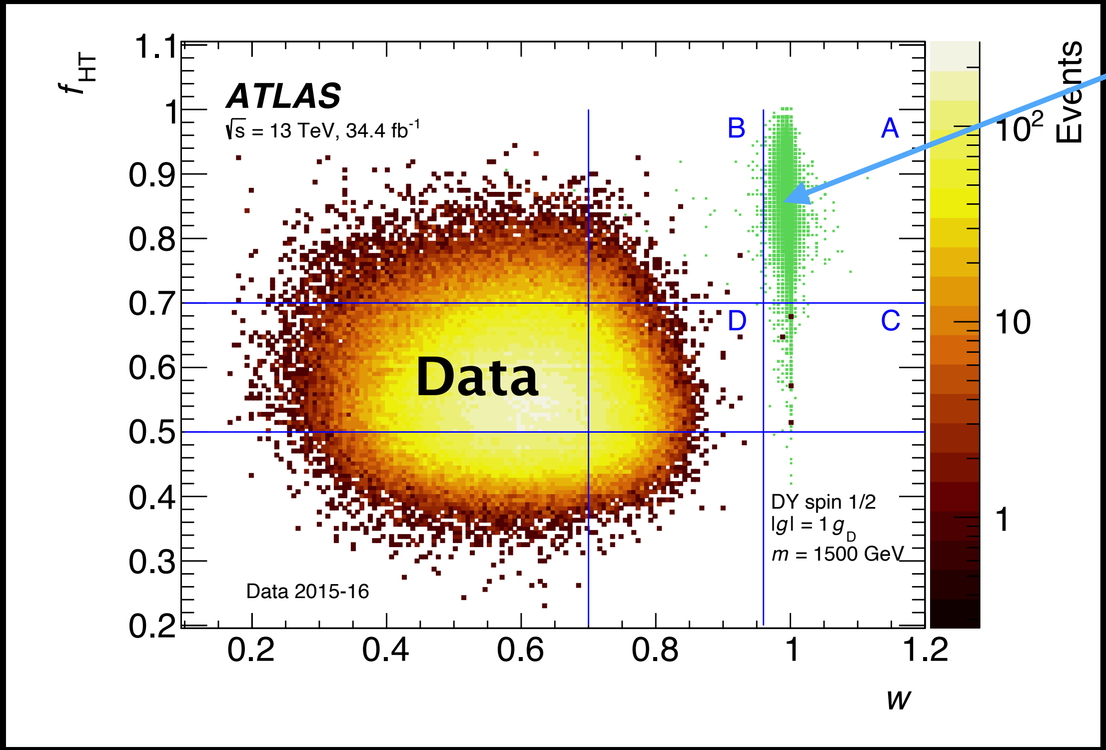
Average lateral energy dispersion of EM layers (Signal has a sharp peak at $w = 1$)

- ★ 2 quasi-orthogonal variables based on TRT and EMCalo.
- ★ Bkg estimation: data-driven ABCD method, assigning η-dependent 10% correlation as systematic uncertainty.

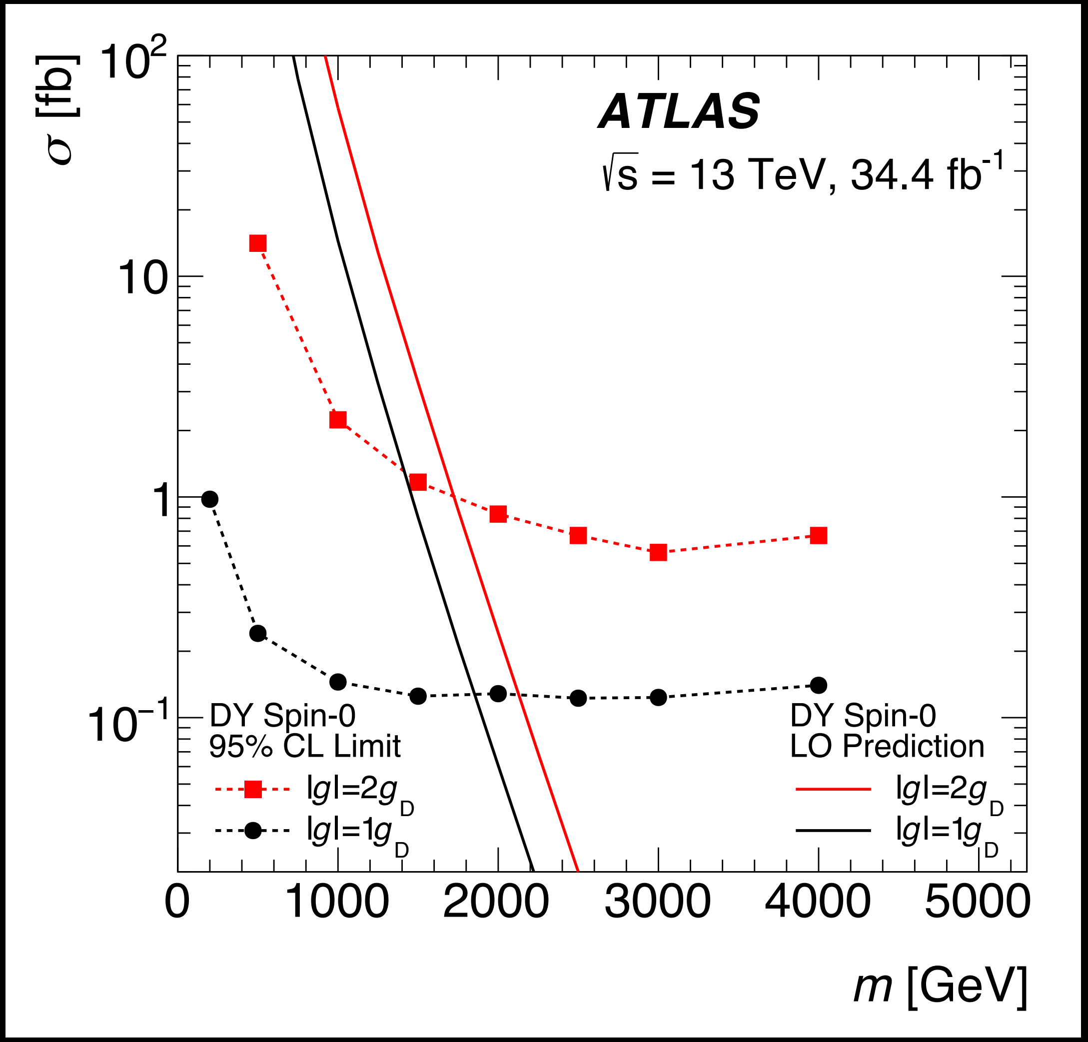
Bkg Prediction: $0.2 \pm 0.11_{\mathrm{stat.}} \pm 0.40_{\mathrm{sys.}}$ evts.

Magnetic monopole search

EXOT-2017-20 / PRL 124 (2020) 031802



Bkg Prediction: $0.2 \pm 0.11_{stat.} \pm 0.40_{sys.}$ evts.



- ★ Zero events observed in SR.
- ★ Limits presented in the scenario of Drell-Yan monopole and high-$|z|$ production models for scalar and fermion respectively.

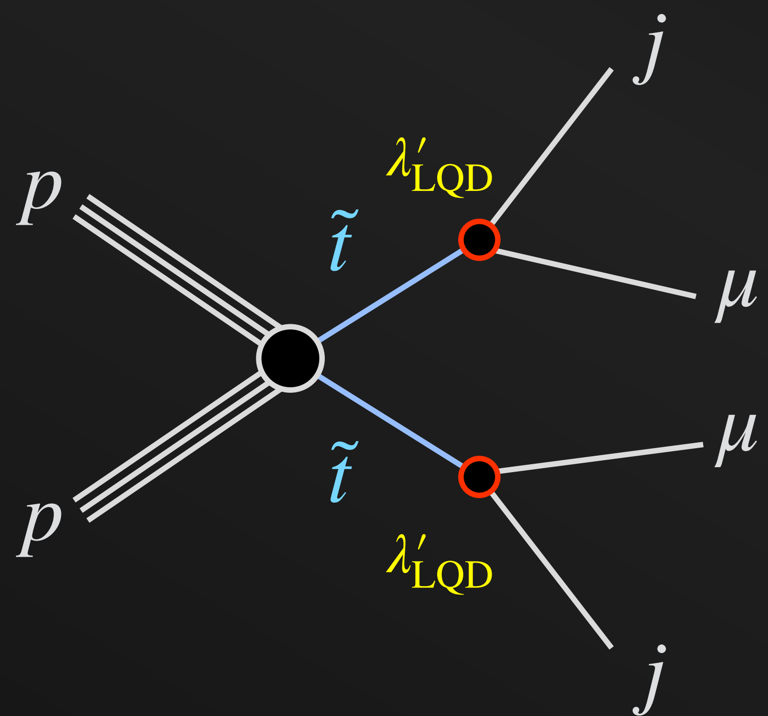
- $|g| = 1g_D$ scalar monopole excluded up to 1850 GeV.
- ~5x improvement to the ATLAS Run1 result.
- Sensitivity comparable to MoEDAL.

Displaced vertices with muons

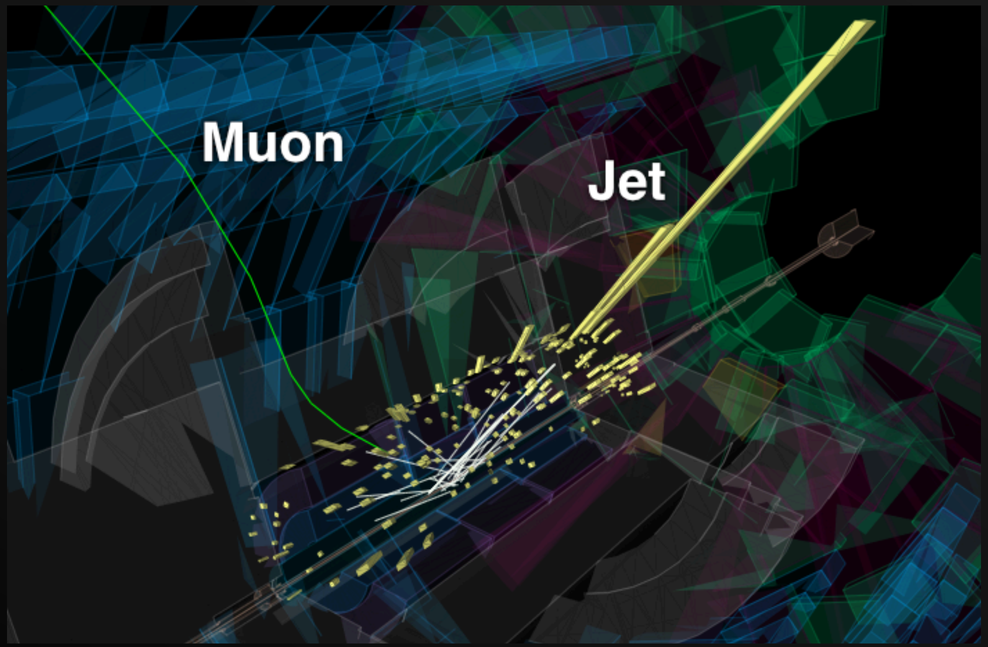
Full Run2

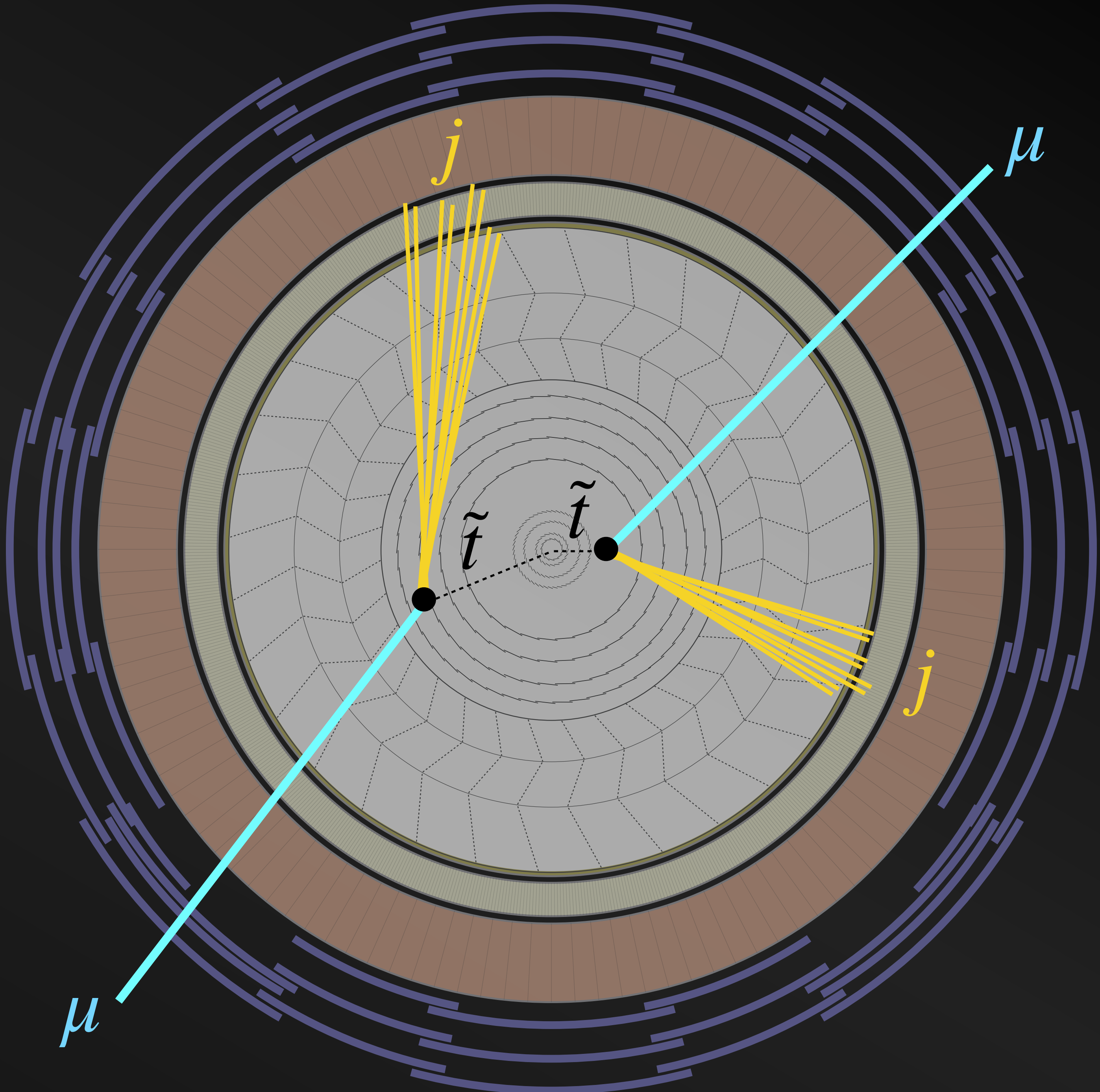
SUSY-2018-33
PRD 102 (2020) 032006

Benchmark model:
A tiny RPV coupling would make stop alive for O(1ns)



$$\tau(\tilde{t}) \sim \left(\frac{500\ \mathrm{GeV}}{m(\tilde{t})}\right)\left(\frac{10^{-7}}{\lambda'_{23k}}\right)^2\left(\frac{0.12}{\cos^2\theta_t}\right) \times 10^{-3}\ \mathrm{ns}$$



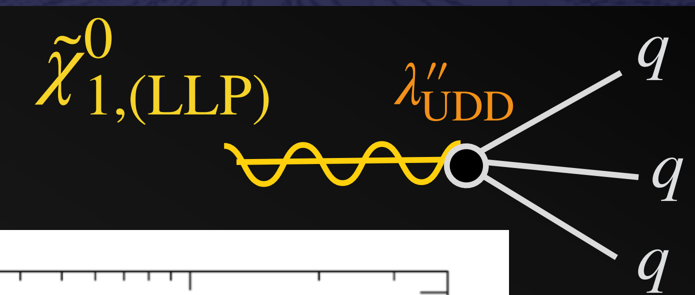


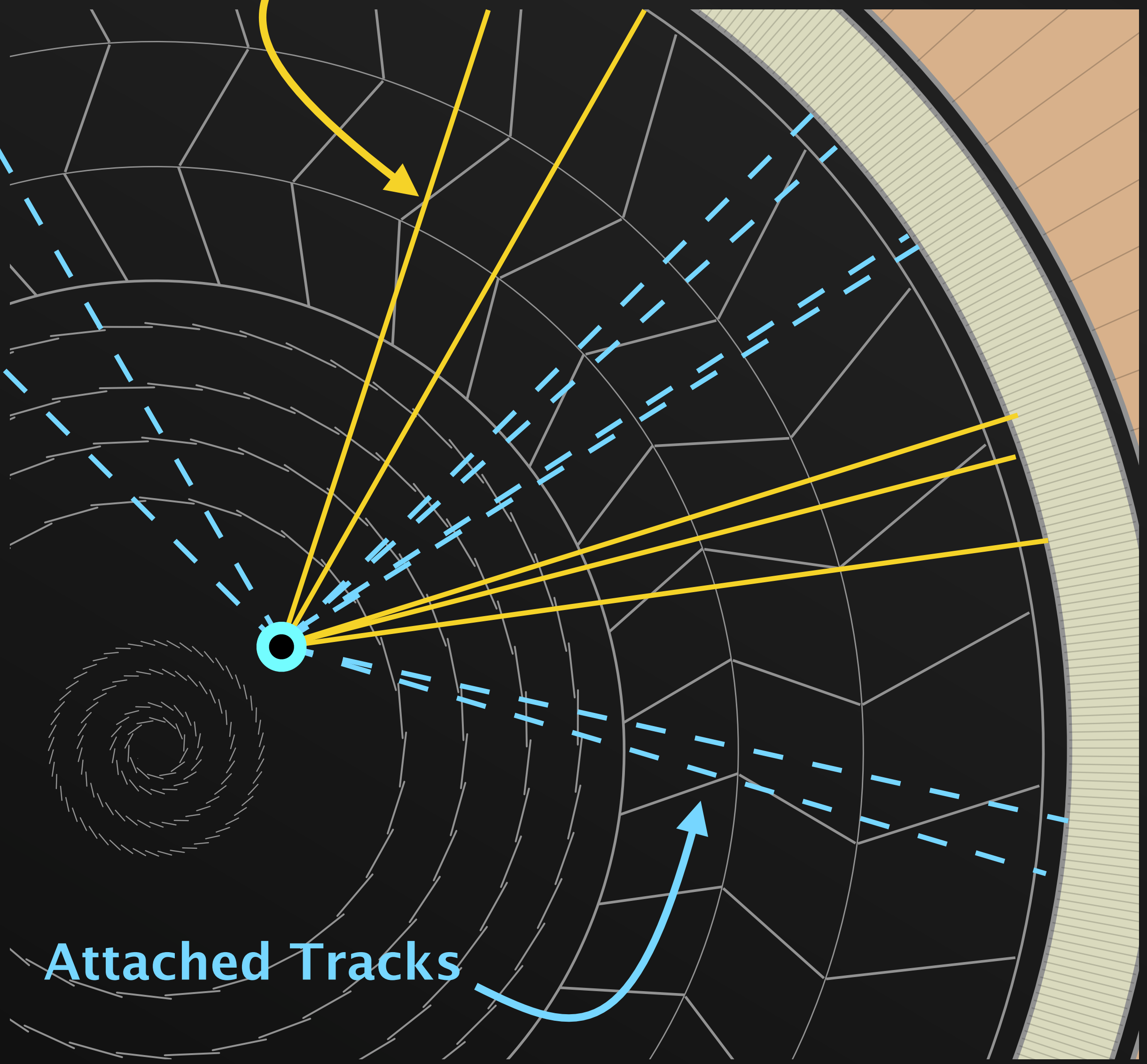
Signal DV: r > 4 mm, ≥3 tracks, m_{vis} > 20 GeV and isolated non-prompt muon (decent cosmic ray veto)

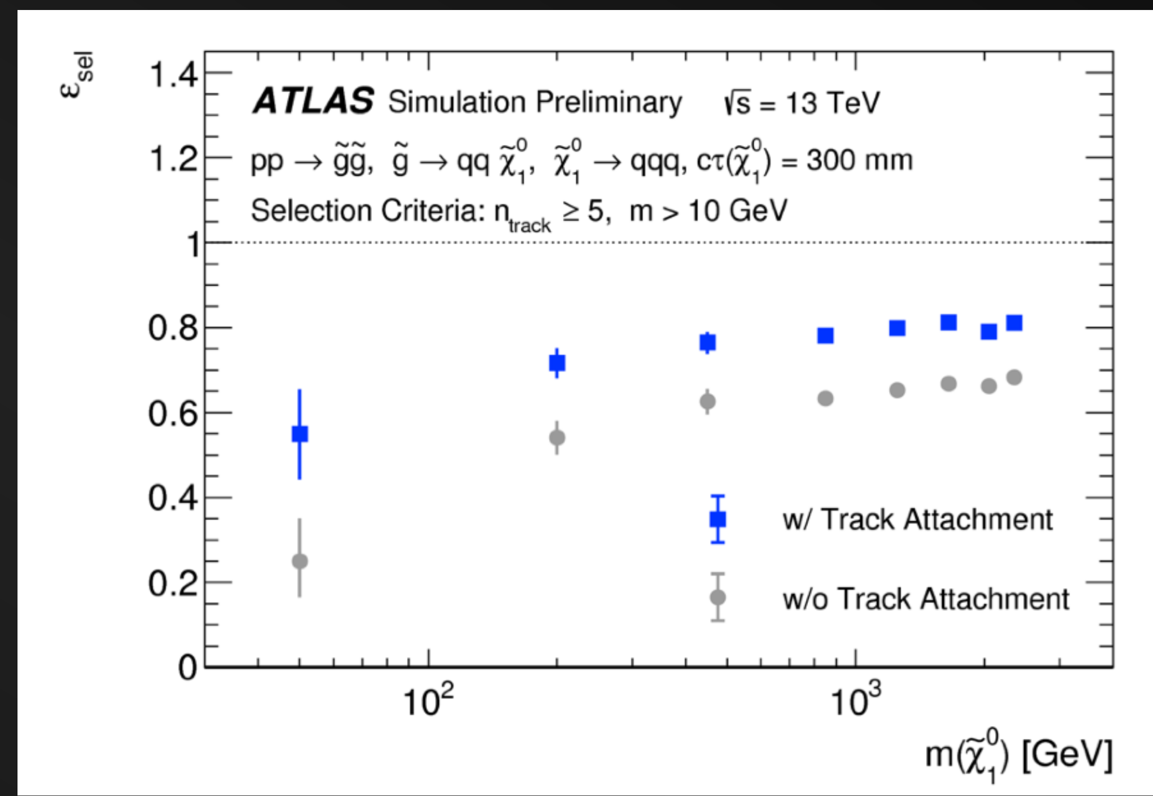
Resembling BGs: cosmic, b-jets, instrumental fakes

Displaced vertices with muons

SUSY-2018-33
PRD 102 (2020) 032006







ATL-PHYS-PUB-2019-013

For DV+μ: around 20-30% of the signal efficiency recovery.

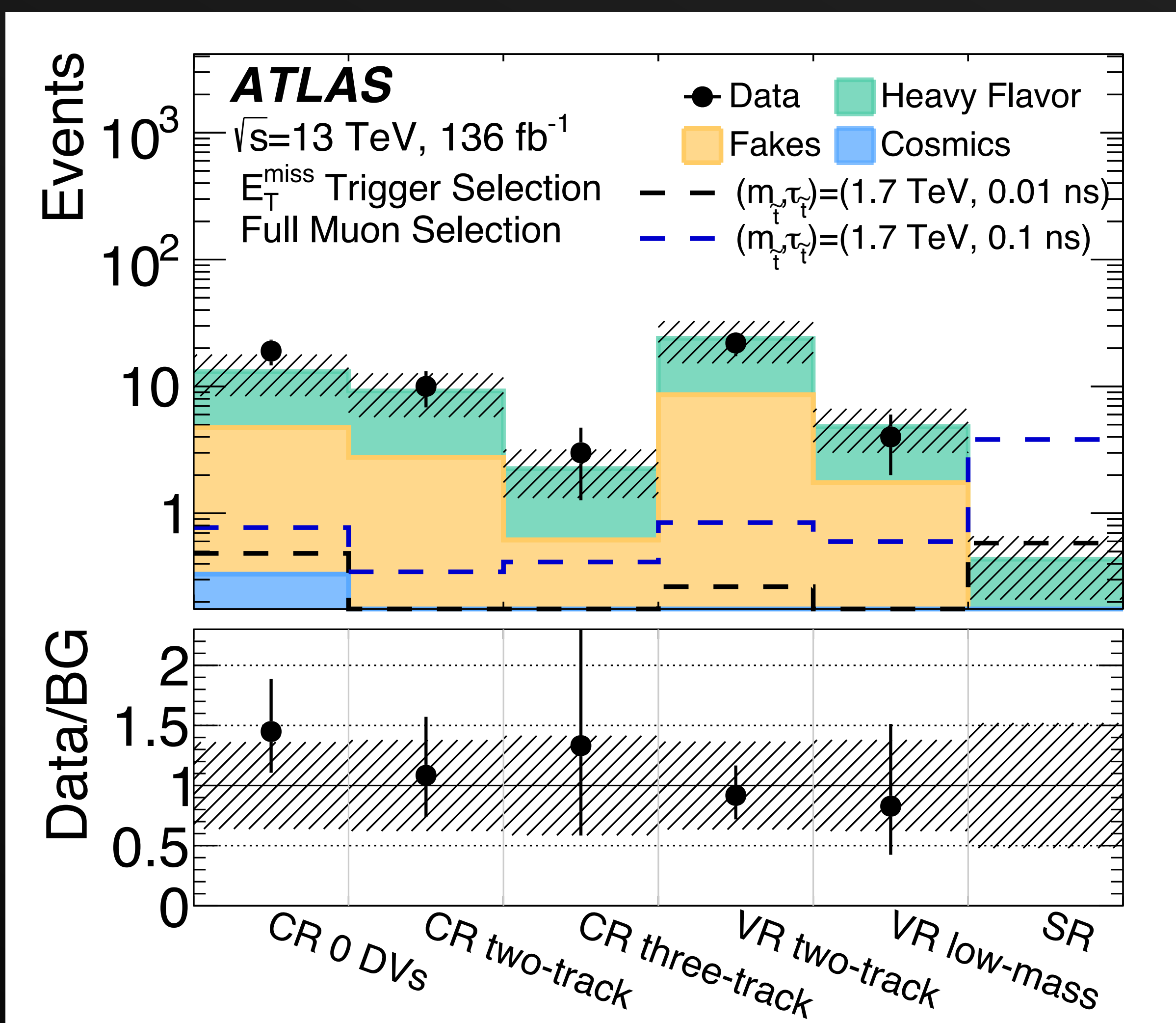
★ For full Run-2 DV analyses: a significant improvement in the vertex reconstruction algorithm in enriching vertex properties of multiplicity and mass.

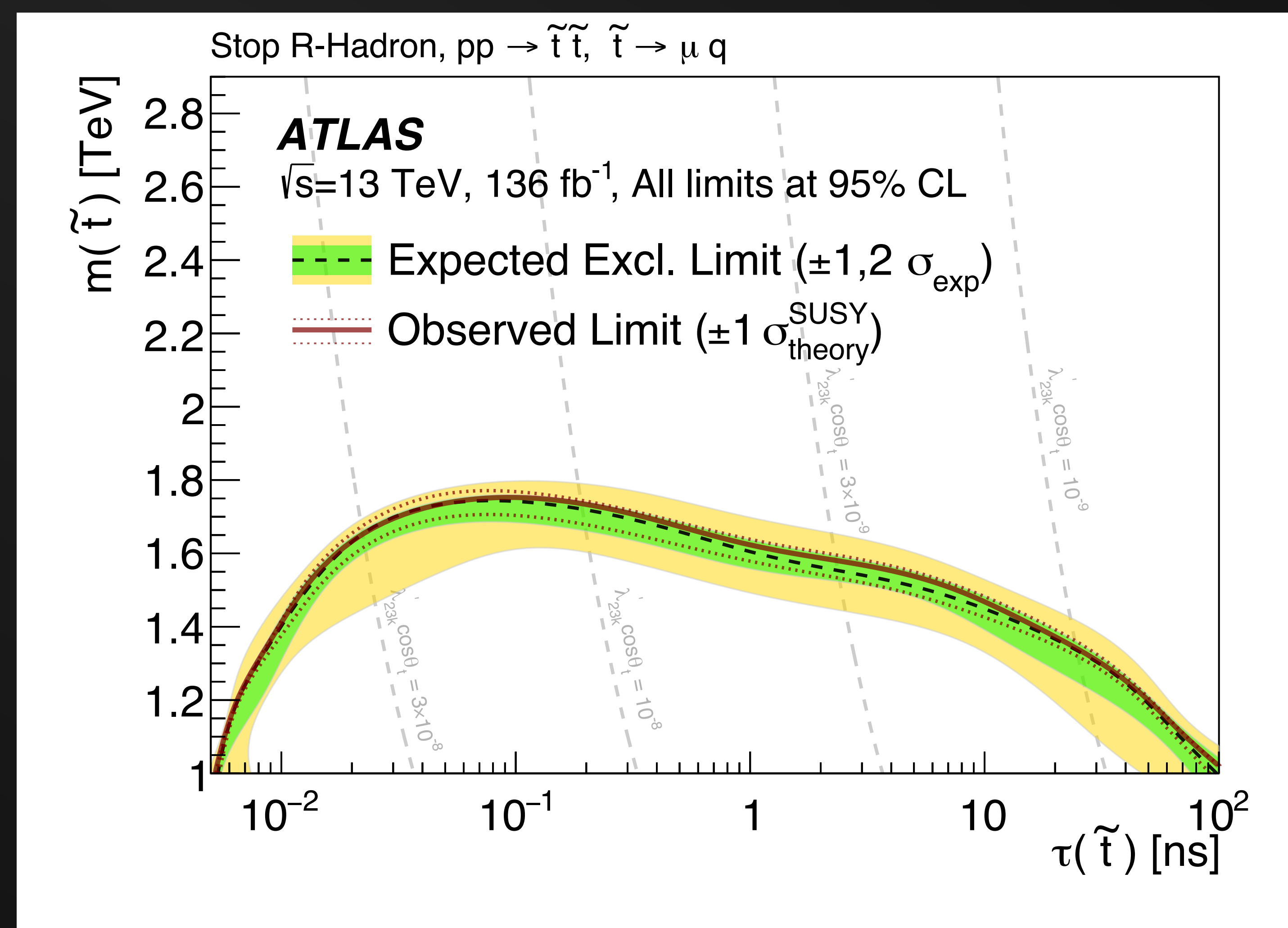
Full Run2

Displaced vertices with muons

SUSY-2018-33
PRD 102 (2020) 032006

- ★ MET or displaced muon trigger; exclusive 2 SRs. Cosmic ray veto + hadronic interaction veto.
- ★ Robust data-driven background estimation for 3 exclusive categories (transfer factor from CR to SR for each of cosmic, heavy-flavor, fake Bkg components)
- ★ SR yields are consistent with background estimation.
- ★ Excluding stop mass up to **1.75 TeV** around ~0.1 ns lifetime.





Displaced vertices with muons

SUSY-2018-33
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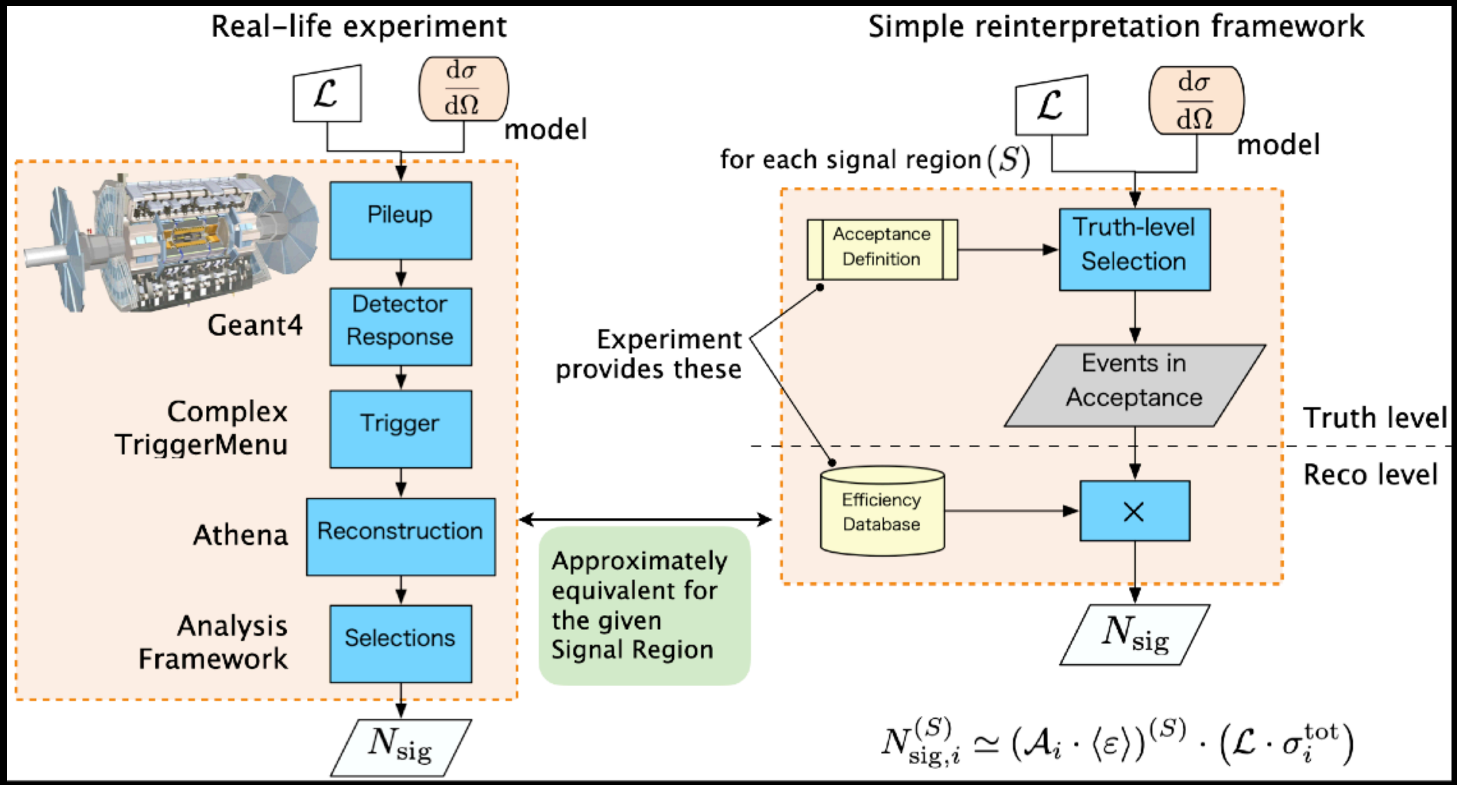
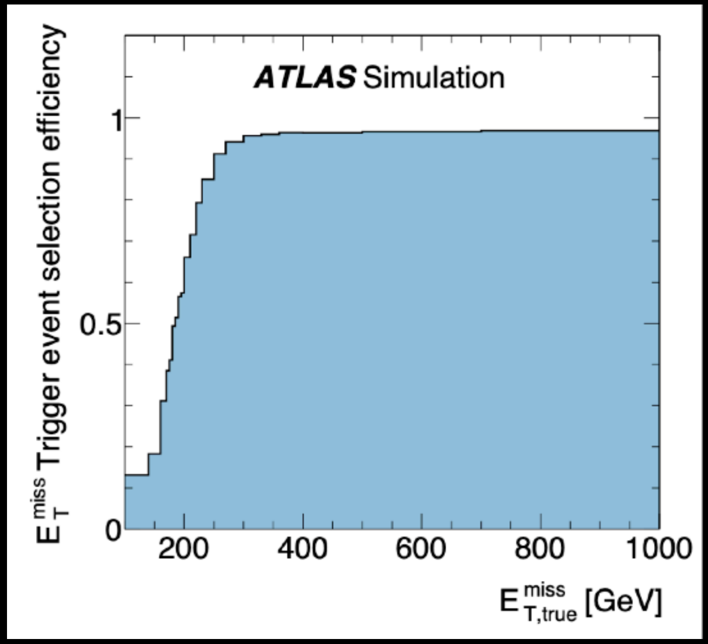
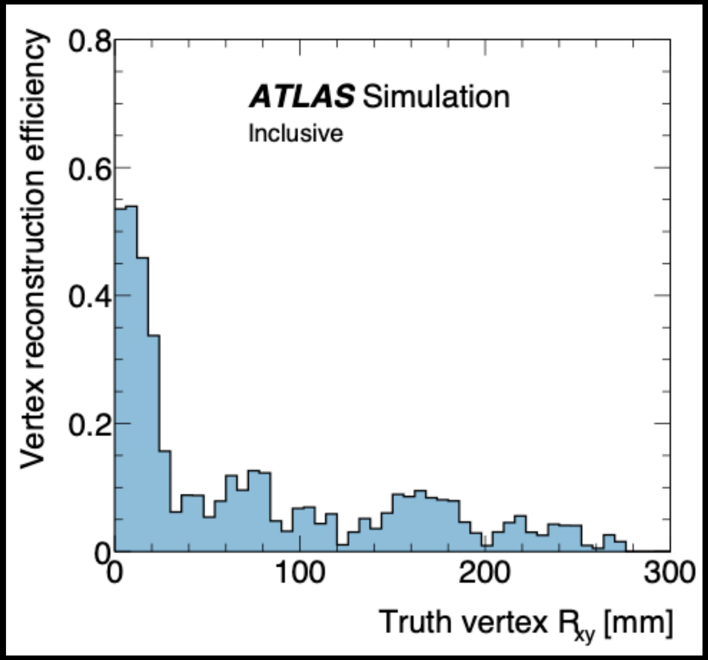


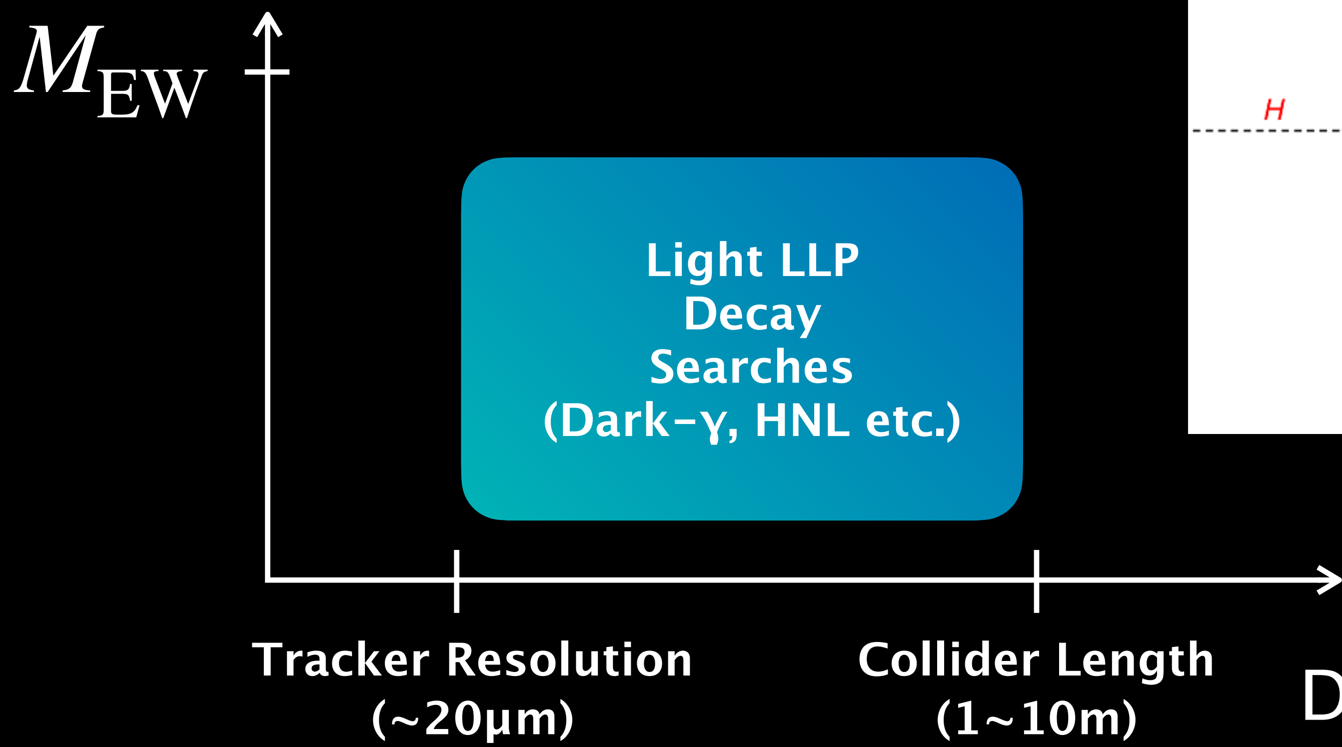


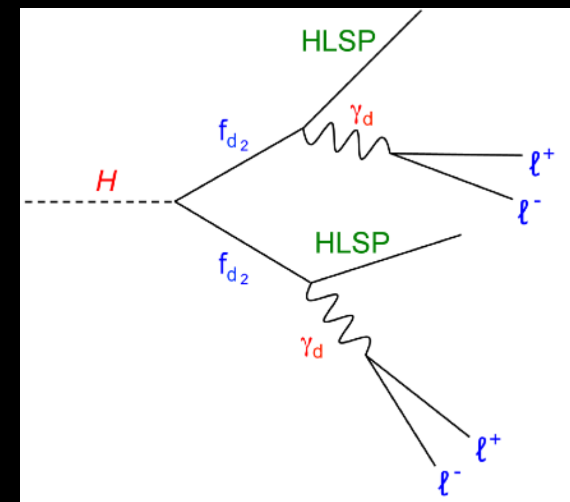


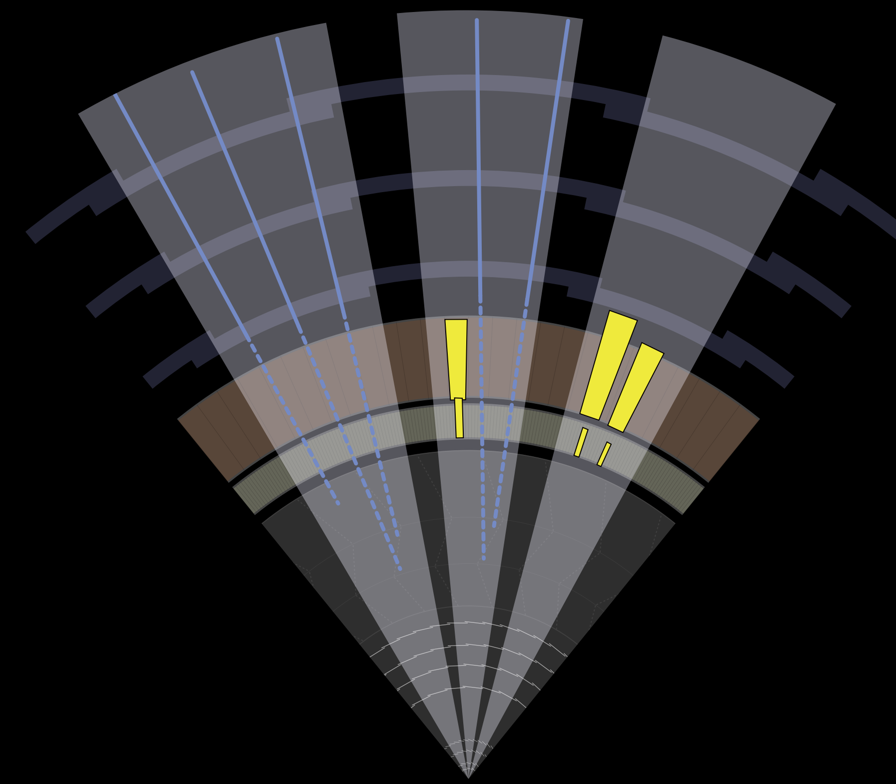
- ★ Displaced objects are tricky to summarize object's reco/selection efficiency due to relatively drastic change of them depending on the decay position/direction.
- ★ We have established a scheme to parameterize those such that they are useful and accurate(*) for reinterpretation works outside the collaboration. The present scheme is appreciated by relevant theorists' community.
- ★ DV+mu analysis also followed this scheme, HepData and document released on paper publication.
- ★ More details of this scheme reviewed here.

(*) within a certain limitation of applicability

NP Mass







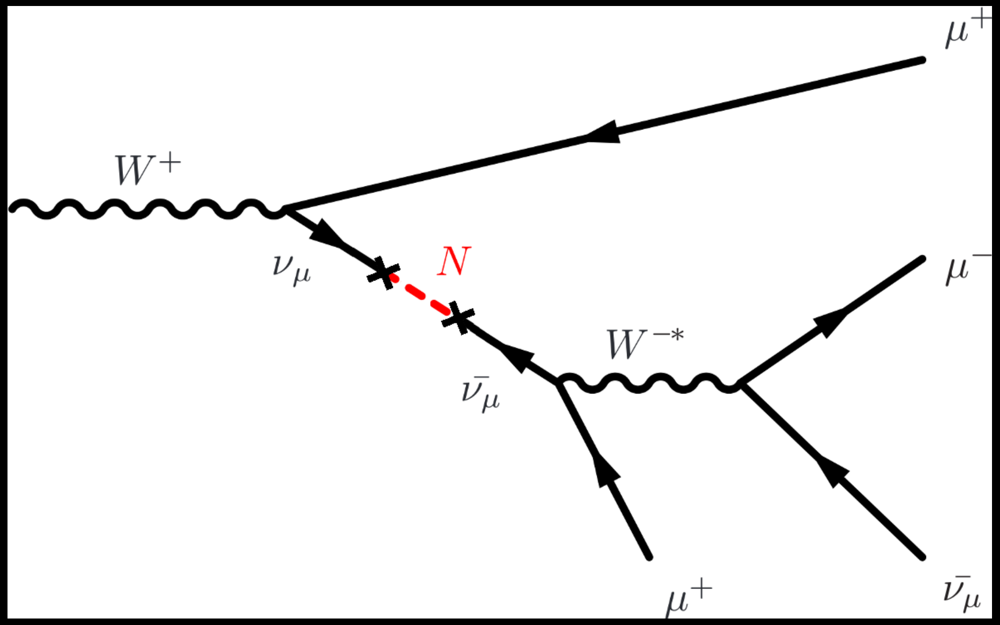
- ★ The target object (e.g. dark photon) is relatively light and highly boosted.
- ★ Signatures are collimated particles:
  collimated lepton appearances, displaced di-muon vertex, etc.
  - ★ For Heavy Neutral Lepton search, a prompt single lepton additionally required.
  - ★ For singlino, double prompt jets could be additionally required.

Mid Run2

Displaced Heavy Neutral Lepton

EXOT-2017-26 / JHEP 10 (2019) 265

- Heavy Neutral Leptons could explain SM neutrino masses, matter-antimatter asymmetry, and is a DM candidate.
- The leptonic decay of SM W boson could yield long-lived HNL.
- Subsequent decay of HNL could yield di-lepton or semi-leptonic displaced vertex
- Signal: Prompt-μ from primary vertex (trigger); DV contains exact opposite-sign 2 leptons: $\mu^+\mu^-$ and μ^+e^-.
  - Inclusive DV reconstruction using large-radius tracking
  - $4\text{ mm} < r < 300\text{ mm}$
  - Cosmic-ray veto $\sqrt{(\Sigma\eta_\mu)^2 + (\phi - \Delta\phi)^2} > 0.04$
  - $m_{\mathrm{DV}} > 4\text{ GeV}$



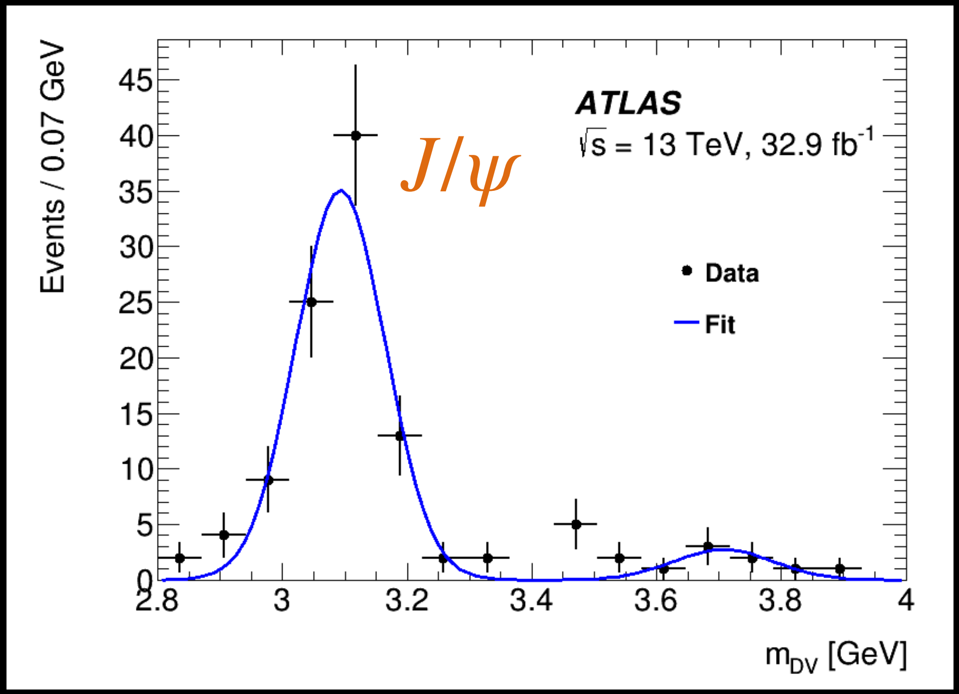
Mid Run2

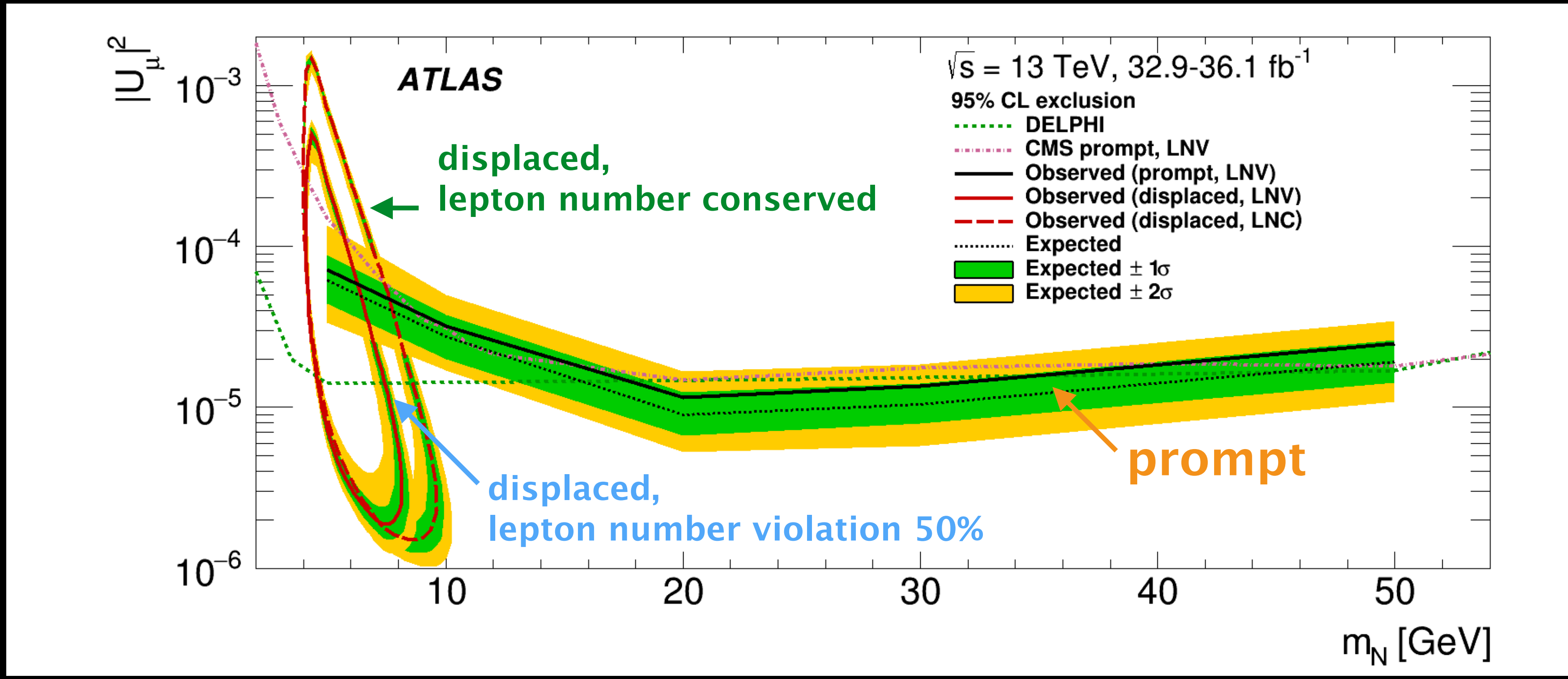
Displaced Heavy Neutral Lepton

EXOT-2017-26 / JHEP 10 (2019) 265

- True dilepton DV (J/ψ, Υ, etc.) found to be negligible.
- Bkg estimation: transfer factor from 0 → 2 leptons extracted from same-sign charge 2-trk DVs, then applied to the opposite-sign charge DVs.
  → estimated < 2.3 (90 % CL).
- Zero signal events observed in the SR.
- Unique sensitivity to HNL coupling strength in relatively low-mass region; complementary to the prompt HNL search.

CR plot (mixture of various triggers) inverting prompt lepton requirement



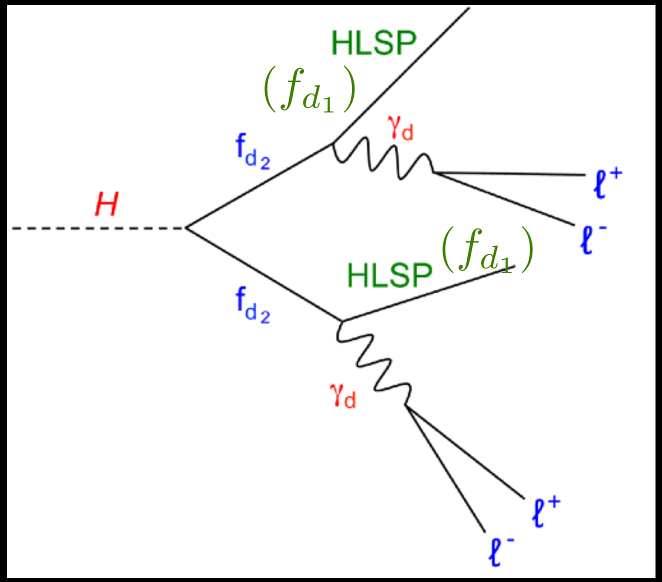


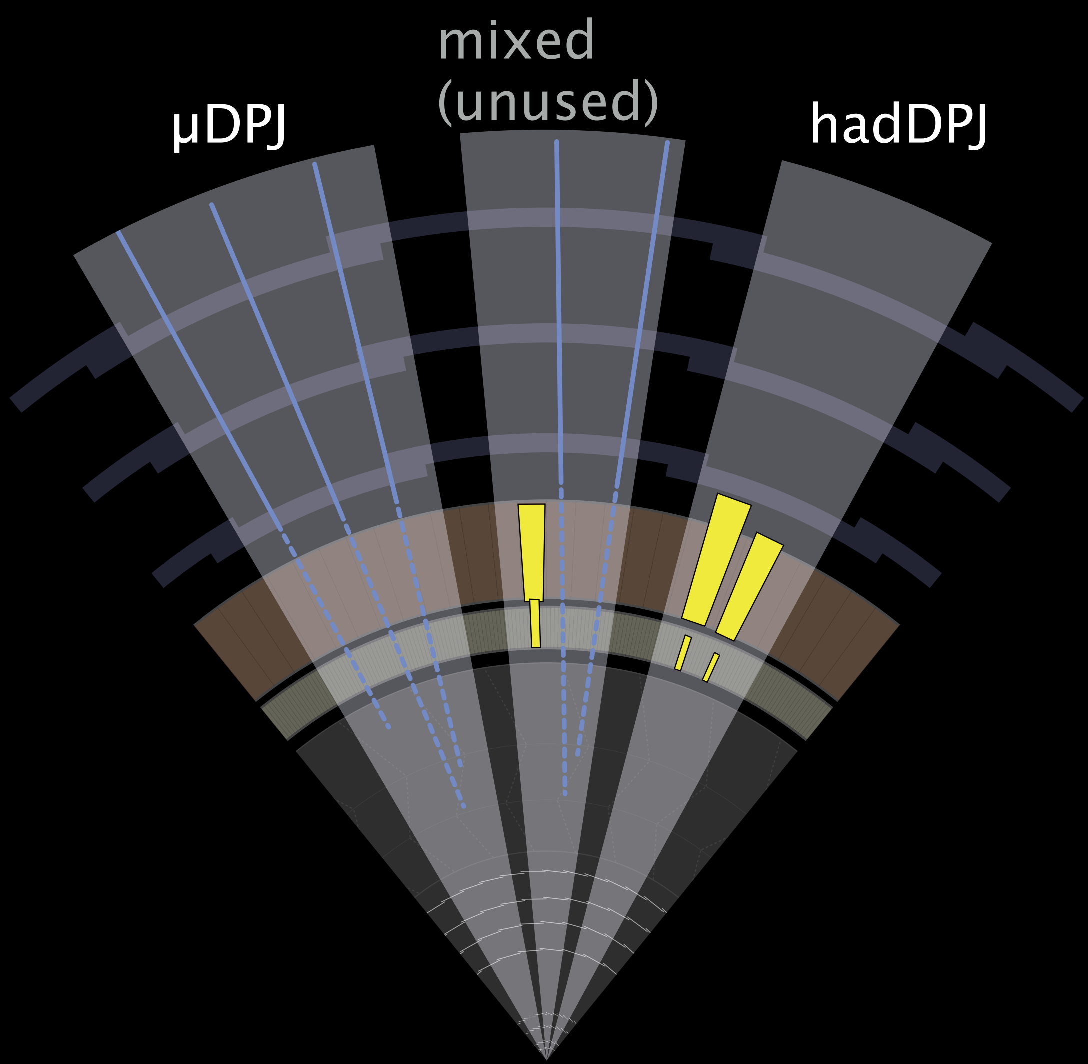
Mid Run2

Dark-photon jets search

EXOT-2017-28 / EPJC 80 (2020) 450

- ★ A light (MeV—GeV) dark photon decays to lepton or light hadron pairs.
- ★ Collimated flow of displaced particles including leptons: dark-photon jets (DPJ).
- ★ Higgs portal to dark fermion pairs producing γ_d.
  - ★ Case1: $f_{d_2} \to f_{d_1} + \gamma_\mathrm{d}$: up to 2μ / DPJ
  - ★ Case2: $f_{d_2} \to s_{d_1} + f_{d_1}$, $s_{d_1} \to \gamma_\mathrm{d}\,\gamma_\mathrm{d}$: up to 4μ / DPJ
- ★ Multiple DPJ types:
  - ★ muonic DPJ (clean ≥2 collimated muons)
  - ★ hadronic DPJ: a jet w/o muons, but CaloRatio required.
- ★ Dedicated trigger objects for DPJs
  - ★ muon “narrow scan” trigger: the dedicated HLT for single-DPJ trigger.
  - ★ A 20 GeV L1 muon is confirmed as MS-only at HLT
  - ★ Ask for the 2nd MS-only muon (6—15 GeV) around the primary muon ($\Delta R < 0.5$).





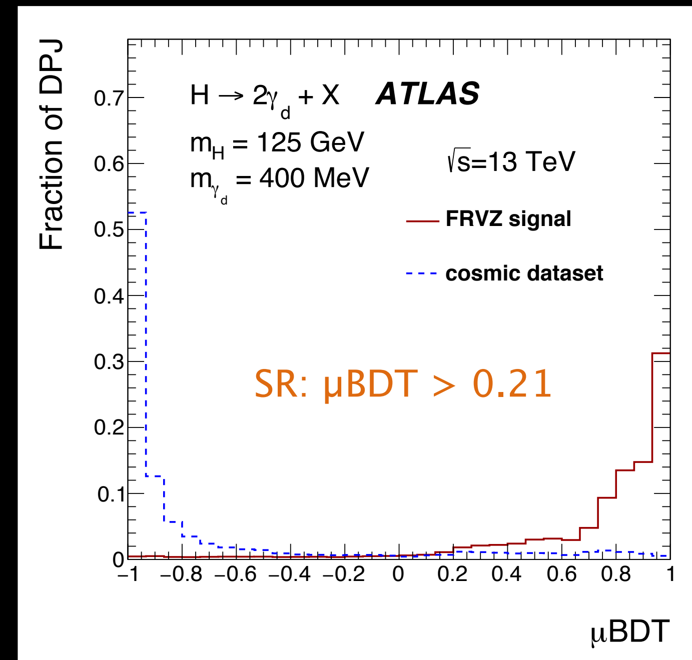
Dark-photon jets search

Mid Run2

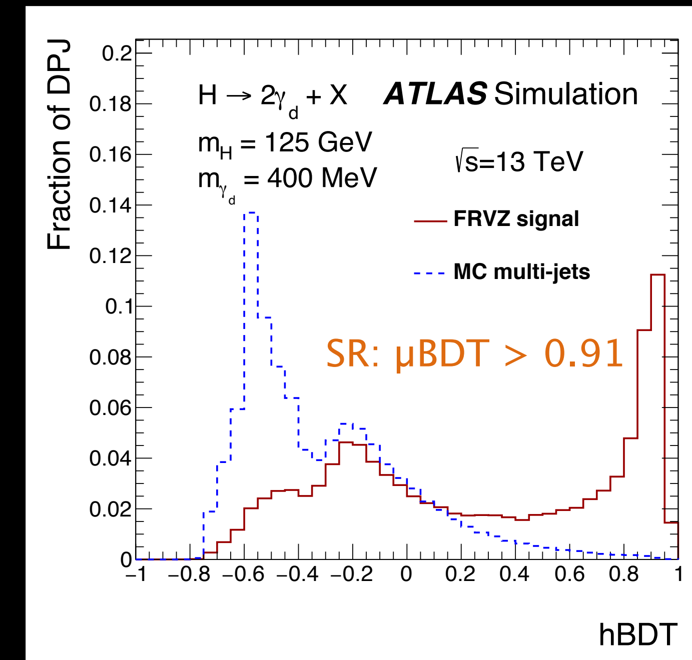
EXOT-2017-28 / EPJC 80 (2020) 450

- BDT-based signal/bkg classifier newly introduced : a major change from the prev. 2015 analysis.
  - μDPJ BDT: trained to separate signal from cosmic-ray MC
  - hadDPJ BDT: trained to separate signal from multijet MC
- 3 types of pairing:
  - μDPJ — μDPJ
  - μDPJ — hadDPJ
  - hadDPJ — hadDPJ
- Data-driven ABCD background estimation.
- ABCD vars: periphery tracks activity around DPJ and the opening angle between the two DPJs.

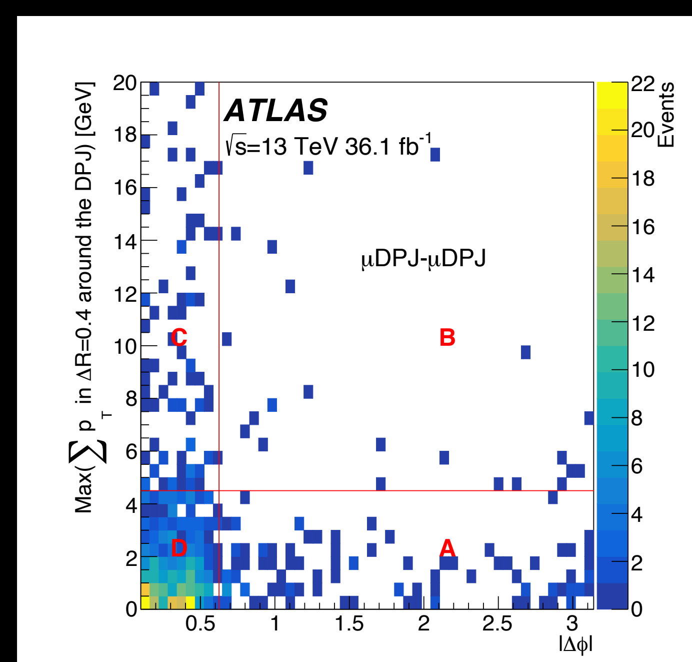
μDPJ BDT



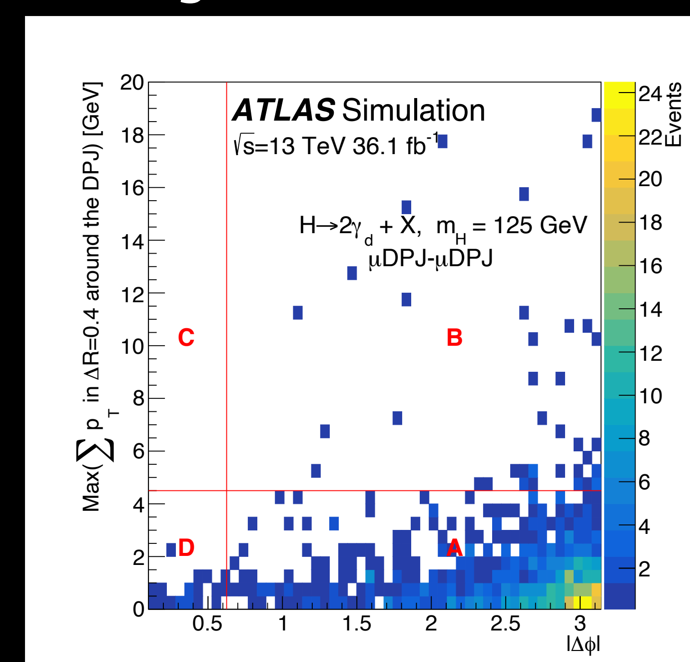
hadDPJ BDT



Data distribution



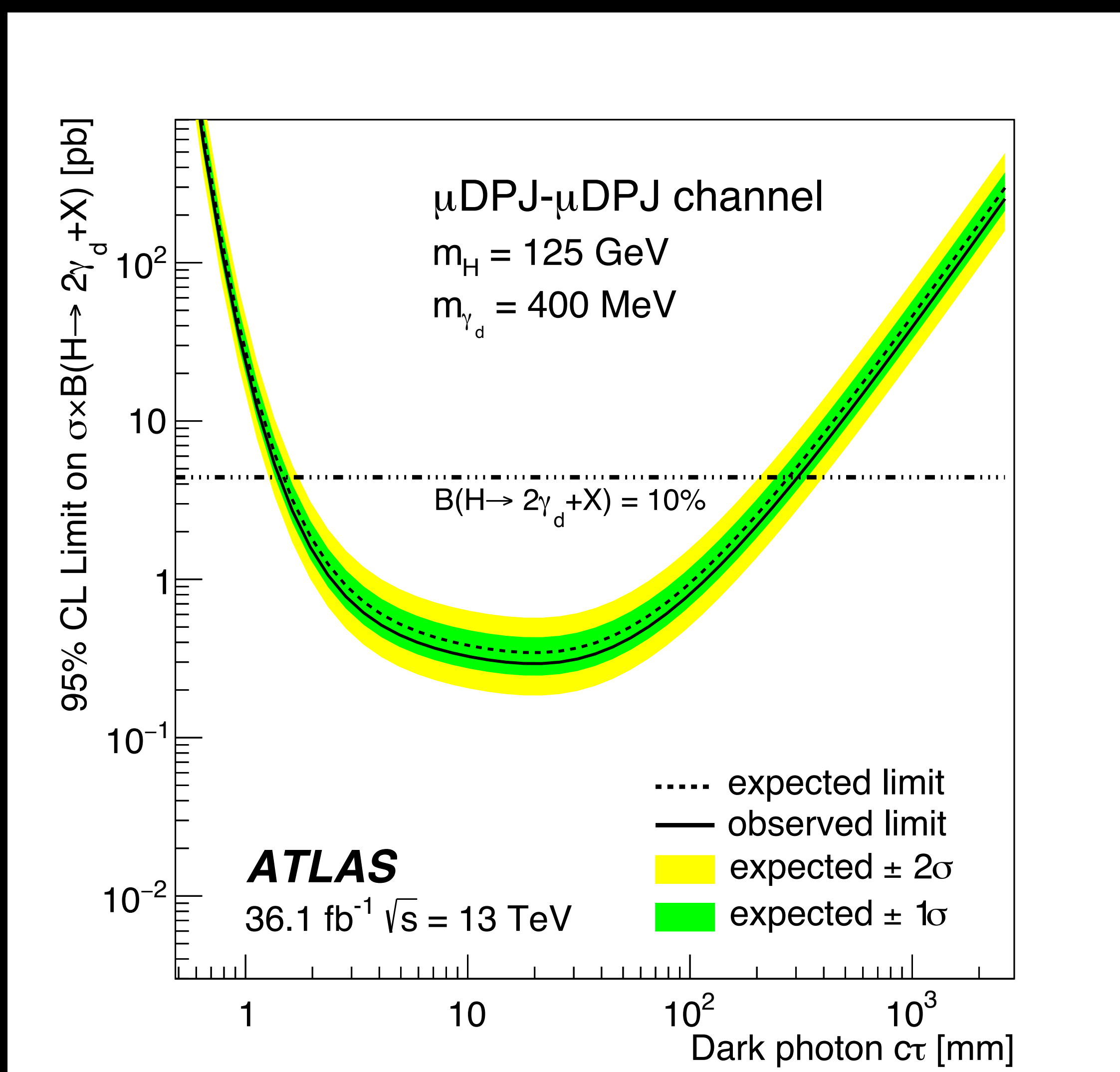
Signal distribution

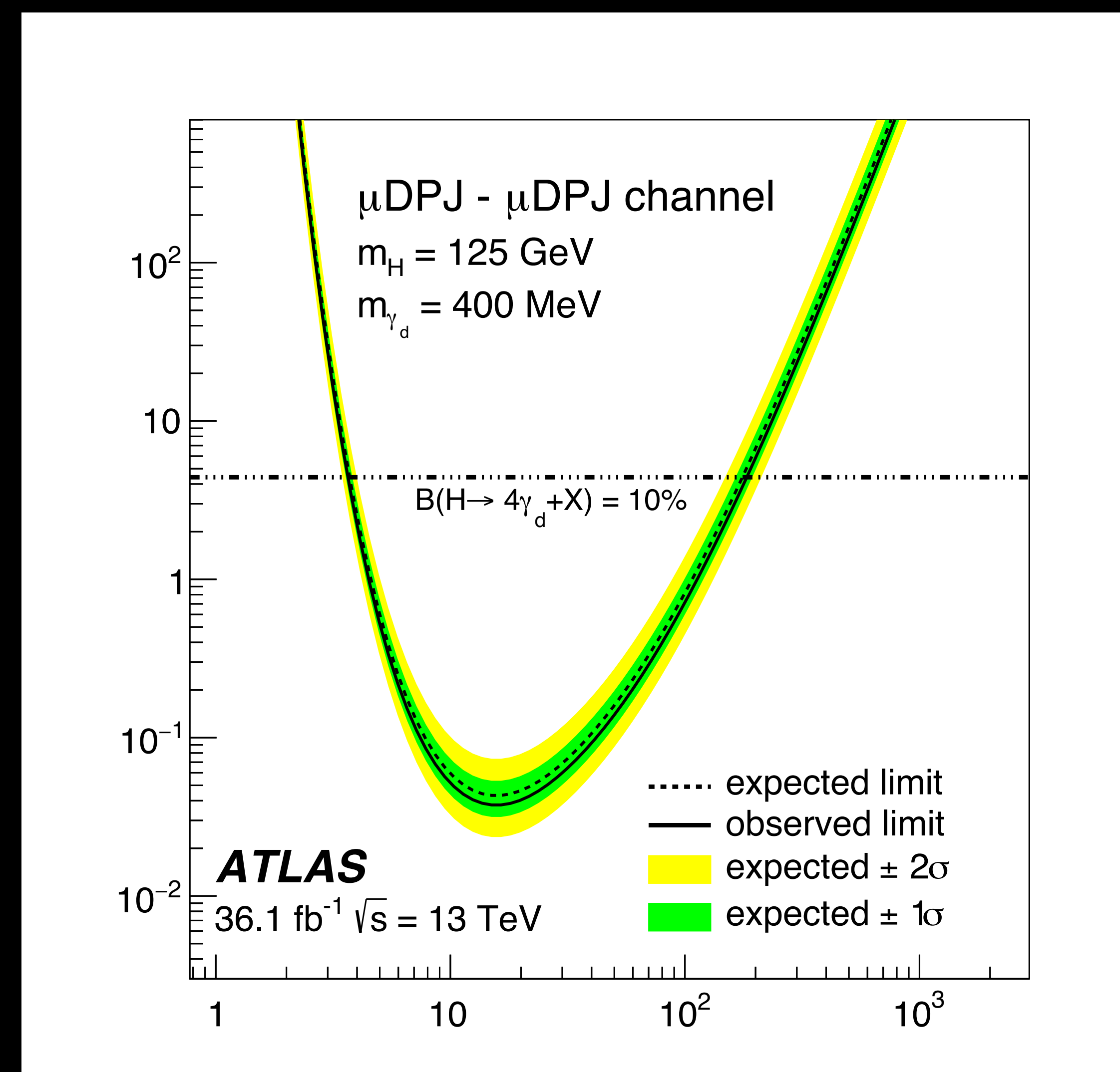


Dark-photon jets search

EXOT-2017-28 / EPJC 80 (2020) 450

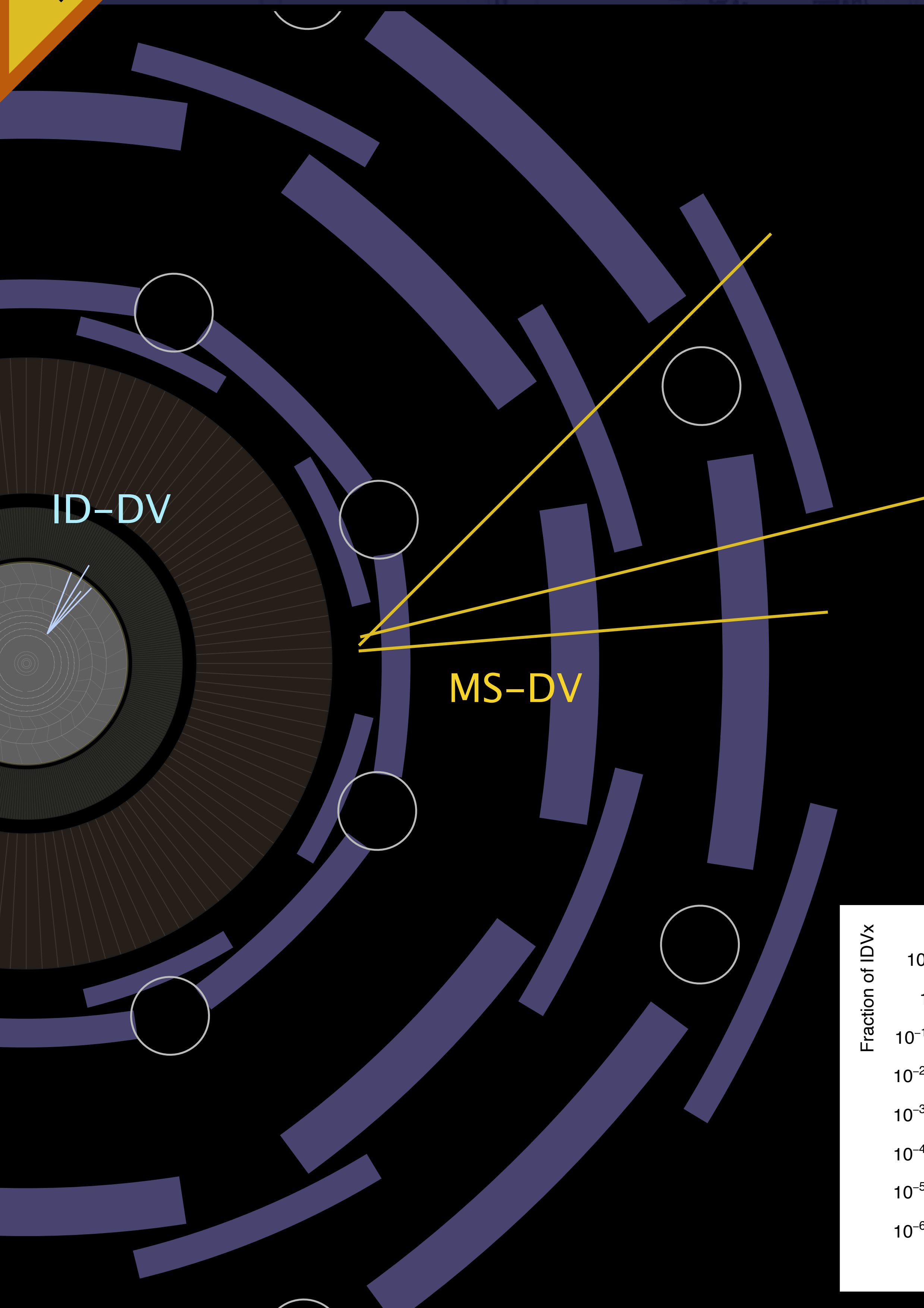
- Observed bkg. yields are all consistent with the expectation.
- Limits presented for 125 GeV higgs decay to $2\gamma_d$ and $4\gamma_d$ (400 MeV), and 800 GeV heavy higgs decay to $2\gamma_d$ (400 MeV).



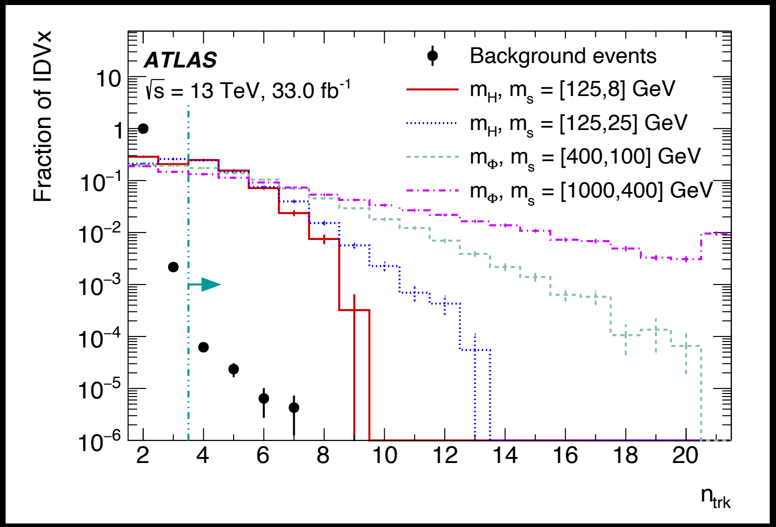


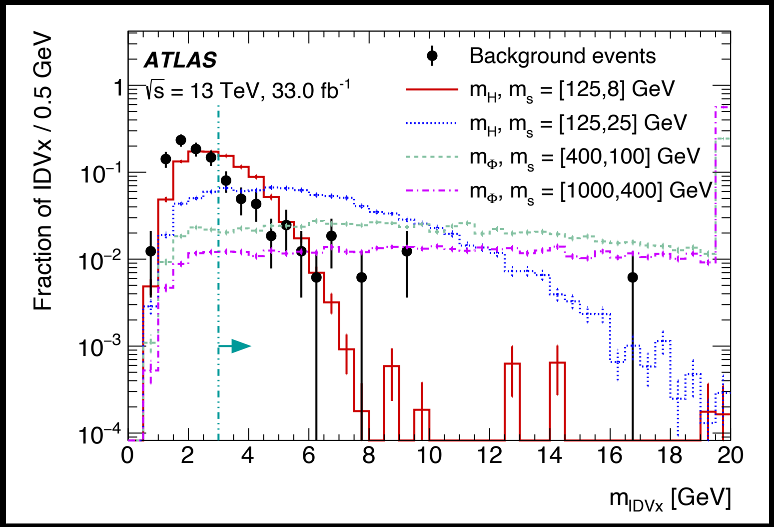
DVs in ID & MS

EXOT-2018-61 / Phys. Rev. D 101 (2020) 052013



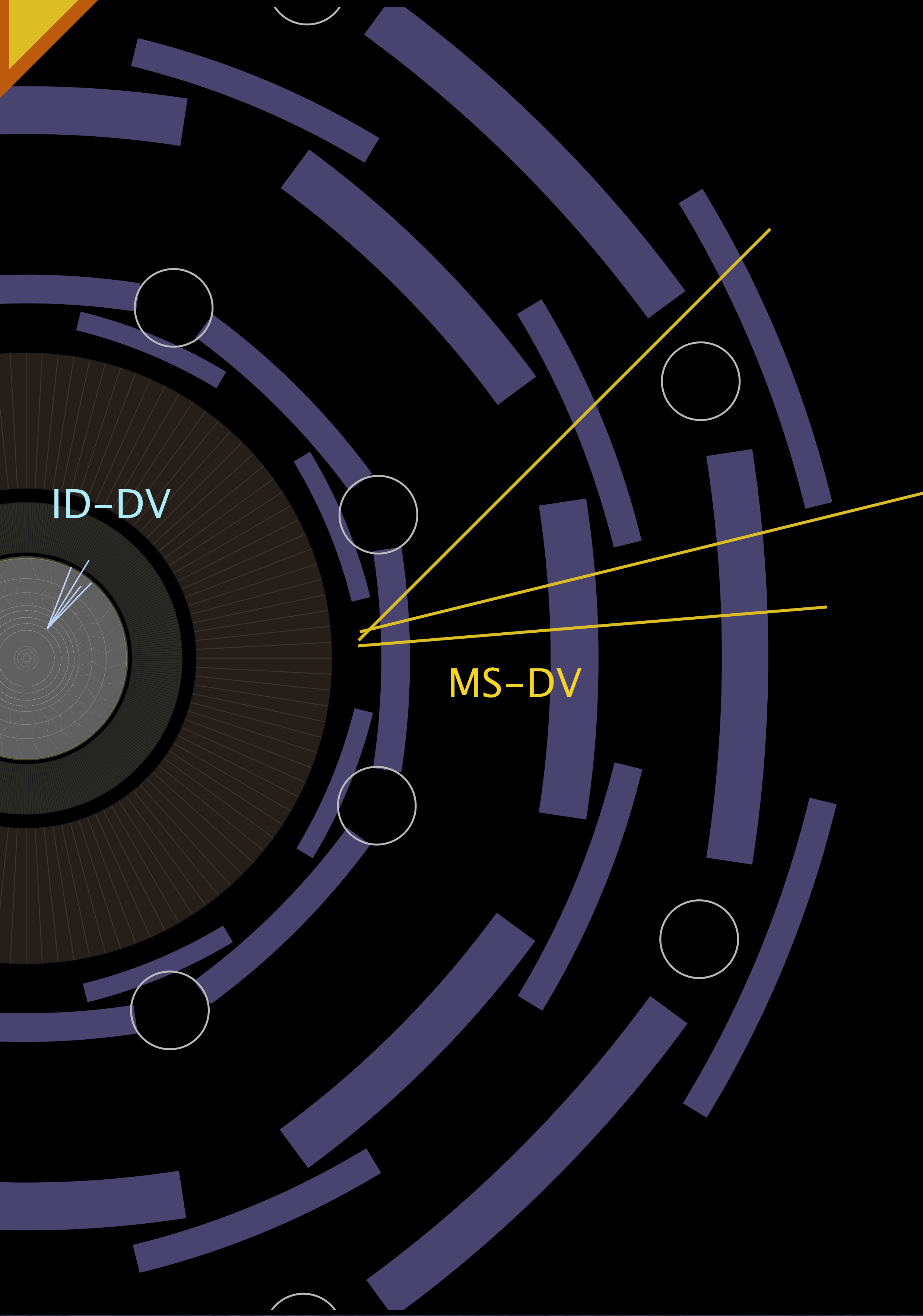
- Another type of search: combination of DVs in different places: ID and MS.
- ID-DV: $n_{\mathrm{trk}} \geq 4$ and $m_{\mathrm{DV}} > 3$ GeV
- MS-DV
  - Sufficient number of MDT hits (300—3000)
  - >250 trigger chamber hits
  - Isolation from $p_{\mathrm{T}} > 5$ GeV tracks $\Delta R > 0.3_{\mathrm{barrel}}$ / 0.6_{endcap}
- Isolation of DVs from jets and other event activities.
- Angular distance between ID-DV and MS-DV. $\Delta R > 0.4$
- ID-DV Bkgs: material interaction, fake trks, accidental crossing
- MS-DV Bkgs: punch-through jets



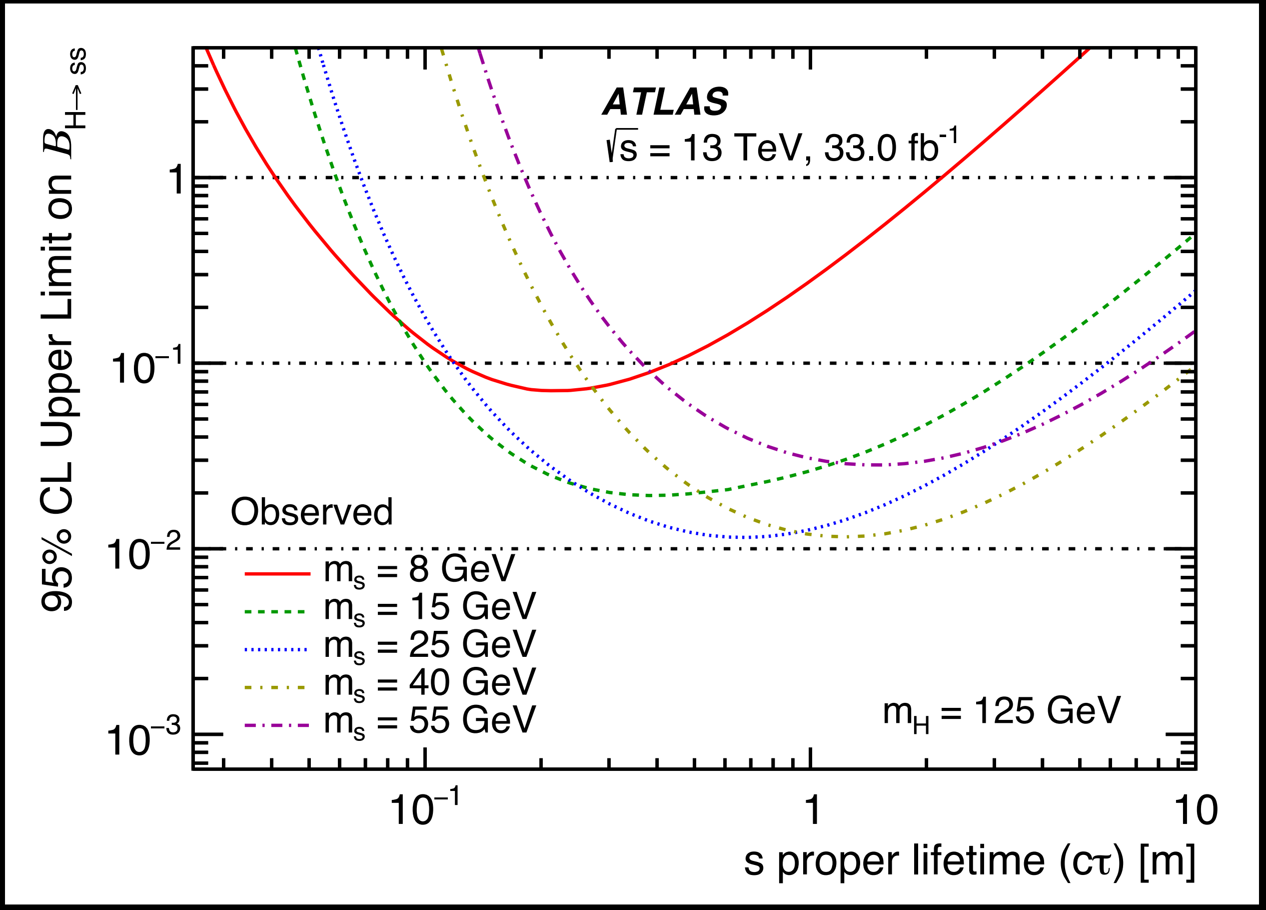


DVs in ID & MS

EXOT-2018-61 / Phys. Rev. D 101 (2020) 052013



- ★ 1 vertex observed in SR
- ★ Prediction: $1.16 \pm 0.18_{(stat)} \pm 0.29_{(sys)}$
  → observation is consistent with Bkg.

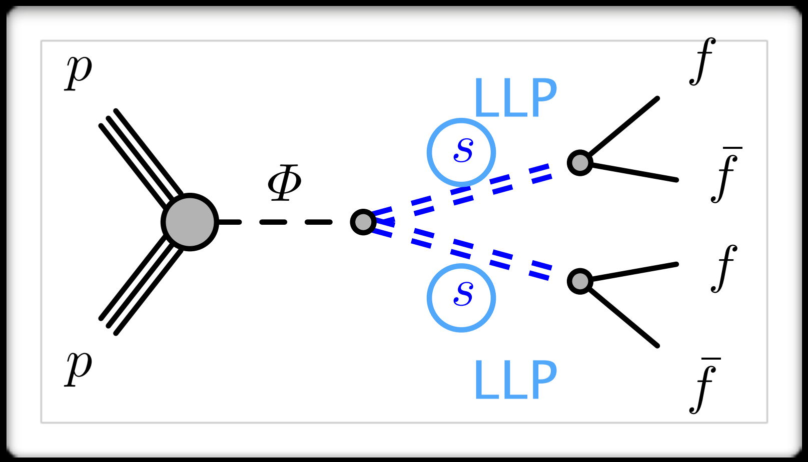


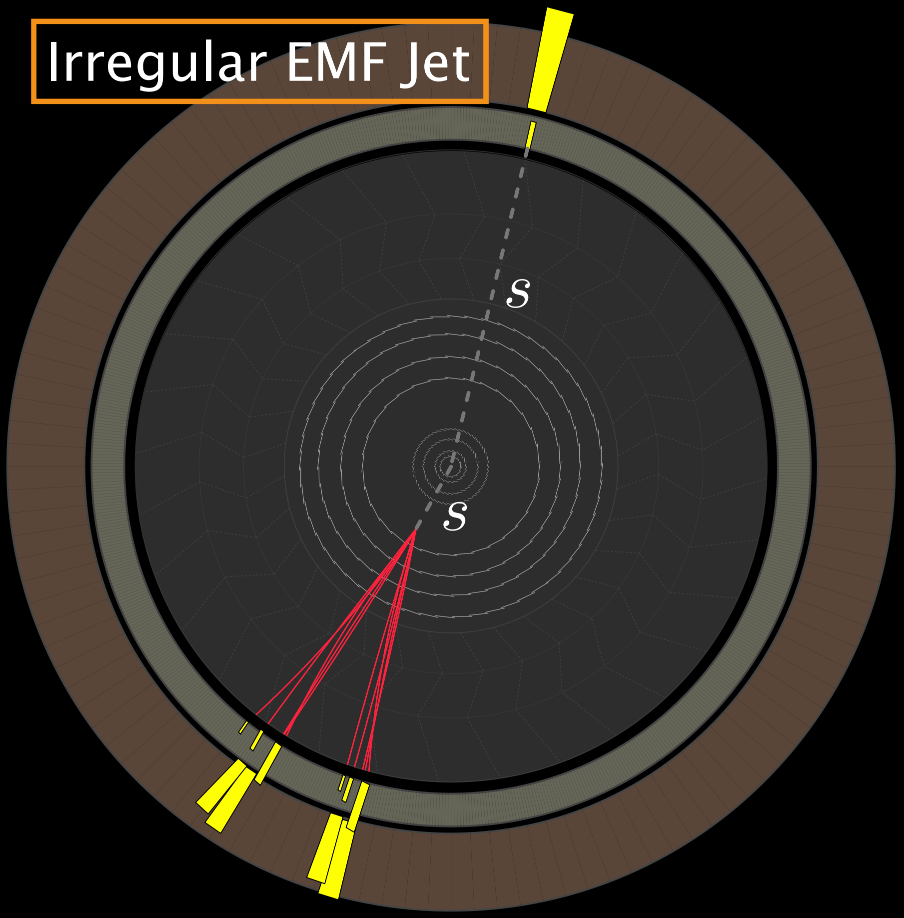
Example limit for the case of $\Phi = H_{SM}$ for various scalar LLP masses.

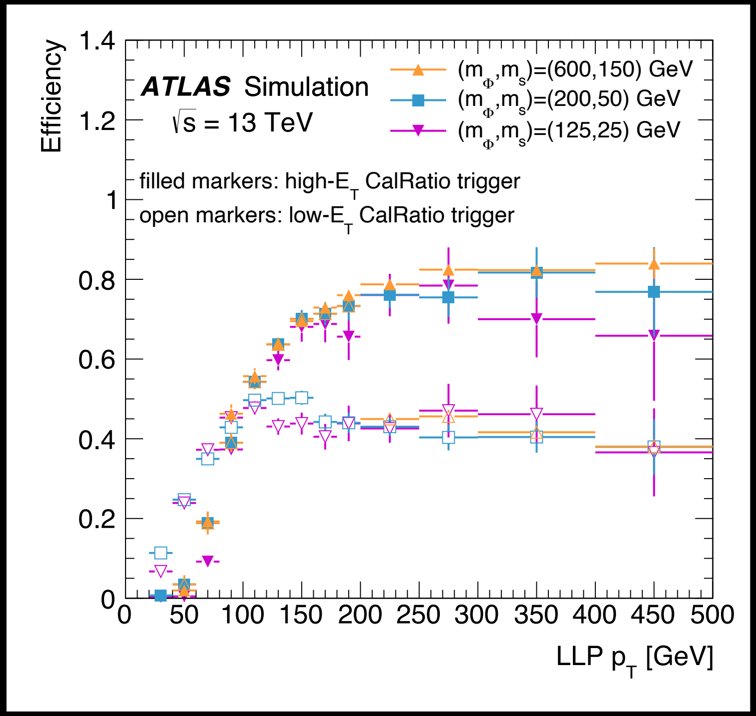
LLP decays in HCal

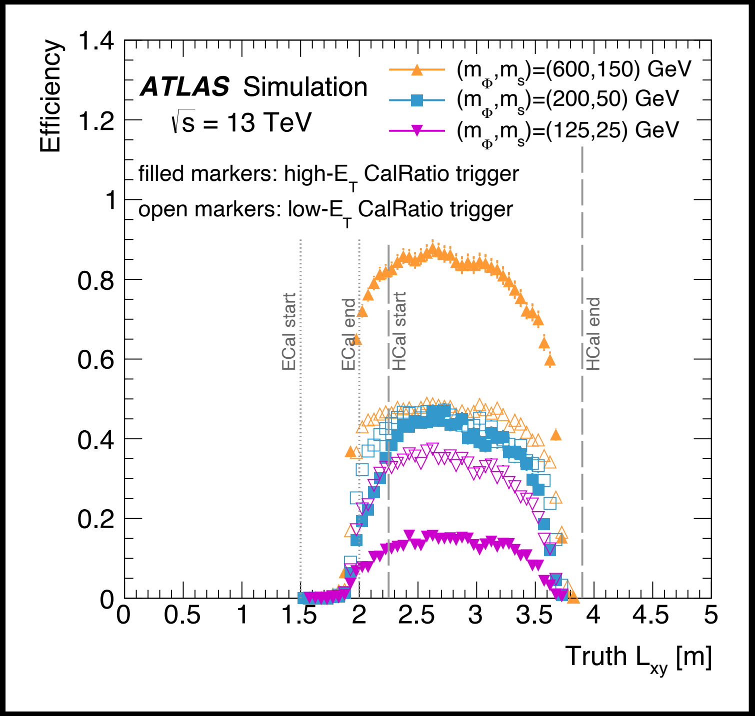
EXOT-2017-25 / EPJC 79 (2019) 481

- ★ A hidden-sector model:
  Heavier scalar Φ → scalar LLPs s → fermion pairs each
  (Yukawa: the dominant decay is $b\bar{b}$)
- ★ Decay inside the tile calorimeter ($1.8\ \mathrm{m} < r < 4\ \mathrm{m}$):
  - ★ Energy fraction $E_{\mathrm{H}}/E_{\mathrm{EM}}$ is irregularly very large
  - ★ The jet shape is much sharper than SM.
- ★ Dedicated triggers for tagging low EM fraction jets
  - ★ Lv1 trg: High-E_{T}: $E_T > 60$ GeV in $\Delta\eta \times \Delta\phi = 0.2^2$ (33 fb^{-1})
    Low-E_{T}: isolated $E_{\mathrm{T}} > 30$ GeV in $\Delta R < 0.2$ (10.8 fb^{-1})
  - ★ HLT: $\log_{10}(E_{\mathrm{HCal}}/E_{\mathrm{EMCal}}) > 1.2$









Main backgrounds:
Cosmic, multijets, non-collision beam-induced backgrounds

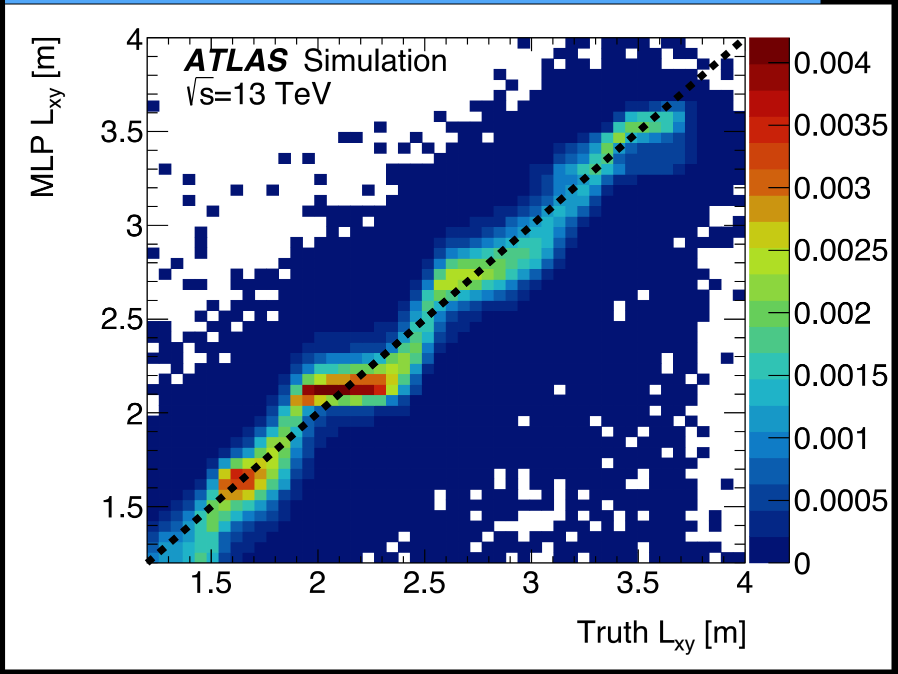
Mid Run2

LLP decays in HCal

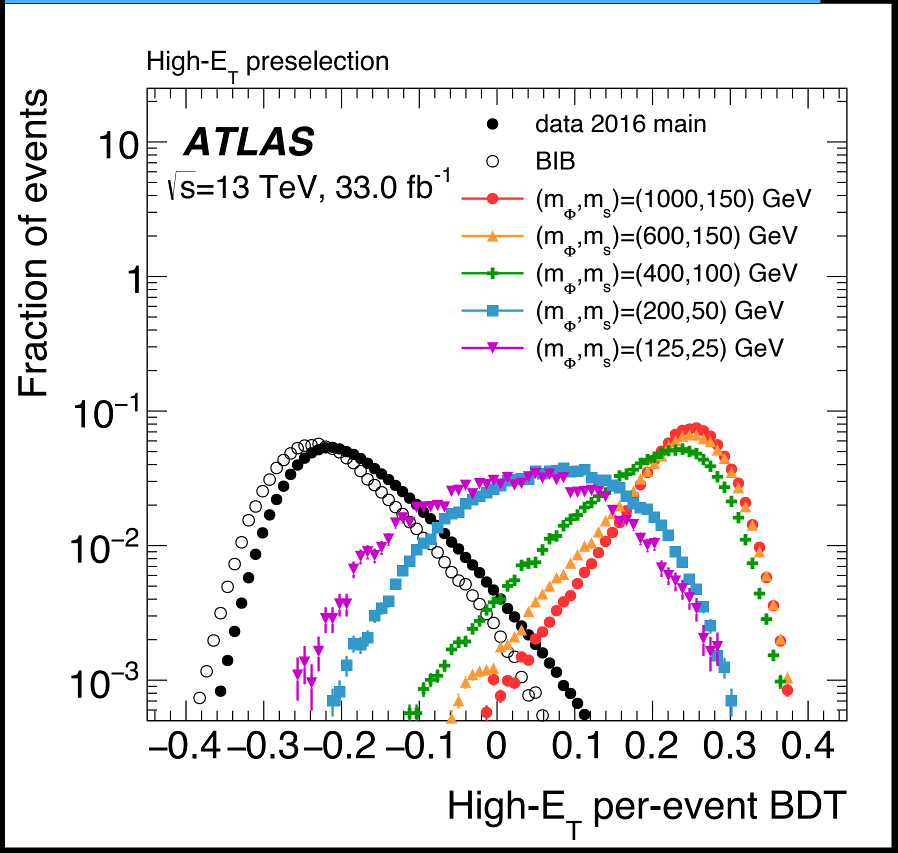
EXOT-2017-25 / EPJC 79 (2019) 481

- 2 sets of jet-level BDT are trained to distinguish Signal, beam-induced bkg (BIB), and QCD multijets.
  - Optimized for high-E_T and low-E_T respectively.
  - Using a multi-layer perceptron (MLP) to make a regression on the decay position.
  - BIB samples are event data in off-bunch-crossing.
- 2 sets of event-level BDT are used to mainly distinguish Signal from BIB events.
  - Effective to reduce QCD multijets as well.
  - Low-mass case is fundamentally challenging.

Decay position regression MLP

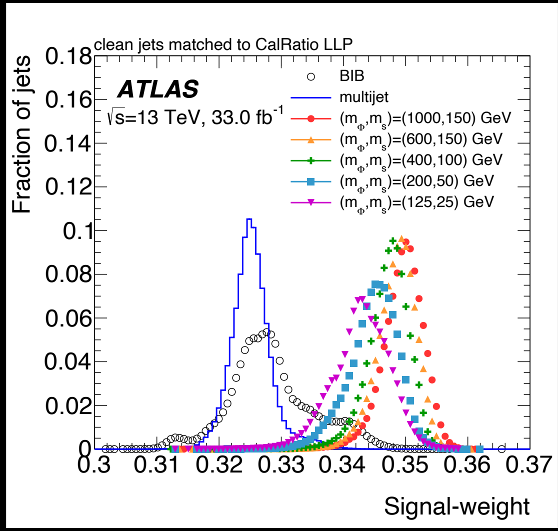


Event-level BDT (high-E_T case)

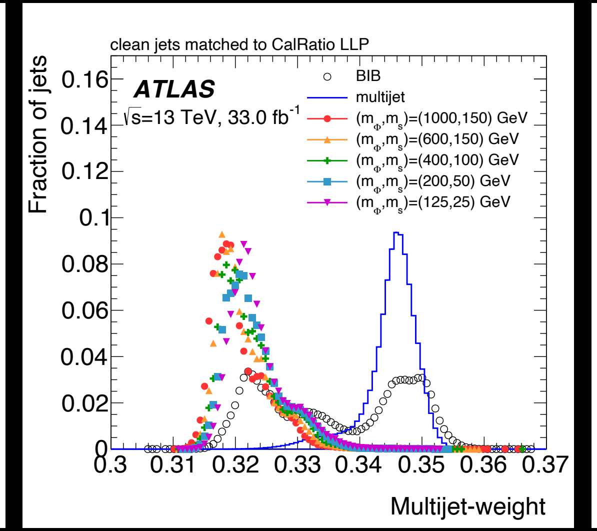


Jet-level signature classification BDT

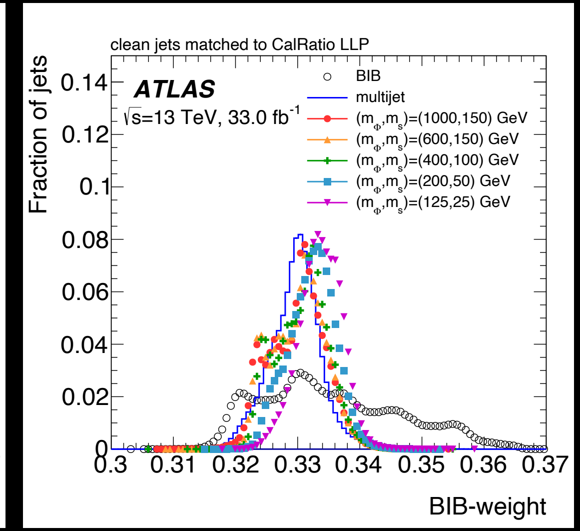
Signal Jet



SM Jet

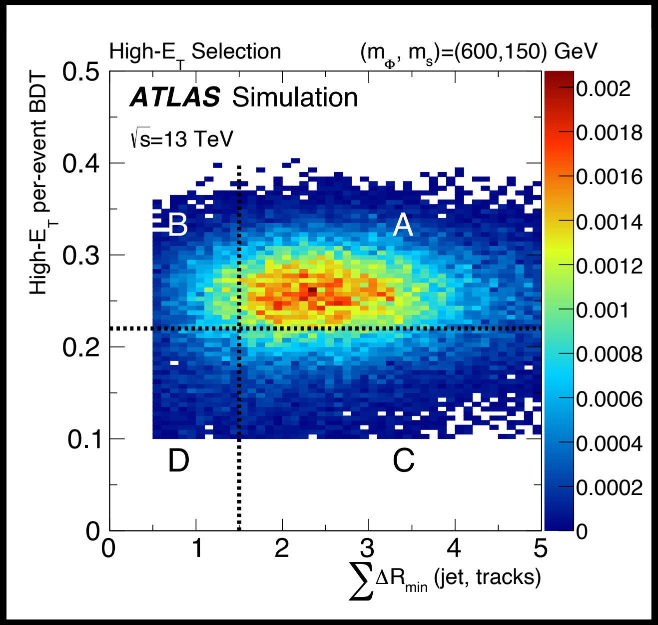


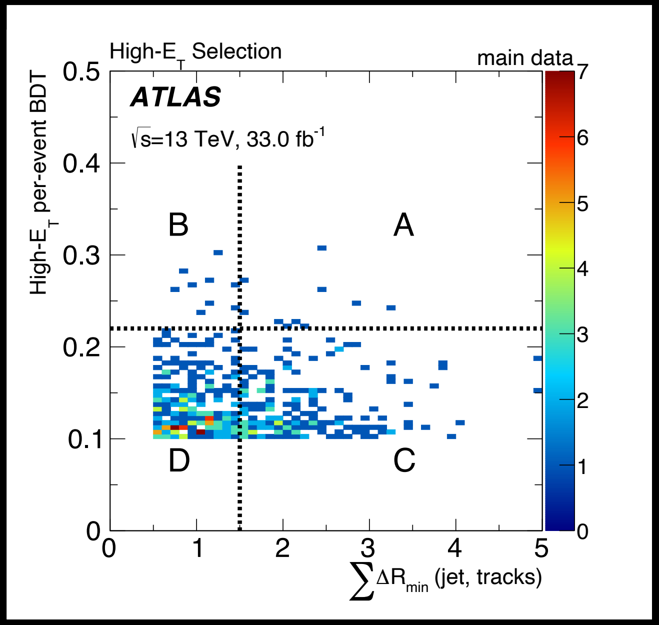
Beam-induced

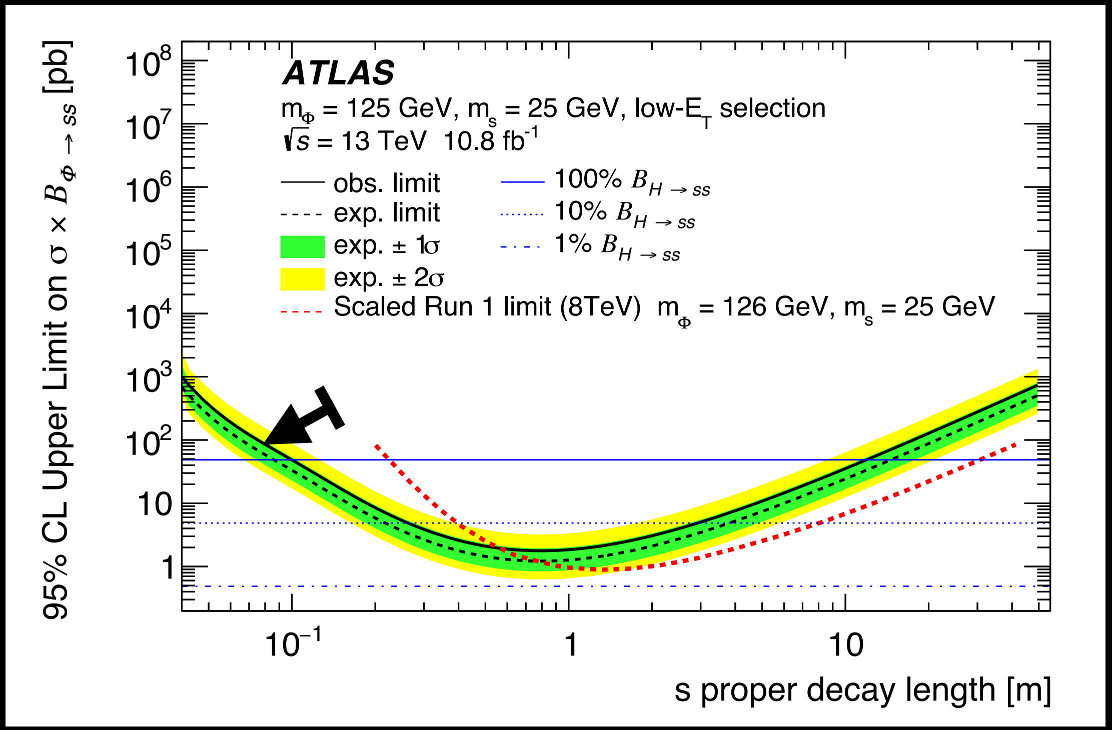


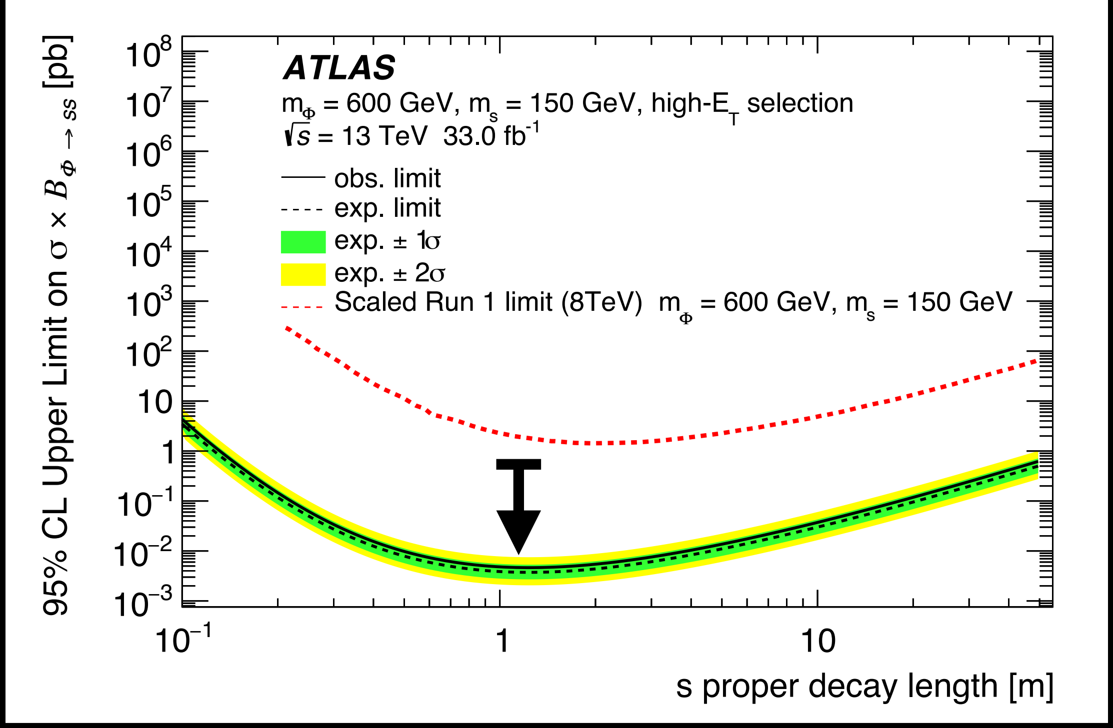
LLP decays in HCal

EXOT-2017-25 / EPJC 79 (2019) 481









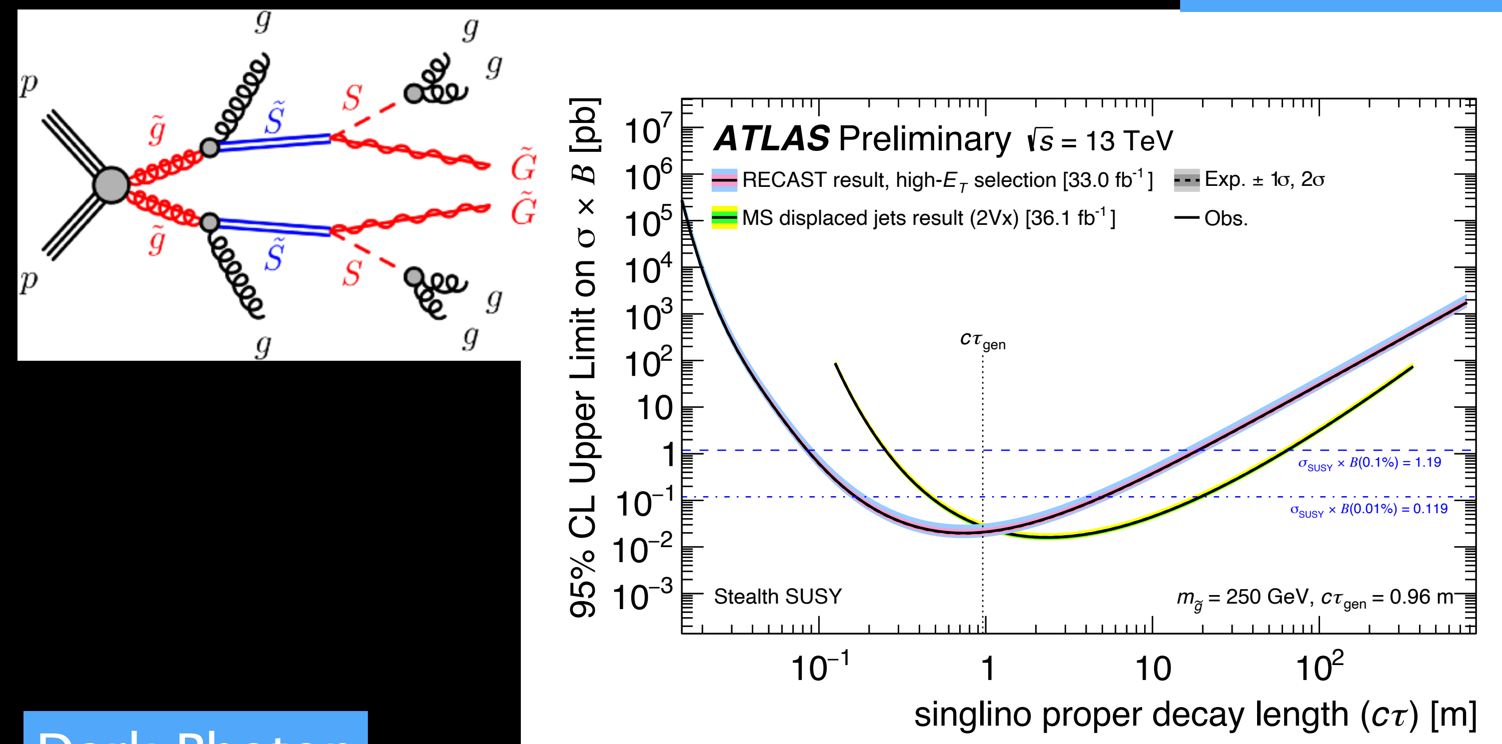
- Bkg estimation: ABCD method using the BDT score and a jet-track isolation metric, $\sum_{\text{jets}} \Delta R_{\text{min}}(\text{jet, trks})$
- Observation in SR is consistent with estimated bkg.
- Limits are presented in various sets of heavy scalar and LLP scalar masses (m_Φ, m_s).

LLP decays in HCal

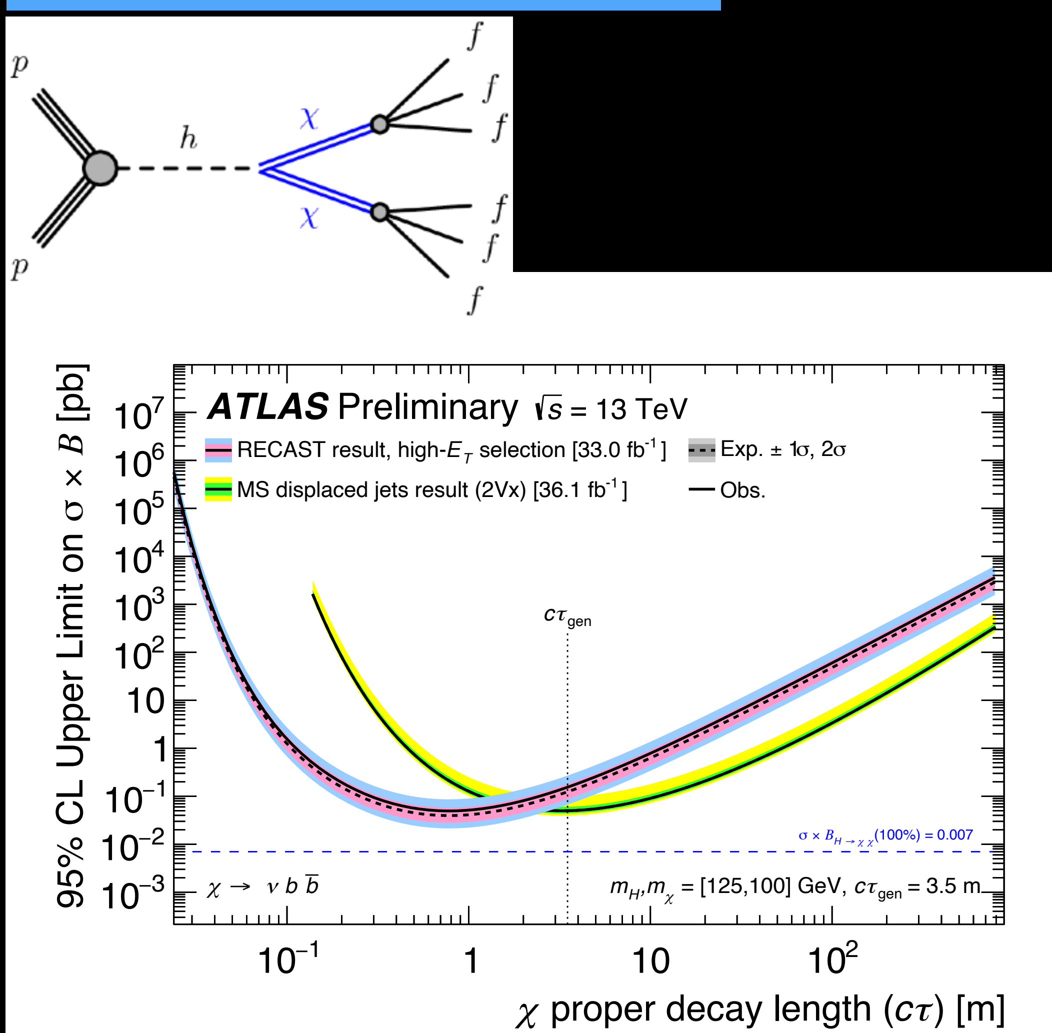
ATL-PHYS-PUB-2020-007

- ★ More systematic/automated re-interpretation using the RECAST framework is progressing within ATLAS
- ★ First application in LLP searches released.

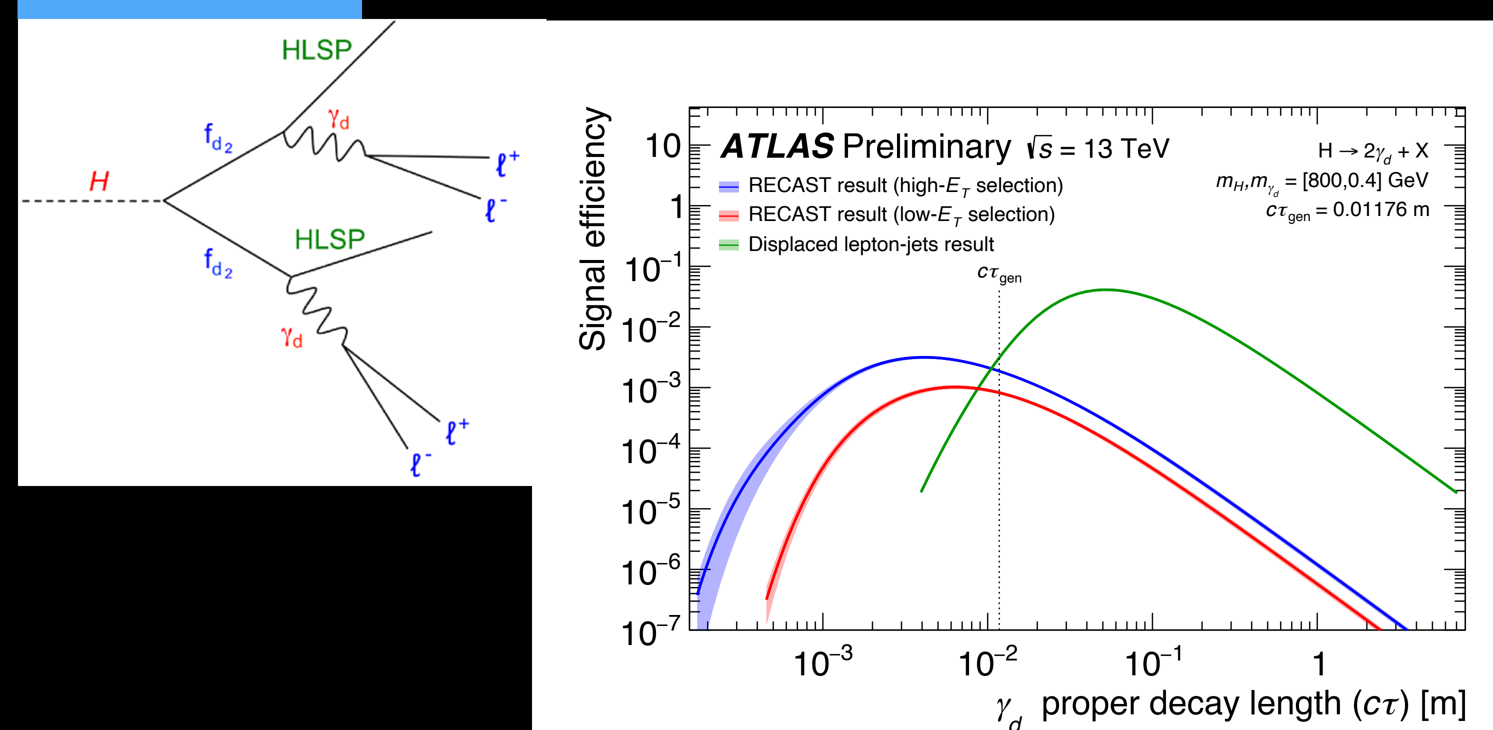
Stealth SUSY



Higgs-portal baryogenesis



Dark Photon

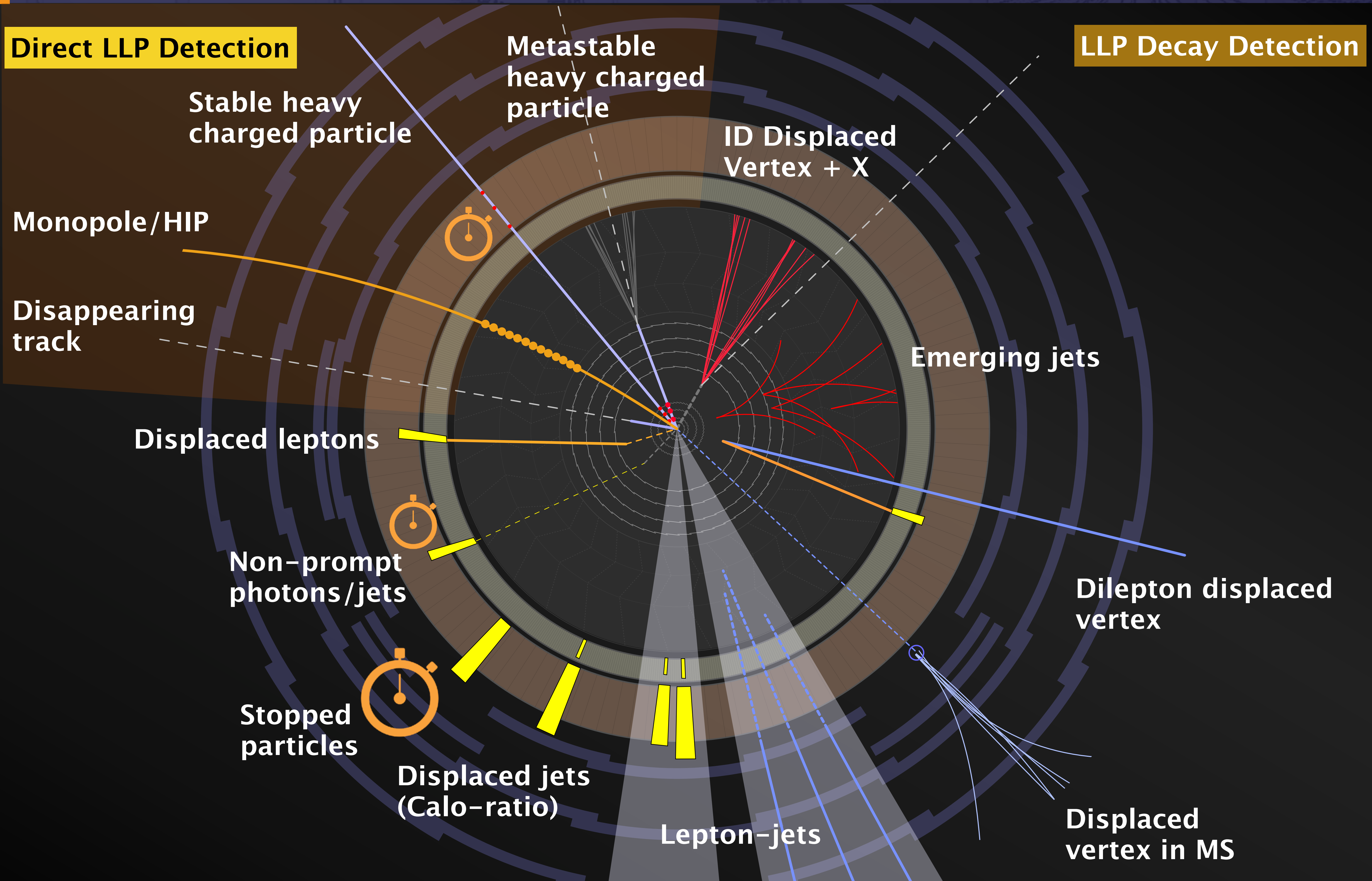


Summary

- LLP searches are creative field in ATLAS new physics/particle searches.
- Research requires vast special techniques ranging in the experiment.
  - Trigger
  - Reconstruction
  - Data-driven estimation for unconventional backgrounds
- Relatively clean signature.
  Search sensitivity will linearly grow with luminosity.
- Most of the Full-Run2 results are yet released.
  Stay tuned for more new things to come.

Backup

LHC LLP Search Classes



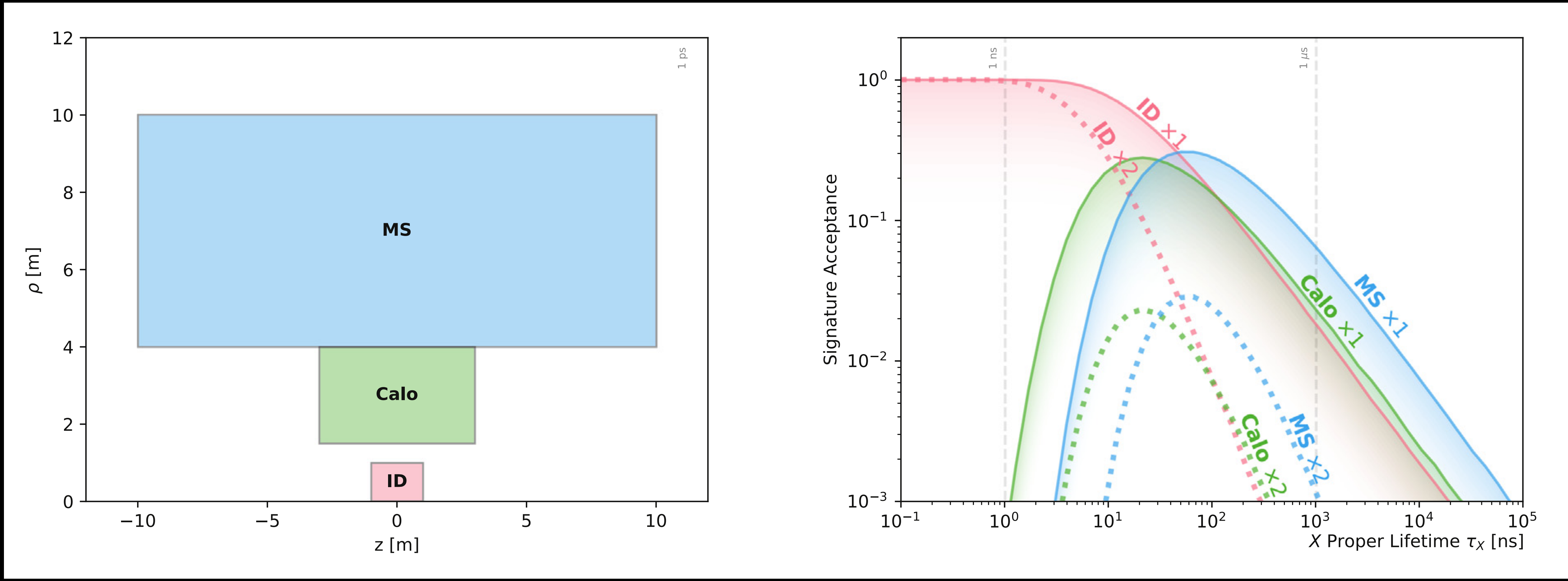
Mechanisms of long lifetime

Analogous situations may be found in SM…

- Scale
  - e.g. lifetime of $\pi^{\pm}$ is determined by a large off-shellness $$\Gamma \sim g_W^2 \left(\frac{m_\pi}{M_W}\right)^4 m_\pi$$
- Degeneracy
  - e.g. neutron lifetime (~15 min) is related to "accidental" degeneracy of (u, d) quark masses and the gap to the EW scale $$\Gamma \sim g_W^2 \left(\frac{m_n - m_p}{M_W}\right)^4 (m_n - m_p)$$
- Rules
  - Lepton flavor conservation: $\mu \to e\gamma$ almost forbidden in SM → Michel decay only.
  - SUSY R-parity conservation: stable neutralino and proton (in the canonical SUSY)
- Coupling
  - If coupling involved in the decay process is very weak, lifetime gets longer.
- Kinematic phase space
  - e.g. $K_L \to 3\pi$has longer lifetime than $K_S \to 2\pi$

Acceptance

PPNP 106 (2019) 210–215, 1810.12602



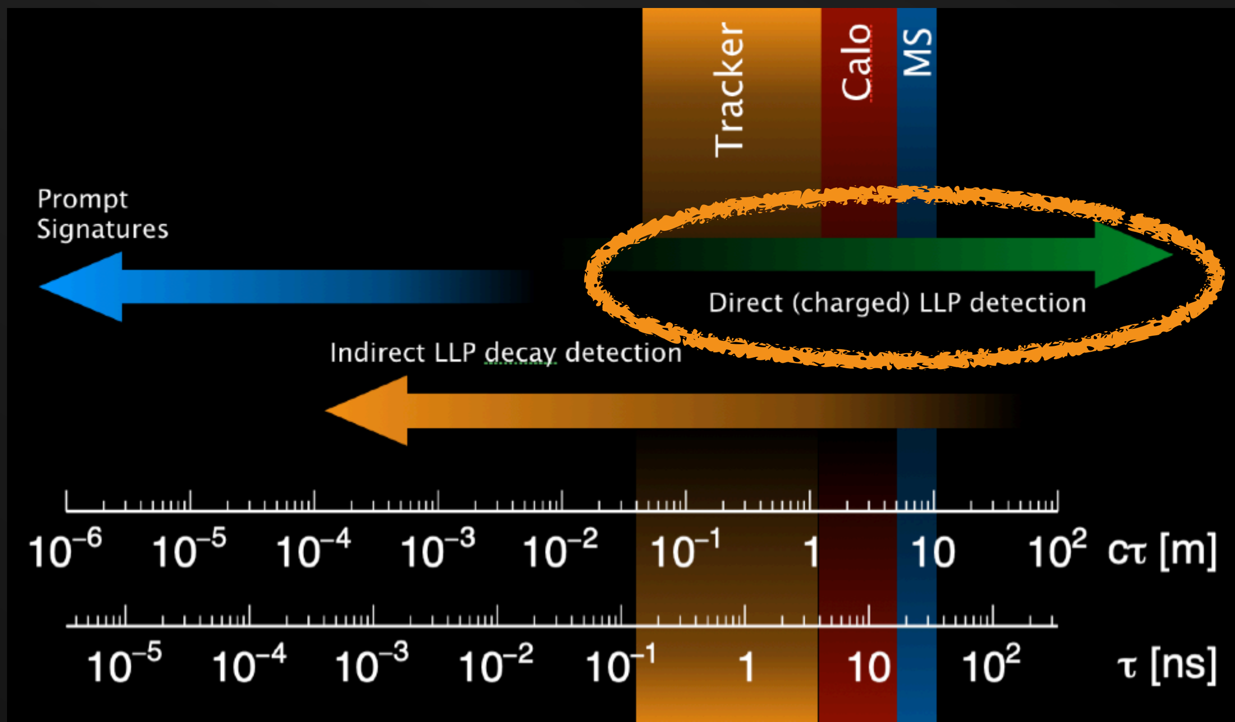
- ★ Valid for the detection of decays of heavy-massive LLP pair-production cases.
  - ★ Roughly $\beta\gamma \lesssim 1$
  - ★ A simple acceptance argument stresses effectiveness of the inner tracker for quite wide lifetime ranges.
- ★ Requirement of 2 LLPs/event is only effective when the background dominates.
- ★ Muon spectrometer can complement the longer lifetime coverage, while calorimeter contribution is only marginal.

Technicality challenges

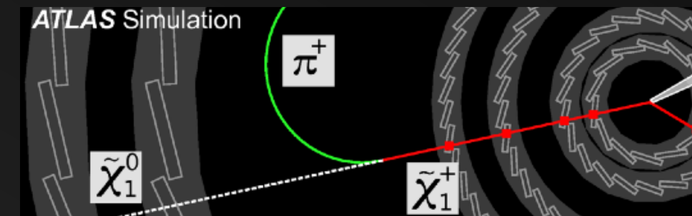
- Often LLP searches require to use:
  - Unconventional objects (e.g. displaced vertices)
  - Un-common properties of standard objects (e.g. ToF of muons)
  - Non-recommended regions (e.g. too low-pT to control)
- Often these informations are not reconstructed, controlled or calibrated, and one firstly needs to cultivate these tools before carrying-out the main analysis.
- Backgrounds are also un-common. Instrumental, cosmic, combinatorial or beam-induced backgrounds are not the subject of reliable MC simulation.
- These are not always bad news in different perspective, or can be even attractive.

Direct charged LLP search series

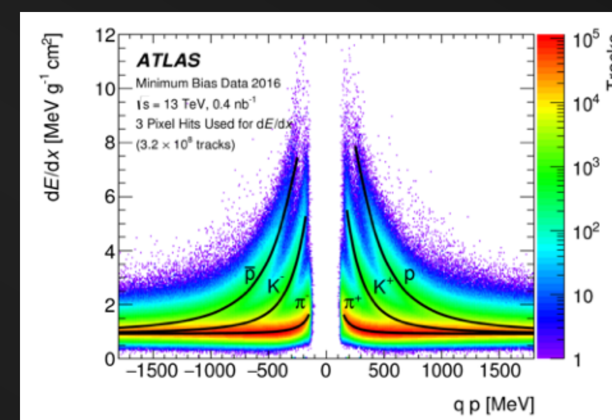
Lifetime coverage >O(0.1 ns) up to stable. Observables depending on lifetime



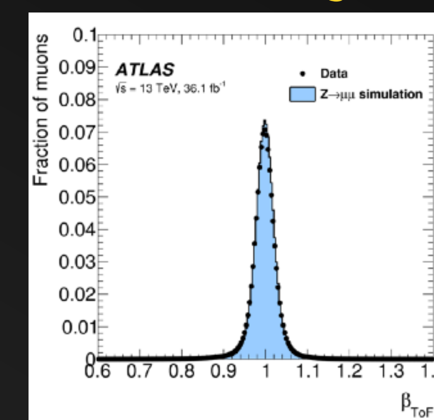
Short (disappearing) track



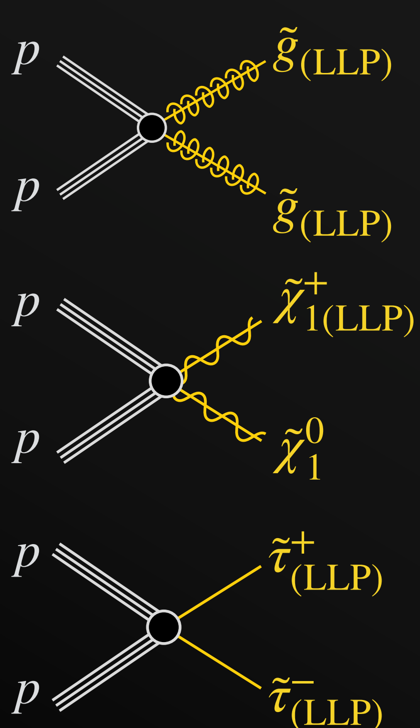
pixel dE/dx



Calo or MS timing



Scenarios



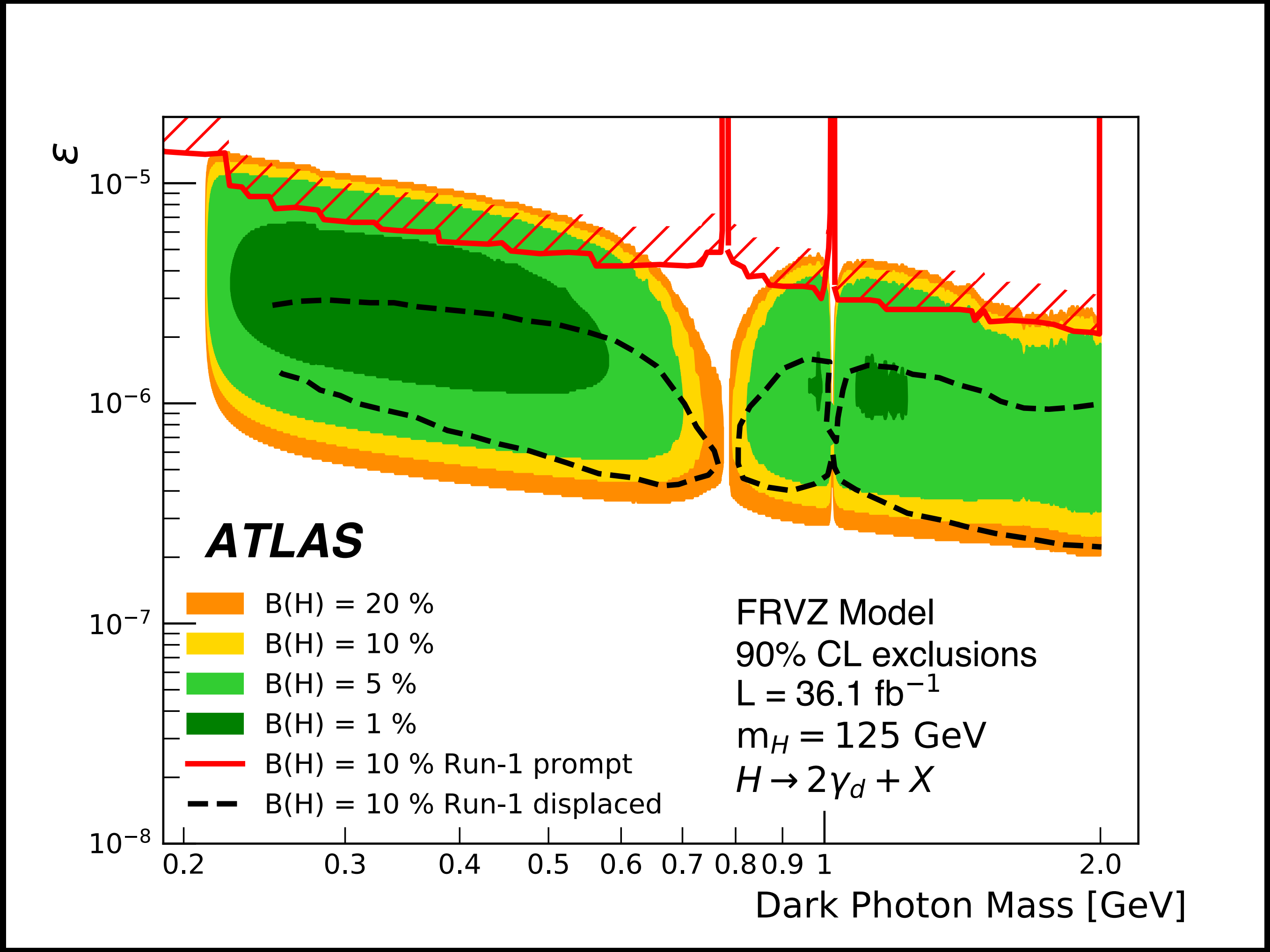
LLP Observable	Short Track	dE/dx		dE/dx & ToF		ToF	
Target Lifetime	< 3 ns	< 50 ns	Stable	Stable		Stable	
Detector	Inner Detector	Inner Detector	Inner&Muon Trackers	ID+Calo	Full Detector	1 track Full Det.	2 track Full Det.
Main Target Interpretations	$\tilde{\chi}_1^{\pm}$	$\tilde{g}$ $\tilde{t}$ $\tilde{b}$ (R-hadron)				$\tilde{\chi}_1^{\pm}$ $\tilde{\tau}^{\pm}$	

ATLAS has a systematic program for charged LLP search. Stay tuned!

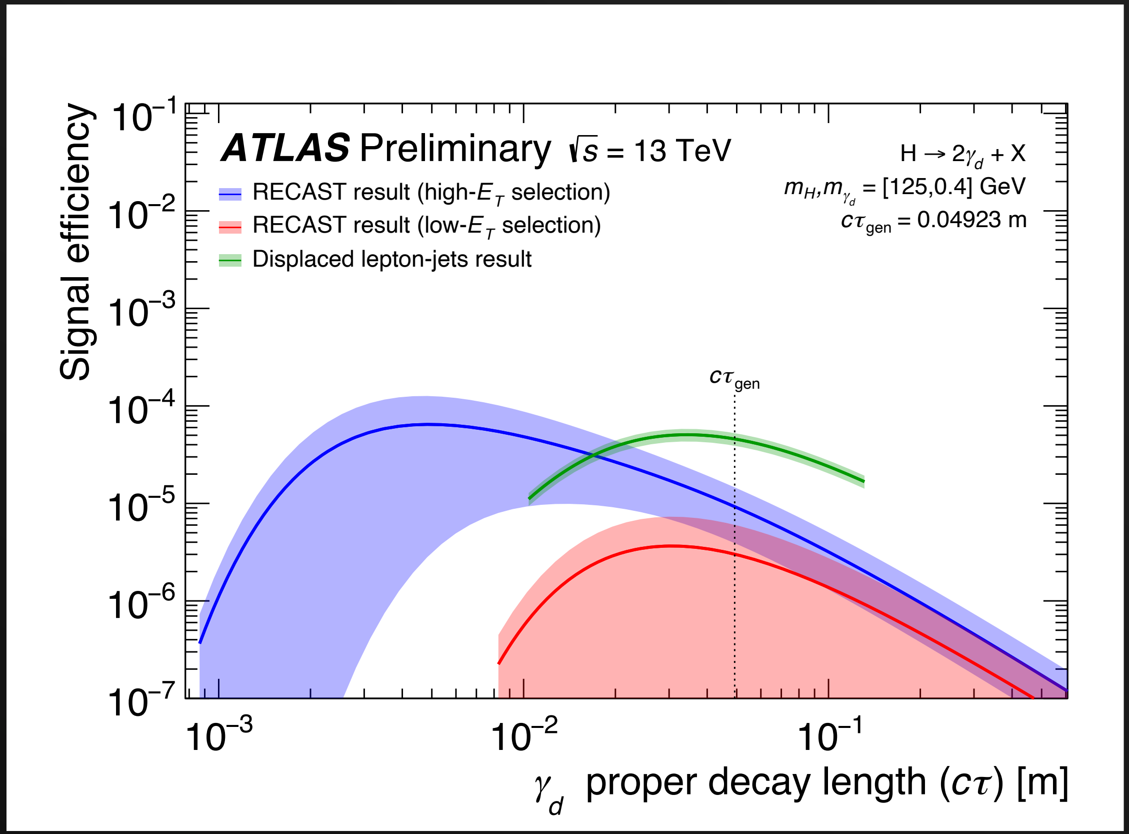
Dark-photon jets search

EXOT-2017-28 / EPJC 80 (2020) 450

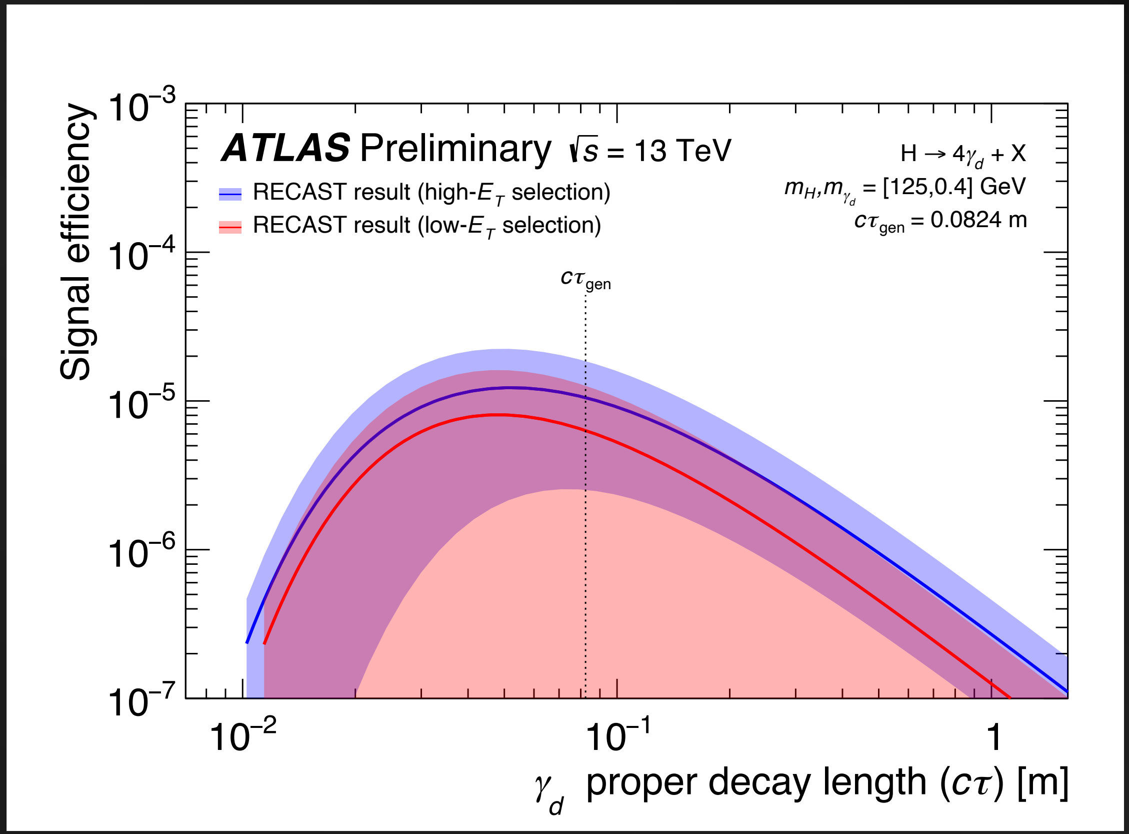
- ★ Observed bkg. yields are all consistent with the expectation.
- ★ Limits presented for 125 GeV higgs decay to $2\gamma_d$ and $4\gamma_d$ (400 MeV), and 800 GeV heavy higgs decay to $2\gamma_d$ (400 MeV).



- ★ Also scan in mass and coupling plane, compared to Run1 prompt and displaced DPJ searches.
- ★ Now gaps are mostly filled between prompt and displaced.



ATLAS Preliminary $\sqrt{s}$ = 13 TeV
$H \to 2\gamma_d + X$
m_H, m_{γ_d} = [125,0.4] GeV
$c\tau_{gen}$ = 0.04923 m
RECAST result (high-E_T selection)
RECAST result (low-E_T selection)
Displaced lepton-jets result
$c\tau_{gen}$
Signal efficiency
γ_d proper decay length ($c\tau$) [m]



ATLAS Preliminary $\sqrt{s}$ = 13 TeV
$H \to 4\gamma_d + X$
m_H, m_{γ_d} = [125,0.4] GeV
$c\tau_{gen}$ = 0.0824 m
RECAST result (high-E_T selection)
RECAST result (low-E_T selection)
$c\tau_{gen}$
Signal efficiency
γ_d proper decay length ($c\tau$) [m]