Lawrence Berkeley National Laboratory

Experimental prospects on LHC searches during Run 3 and 4(+)

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Fourth workshop of the LHC LLP Community

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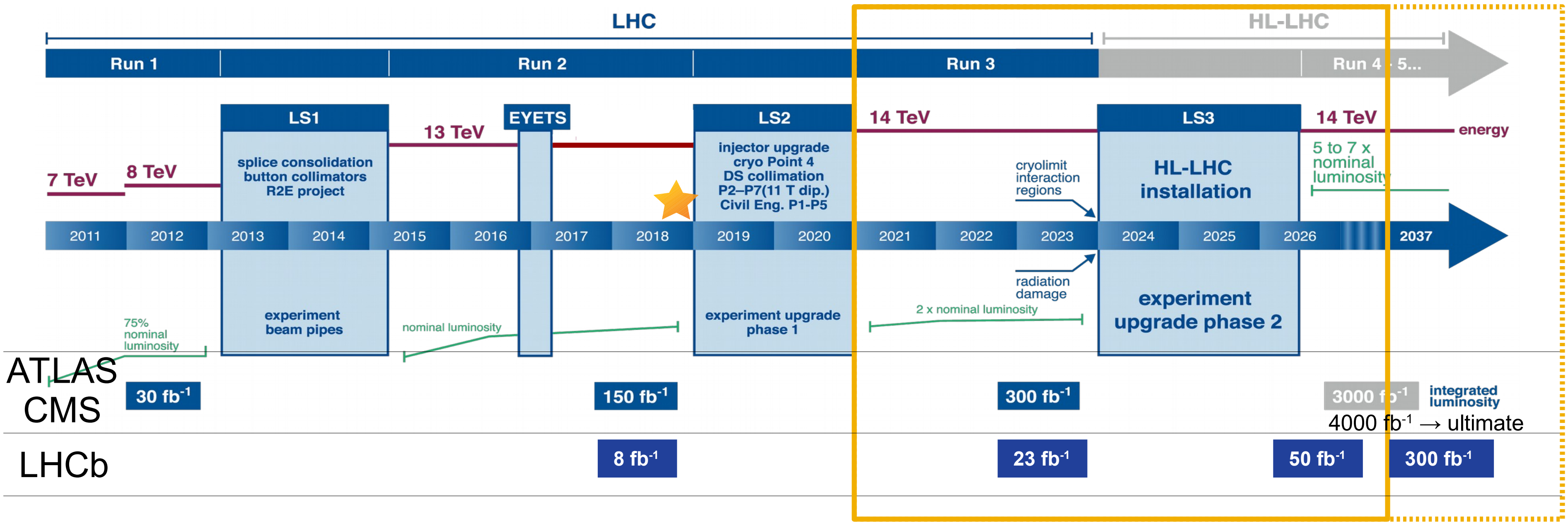
Outline

- Timeline, expected running conditions
- Run-3 opportunities
- Run-4(+) opportunities
  - Inner Tracker signatures
  - Calorimeter signatures
  - Muon spectrometer signatures
  - Timing detectors signatures
  - LHCb in Run 4 and beyond
- Conclusions

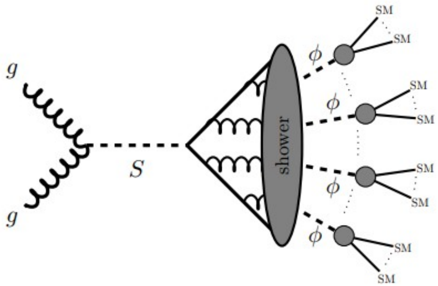
Timeline



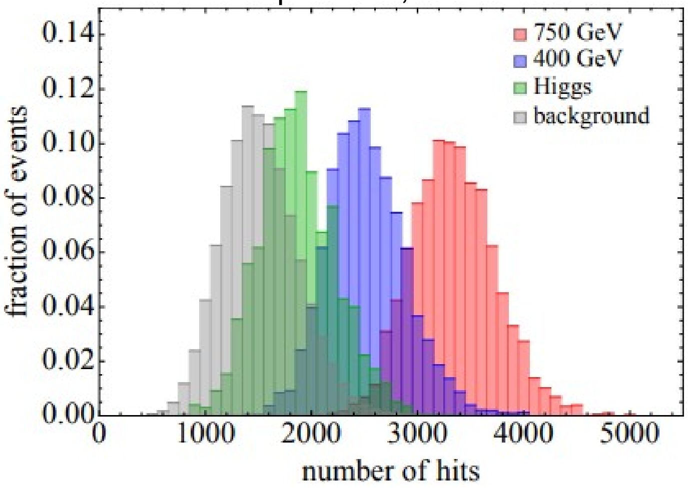
- Run 3 (~ 2021, ~3 years)
  - ATLAS and CMS will run at just slightly higher inst. lumi than 2018, significant upgrades in the detector and upgrade systems
  - LHCb will undergo a major detector upgrade, move to μ~5
- Run 4 (~ 2027, ~3 years)
  - Marks officially the start of HL-LHC
  - ATLAS and CMS will undergo major detector upgrades, μ up to 140 (200)
  - LHCb undergoes consolidation upgrades (phase Ib)
  - LHCb phase II upgrade for Run 5

ATLAS/CMS Run 3 opportunities

- Overall small increase of energy and double of Run 2 dataset is not extremely likely by itself to open the door to large new parameter space
  - e.g. we'll not exceed Run-2 dataset before ~2 years into Run 3, albeit @ 14 TeV
- A key point for Run 3 will be to **trigger** on what we may have missed!
- Example: dedicated triggers for soft-unclustered-energy-patterns



S. Knapen et al, arxiv:1612.00850



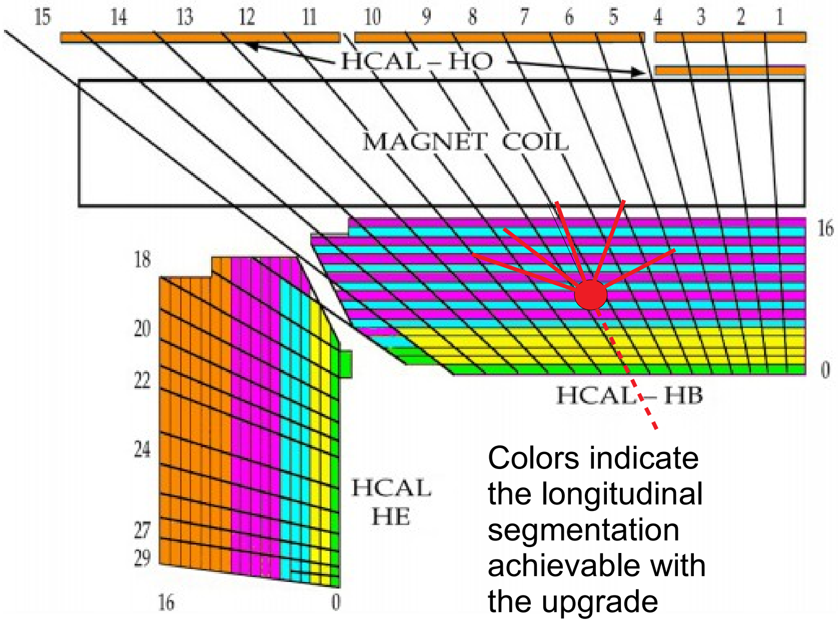
#hits in first silicon layer of tracker

  - Studied for the prompt case, but can be applied in the long-lived case as well
  - Possible to enhance significantly the sensitivity of existing triggers and be less model-dependent

ATLAS/CMS Run 3 trigger upgrades

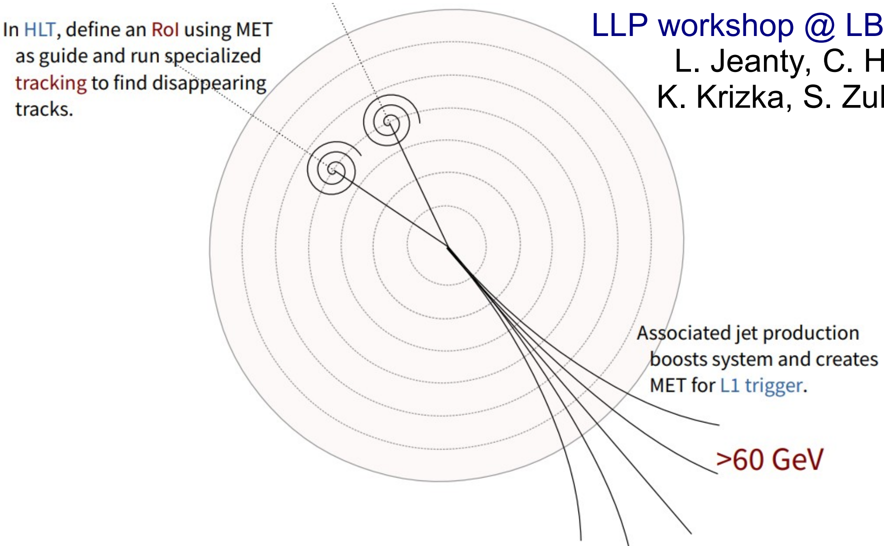
- Significant upgrade to the trigger and calorimeters electronics
  - Better granularity/timing available at early stages of the trigger (L1)
  - More sophisticated algorithms can be run early in the trigger decision
- FTK provides HLT full-event prompt track reco down to p_T ~ 1GeV
  - May be able to extend for non-prompt tracks produced within ~5cm from IP

CMS Phase-1 HCAL TDR



Colors indicate the longitudinal segmentation achievable with the upgrade

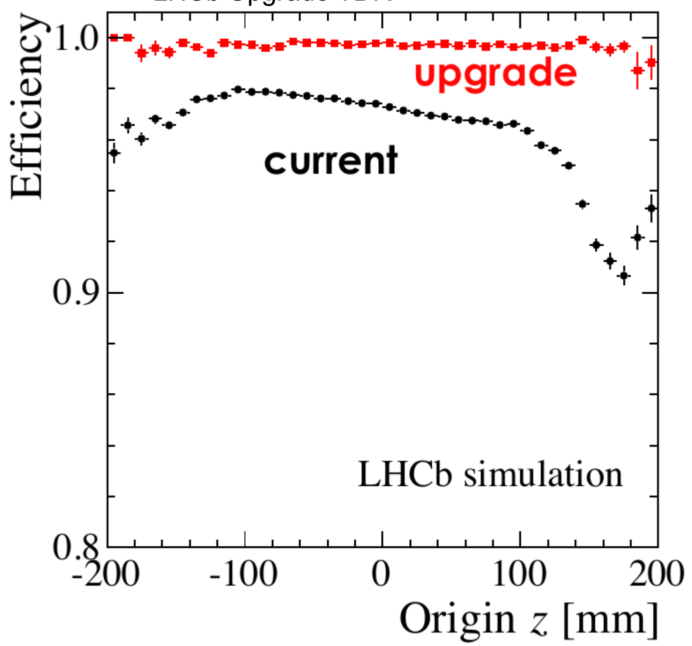
LLP workshop @ LBNL
L. Jeanty, C. Hill, K. Krizka, S. Zuber



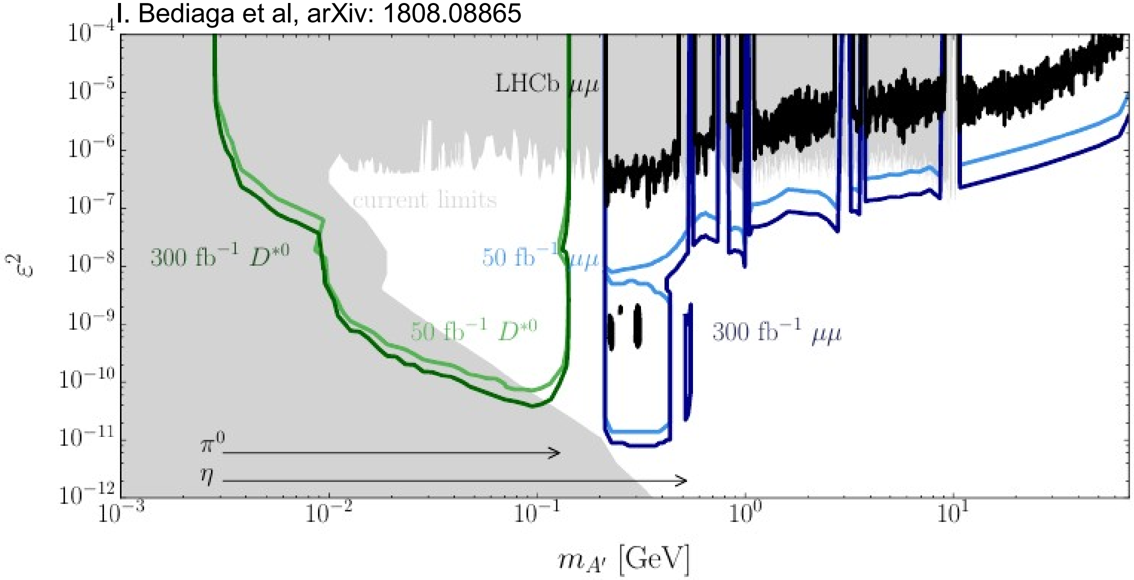
High-pT isolated track(-lets) could be reconstructed at HLT or (in some cases) with FTK
Example above: investigation of Region-Of-Interest definition in disappearing track triggering → turned out not promising

LHCb Run 3 opportunities

- New software-based “trigger” with offline-quality
- New VELO detector, similar material budget
  - No expected increase of backgrounds from had. Int.
- Search for light BSM gauge bosons in μμ final states, either inclusively or in D* decays
  - Expect increasing of the low m(μμ) yield by a factor of 100-1000 (lumi, trigger, new detector)



I. Bediaga et al, arXiv: 1808.08865

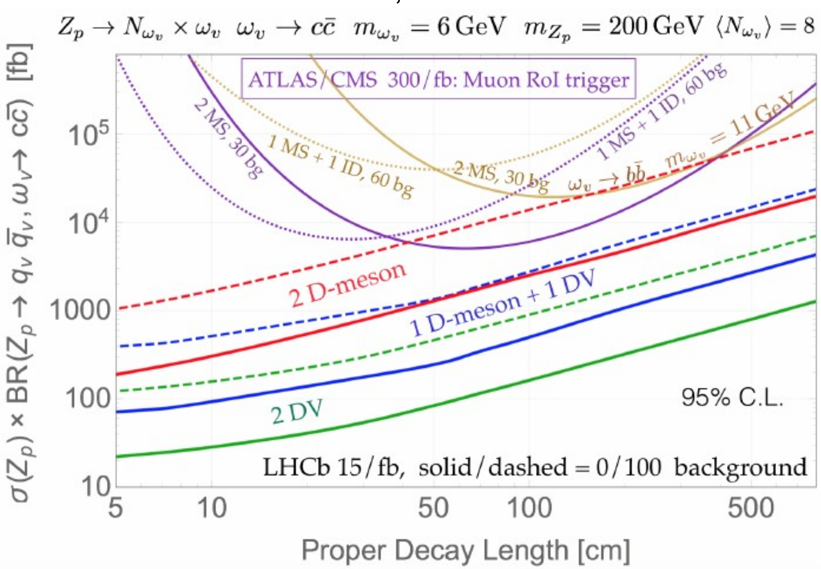


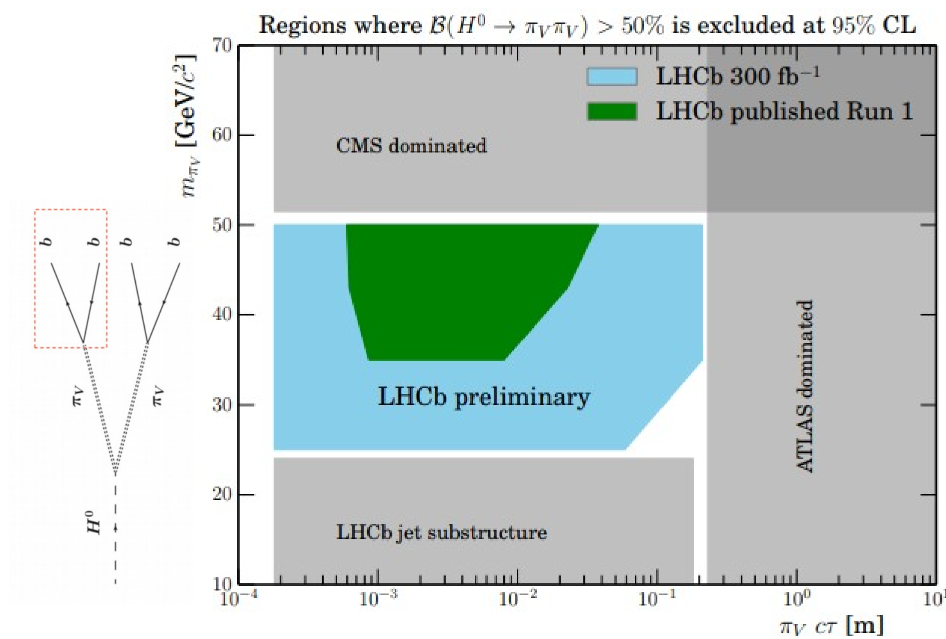
Also sensitive to hidden-valley models with dark-mesons decays involving μμ final states.

LHCb in Run 3: hadronic decays

- Also hadronically decaying mesons from Hidden Valley scenarios
  - Profit from capabilities of triggering displaced vertices and possibility of more sophisticated algorithm at trigger-level
- Displaced jets searches already performed in Run 1
  - Expected significant reduction of background due to new VELO detector
  - Selection efficiency higher due to software-based displaced-vertex trigger

A. Pierce et al., arXiv:1708.05389



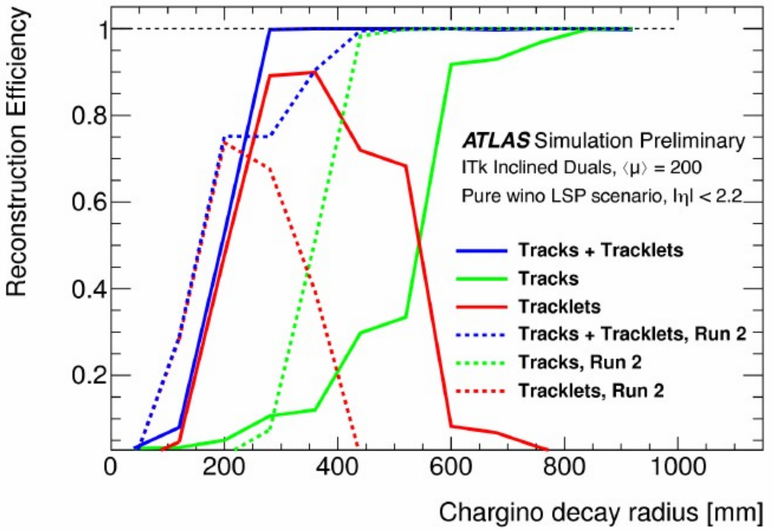


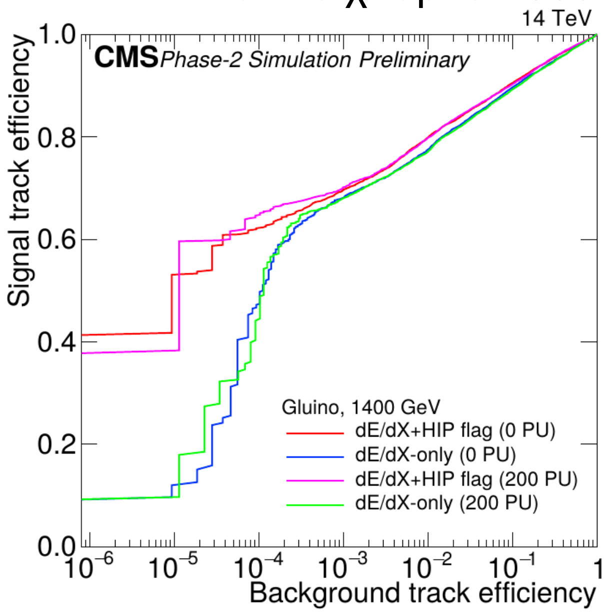
Run 4

- Major upgrade of the ATLAS/CMS detector
  - Marks the start of the HL-LHC era
  - Allow ATLAS/CMS experiments to sustain 4 times higher inst. Luminosity
- First Run (3 years) of HL-LHC could give ~300/fb
  - Mandatory to make best use of new detector capabilities to surpass Run 3
- Incremental upgrade of LHCb for Run-4
  - LHCb to perform a phase-II upgrade after Run-4 → inst. luminosity x 10
- Updated HL-LHC projections for LHC experiments in the context of the CERN HL/HE-LHC Yellow Report
  - Updated projections being finalized by experiments, likely public imminently
  - Expected YR on arXiv ~mid December, final update around January
  - Most projection tuned for full HL-LHC dataset

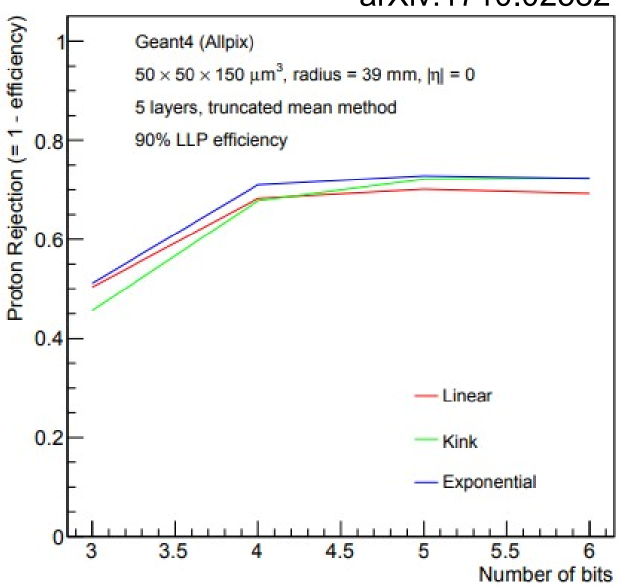
Inner Tracker signatures

- Long-lived massive particles
- Short lifetime regime (disappearing track)
  - ATLAS will loose unique sensitivity to very short lifetimes → “expanded” pixel detector
  - Still expect better results due to large dataset available: 95%CL sensitivity to
    - Higgsino-like $\chi^{\pm}$ up to 250 GeV
    - Wino-like $\chi^{\pm}$ up to ~800 GeV





arXiv:1710.02582

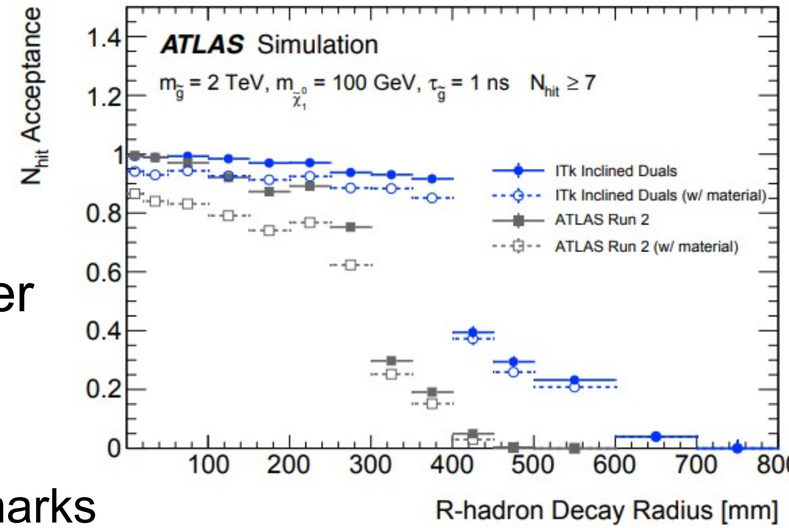


Use of dE/dx:

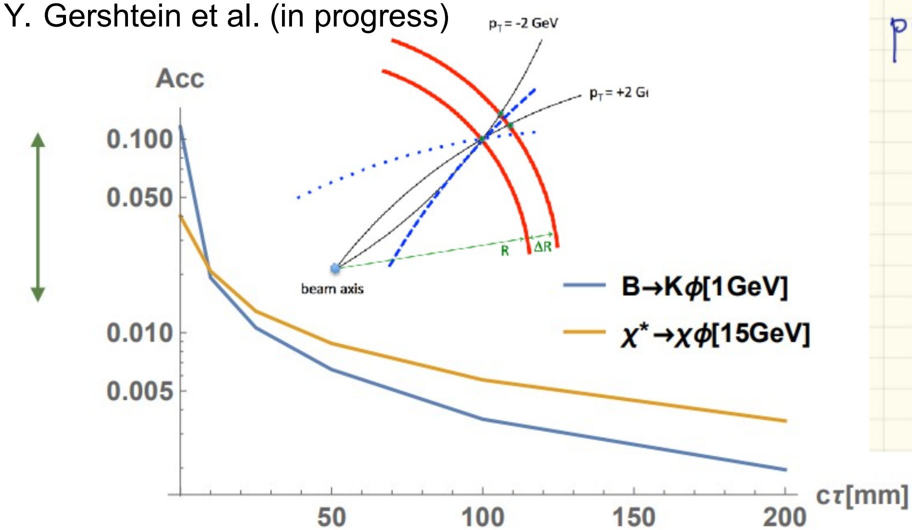
- CMS adding dedicated flag to outer tracker to improve discrimination
- Different schemes of data digitization are possible, 4-bit resolution seems best compromise performance/feasibility

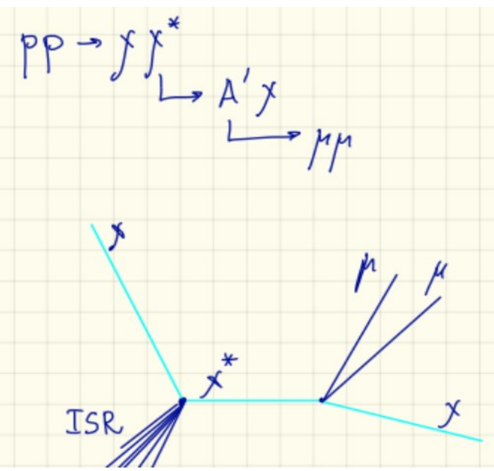
Inner Tracker: displaced decays

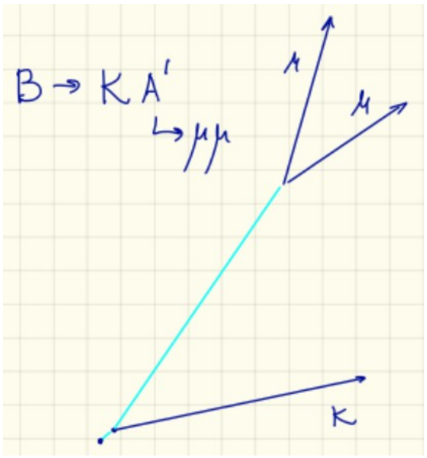
- Increased lifetime coverage for ATLAS
  - Acceptance (>= 7 hits in detector) dominates reconstruction efficiency for displaced tracks
- Stub-finding capability + muon spectrometer information to trigger on displaced muons at CMS (in progress)
  - Efficiency below for quite “aggressive” benchmarks



LLP workshop @ LBNL
Y. Gershtein et al. (in progress)

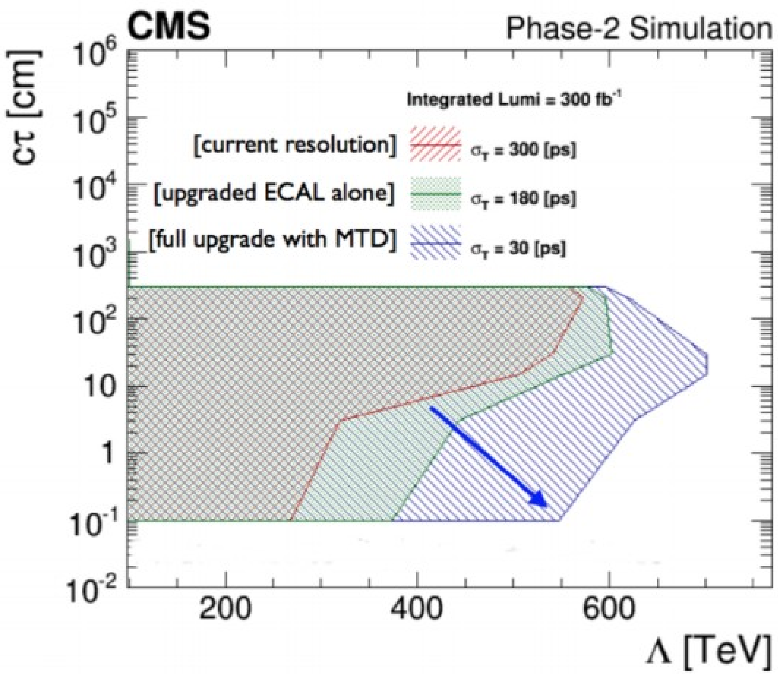


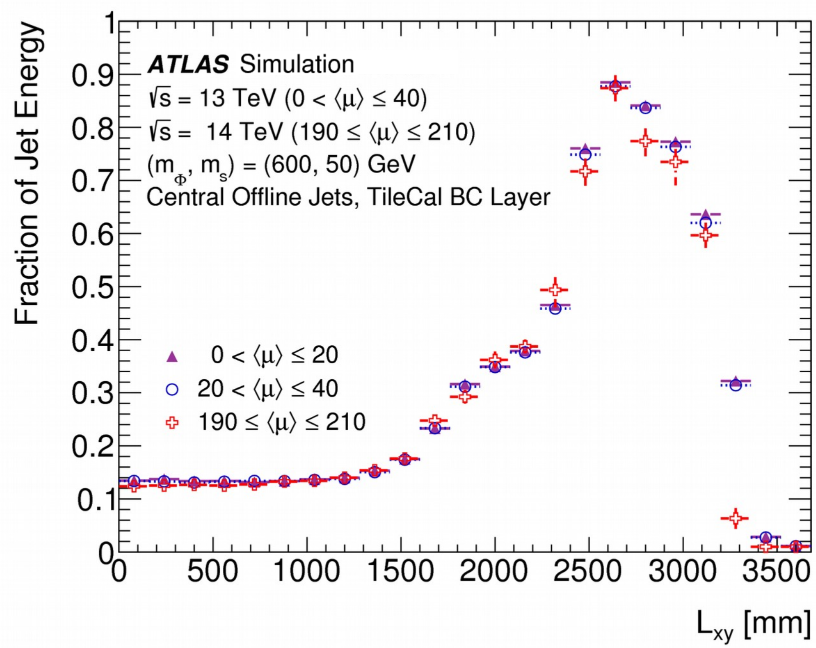




Calorimeter-based signatures

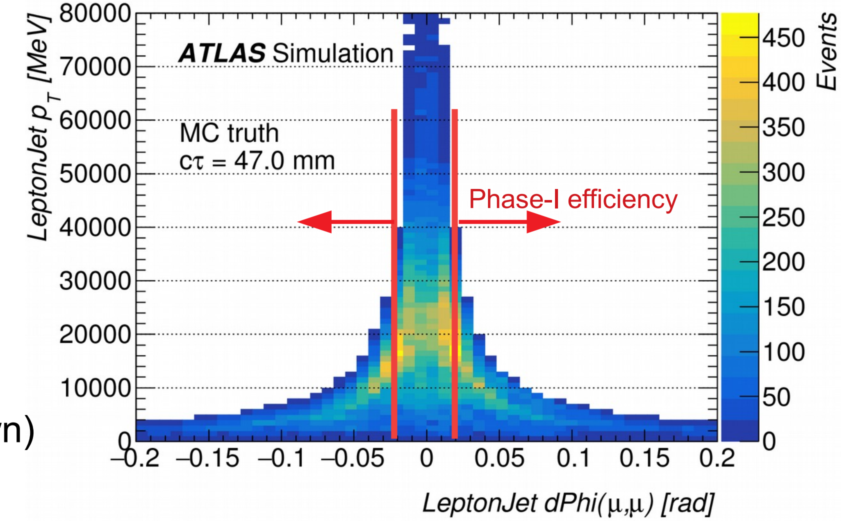
- Delayed photons/Z → ee from e.g. χ^0 decay chain pointing away from interaction point detected in the EM calo
  - Increased timing resolution
  - Reconstruct χ^0 mass in some cases
- Decays of neutral LLP in the calorimeter can profit from dedicated triggers
  - Rely on isolated activity in had. calo
  - The same approach will still viable in harsh HL-LHC environment

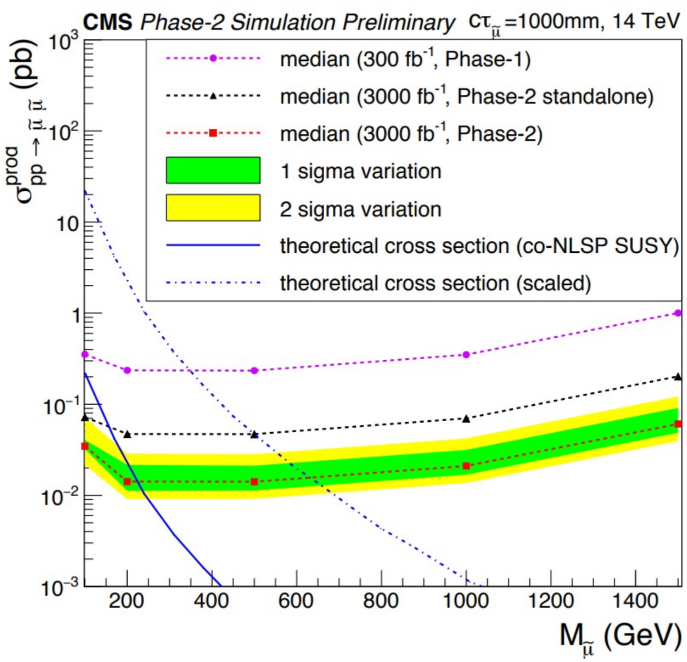


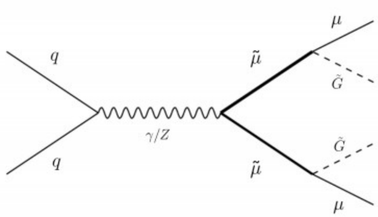


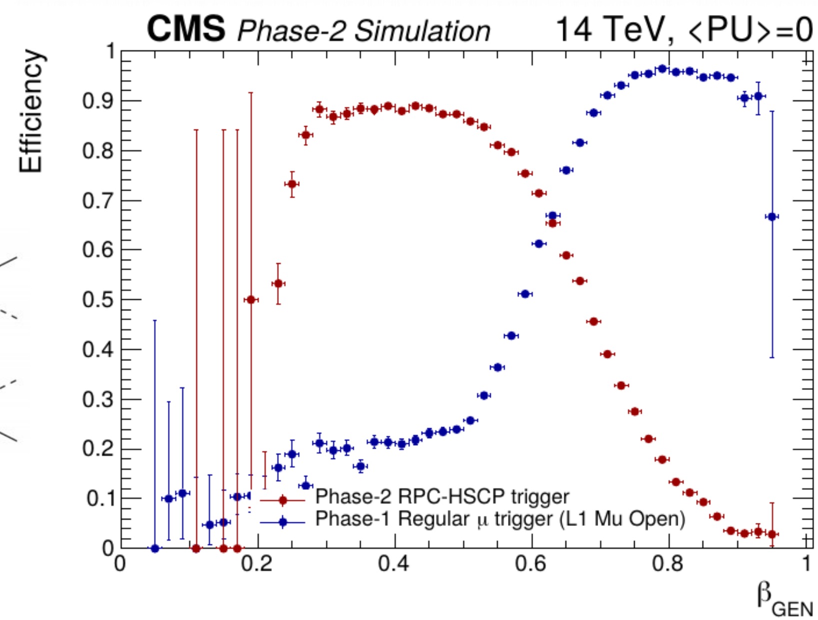
Muon-based signatures

- Great effort to ensure ability to trigger on non-prompt muons
  - Single-muon triggers
  - Displaced-vertices (not shown here)
- Studied for e.g. $\tilde{\mu}$ production
- Improved timing resolution as well (not shown)









Timing detectors

- Additional timing information can benefit LLP program at large

Big Signal selection enhancement
Big trigger efficiency enhancement

Neutral LLP

Production \ Decay	$\gamma\gamma(+\text{inv.})$	$\gamma+\text{inv.}$	$jj(+\text{inv.})$	$jj\ell$	$\ell^+\ell^-(+\text{inv.})$	$\ell^+_\alpha\ell^-_{\beta\neq\alpha}(+\text{inv.})$
DPP: sneutrino pair	†	SUSY	SUSY	SUSY	SUSY	SUSY
HP: squark pair, $\tilde{q}\to jX$ or gluino pair $\tilde{g}\to jjX$	†	SUSY	SUSY	SUSY	SUSY	SUSY
HP: slepton pair, $\tilde{\ell}\to \ell X$ or chargino pair, $\tilde{\chi}\to WX$	†	SUSY	SUSY	SUSY	SUSY	SUSY
HIG: $h\to XX$ or $\to XX+\text{inv.}$	Higgs, DM*	†	Higgs, DM*	RHν	Higgs, DM* RHν*	RHν*
HIG: $h\to X+\text{inv.}$	DM*, RHν	†	DM*	RHν	DM*	†
RES: $Z(Z')\to XX$ or $\to XX+\text{inv.}$	Z', DM*	†	Z', DM*	RHν	Z', DM*	†
RES: $Z(Z')\to X+\text{inv.}$	DM	†	DM	RHν	DM	†
CC: $W(W')\to \ell X$	†	†	RHν*	RHν	RHν*	RHν*

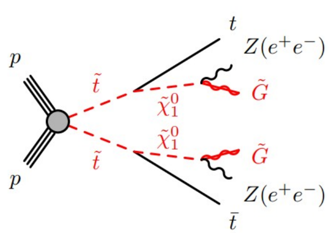
Charged LLP

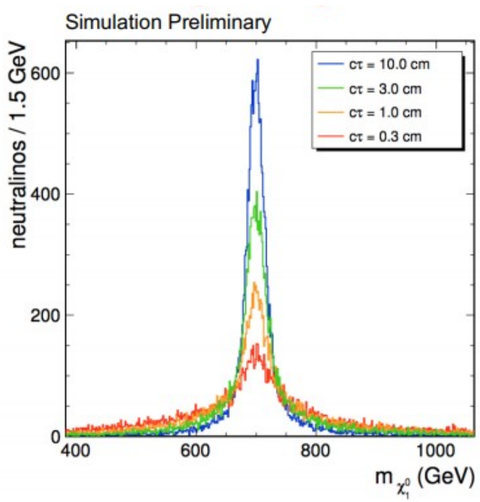
Production \ Decay	$\ell+\text{inv.}$	$jj(+\text{inv.})$	$jj\ell$	$\ell\gamma$
DPP: chargino pair or slepton pair	SUSY	SUSY	SUSY	
HP: $\tilde{q}\to jX$	SUSY	SUSY	SUSY	
ZP: $Z'\to XX$	Z', DM*	Z', DM*	Z'	
CC: $W'\to X+\text{inv.}$	DM*	DM*		

Colored LLP

Production \ Decay	$j+\text{inv.}$	$jj(+\text{inv.})$	$j\ell$	$j\gamma$
DPP: squark pair or gluino pair	SUSY	SUSY	SUSY	

Chapter 2 LLP Whitepaper +
Si Xie et al.



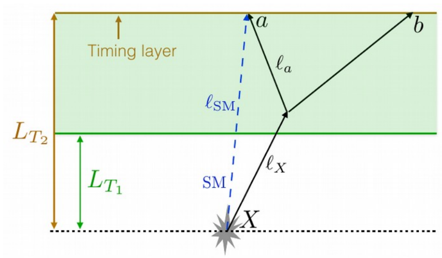


- Just starting to learn its potential
  - e.g. reconstruction of parent particle in particular decay chains
- Usage of timing at trigger-level
  - See e.g. brainstorming here

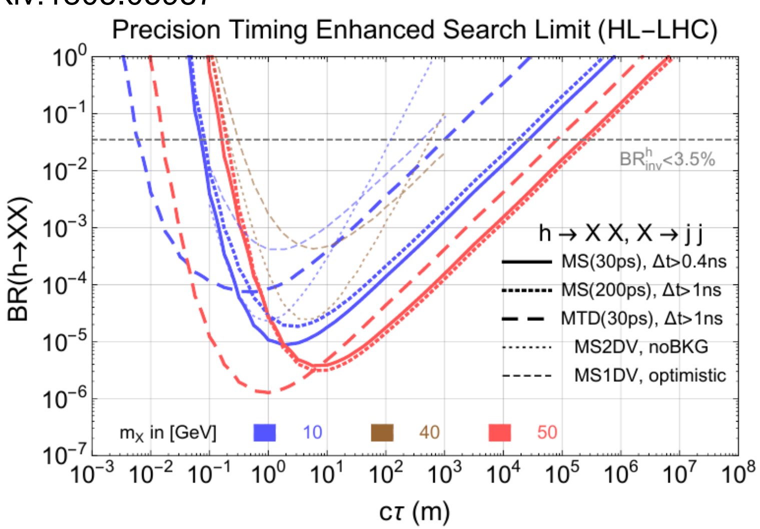
Timing detectors

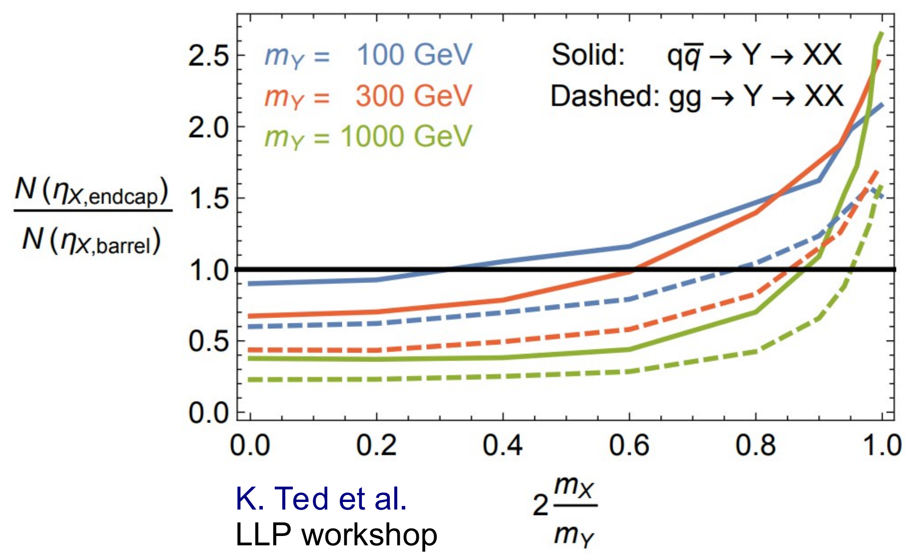
- Example study from Higgs decays
  - Requires “timestamp” of event
  - Some backgrounds non-trivial to estimate without detailed simulation

- Forward timing impact on LLP search program?
  - ATLAS high-granularity timing det.
  - CMS forward calorimeter
- More studies very welcome in order to assess its potential



J. Liu et al.,
arXiv:1805.05957



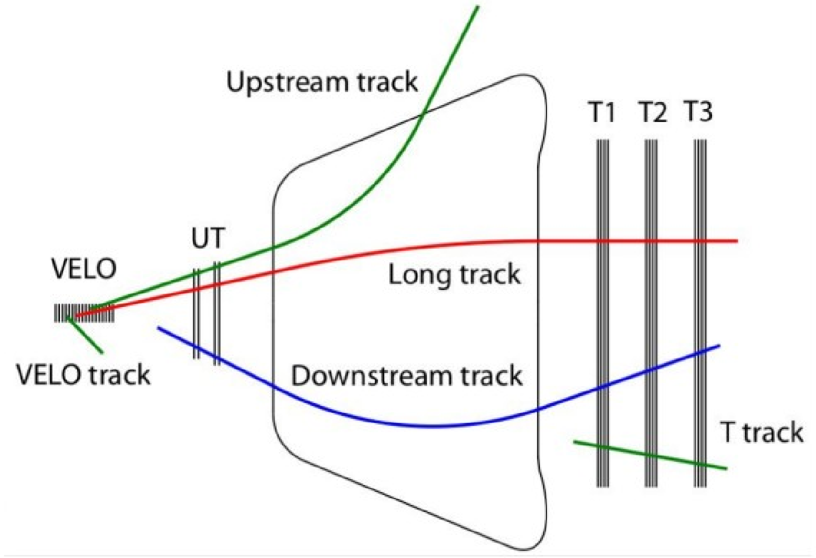


K. Ted et al.
LLP workshop

LHCb in Run 4+ and beyond

- LHCb will undergo its next major uprade after Run 4
- Several planned or proposed upgrades directly favor the LLP program

- VELO detector without protective RF-foil → reduce had. int. background for displaced vertex searches (d > 5 mm)
- Downstream tracks can profit from additional detectors information, as TORCH (σ_t~15 ps per-track)
- Enough time to still profit for new ideas
  - Adding timing information to some of the VELO layers? Useful for LLP?
  - Additional tracking stations on the magnet to recover upstream tracks



Conclusions

- The LHC and HL-LHC physics program is set to last many more years
- Run 3, however, is just around the corner
  - New trigger strategies are a key to profit early on from the new data for ATLAS and CMS
  - LHCb will see a major upgrade that enhances many of the LLP searches
    - Especially true for soft decay products and ability to analyze full 40MHz data stream with non-conventional algorithms
- Run 4 will see major ATLAS and CMS upgrades
  - To rapidly surpass Run 3 sensitivity we need to make the best use of the new upgraded detector capabilities
  - After Run-4, LHCb upgrade still leaves new possibilities for fresh ideas
- The long-lived particle community is having a very positive impact in the design of the future LHC detectors!