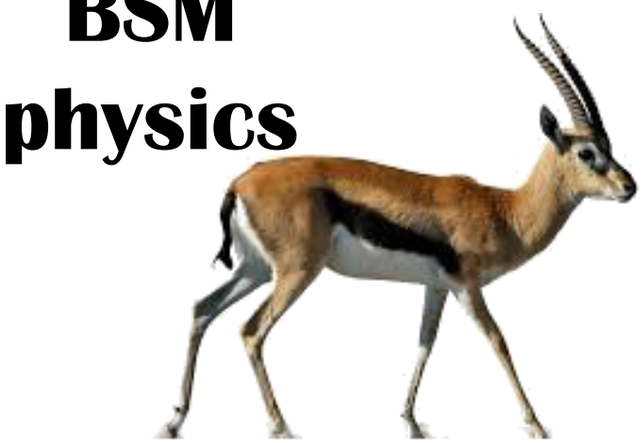
Closeout and taking stock

X. Cid Vidal

Searching for long-lived particles at the LHC:
Third workshop of the LHC LLP Community
May 18th 2018

IGFAE
Instituto Galego de Física de Altas Enerxías

The LHC jungle



The LHC jungle

MILLIQAN

MATUSHLA

SHIP

MOEDAL

CODEX-b

NA62

SEAQUEST

FASER

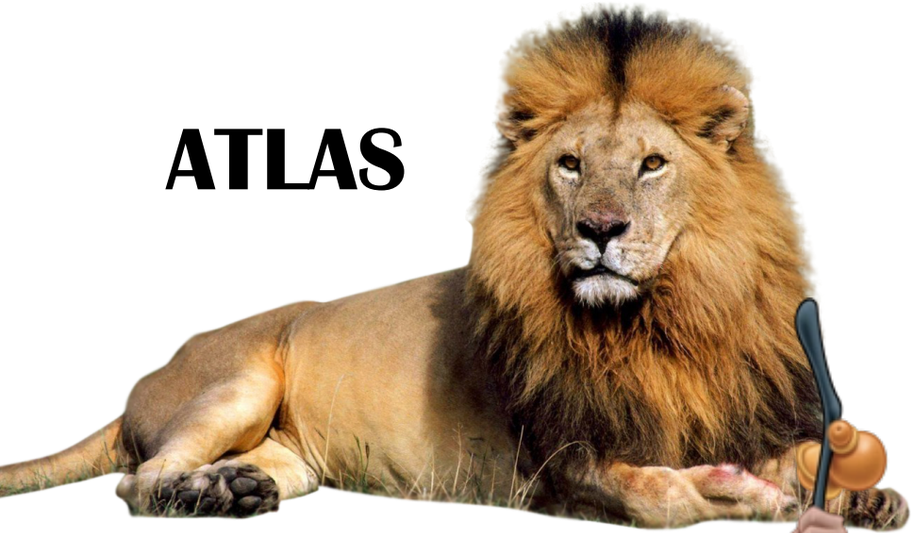
ATLAS

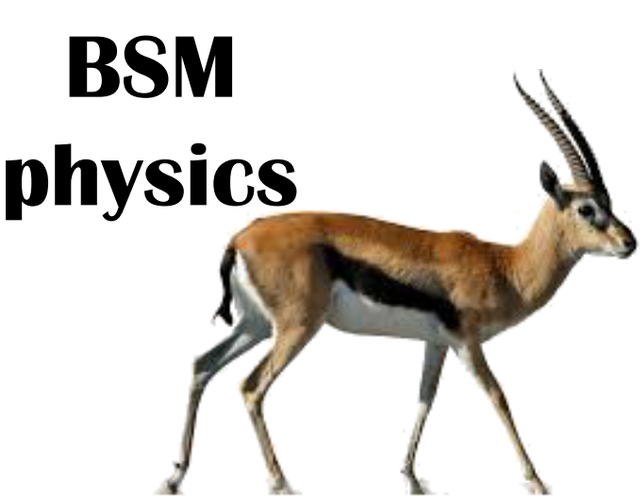
BSM physics

CMS

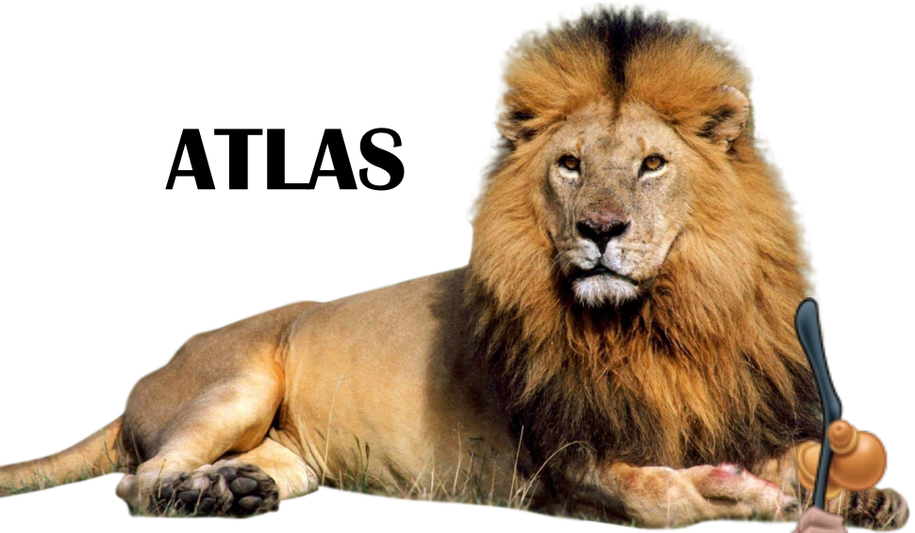
LHCb

The LHC jungle





The LHC jungle



My personal (biased) perspective

- Very productive and useful workshop (as usual)
  - Not my intention to summarize all of it here!
  - Will try to avoid you missing your flight!
- Instead, will try to present some ideas that caught my attention
  - Not ATLAS/CMS or theory person: different perspective?
  - Focus in global aspects
  - Apologies in advance for the omissions (>40 talks!)
  - And 

everyone for your participation!

    + material and ideas stolen!

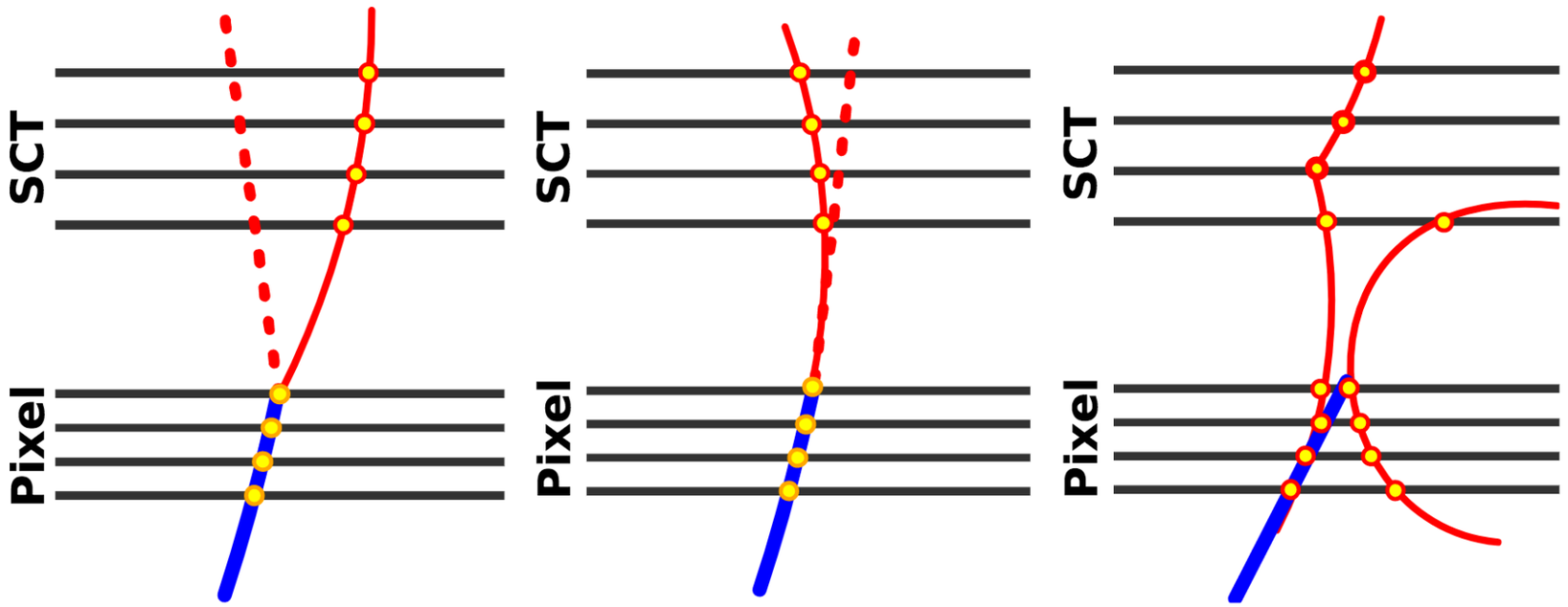
ATLAS, CMS and LHCb

- Dealing with **backgrounds**, common problems, common solutions?

Will be **worse** from Run 3 on!
Machine Learning?
Session for next workshop?!

Disappearing Tracks: Backgrounds

ATLAS



Hard hadronic interactions

Lepton emitting hard photon

Random combination of hits

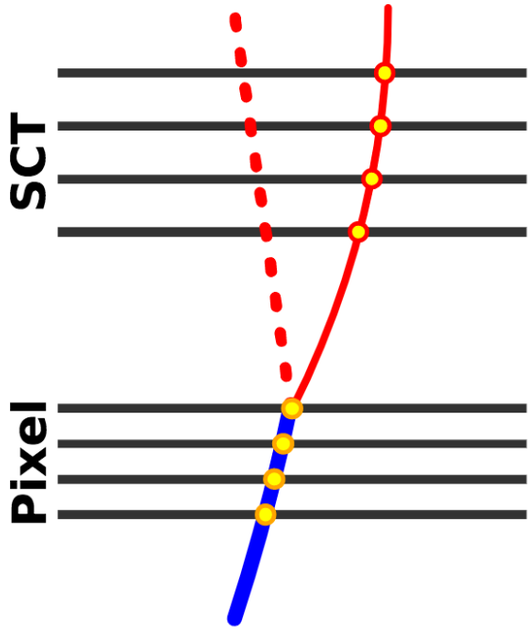
Roloff

ATLAS, CMS and LHCb

- Dealing with **backgrounds**, common problems, common solutions?

Disappearing Tracks: Backgrounds

ATLAS



Hard hadronic interactions

Roloff, Dall'Occo

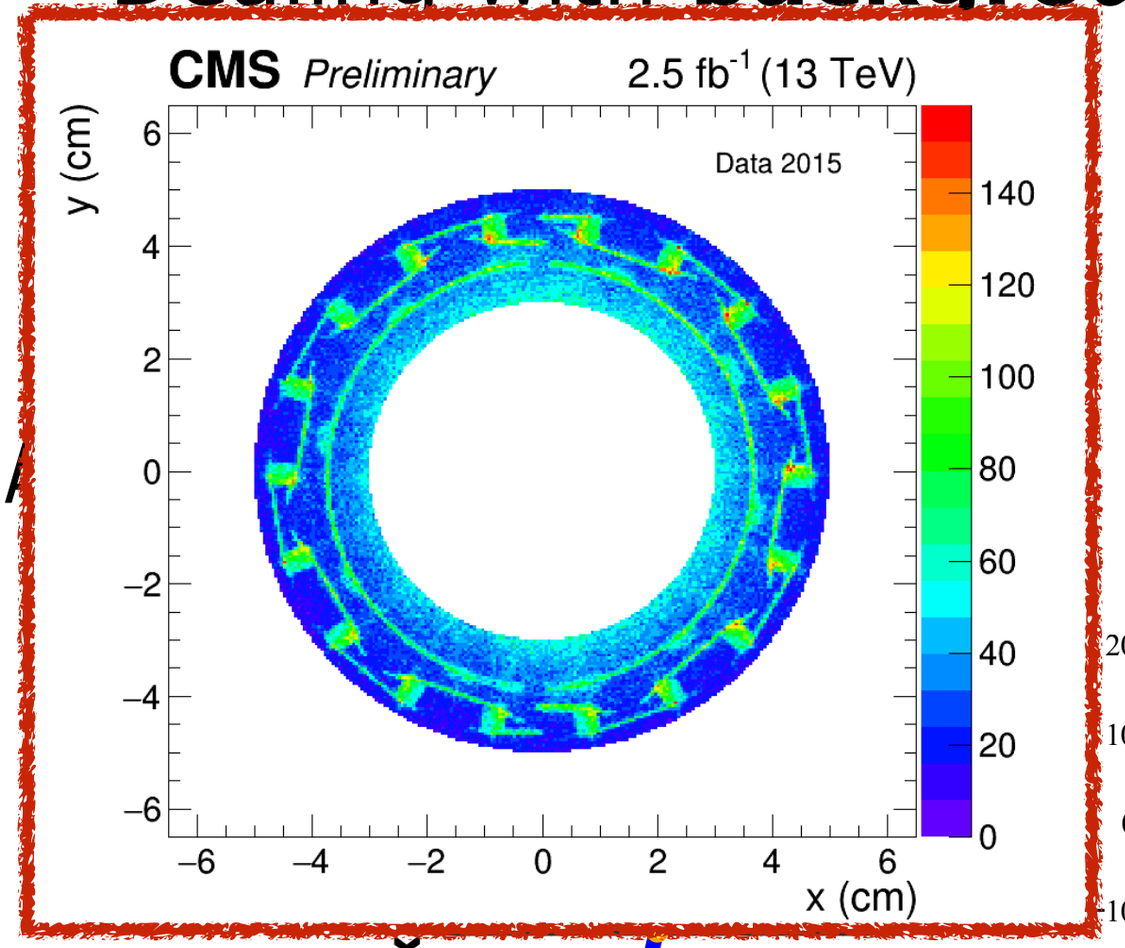
LHCb

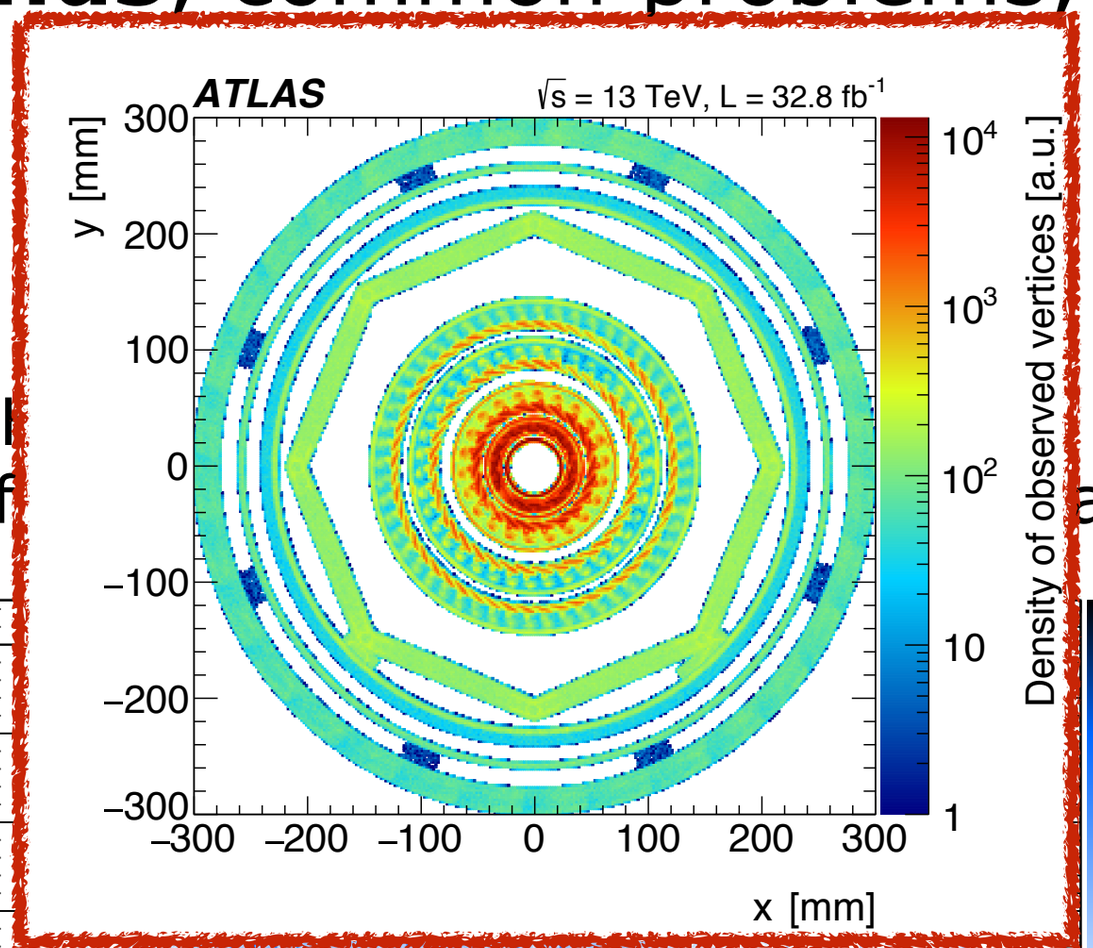
LHCb material map of the VELO (from hadronic interactions in data)

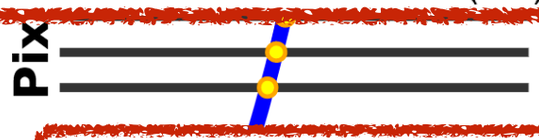
Could something similar be conceived at ATLAS/CMS?

ATLAS, CMS and LHCb

- Dealing with **backgrounds**, common problems,







Part of the work is already there

Roloff, Dall'Occo

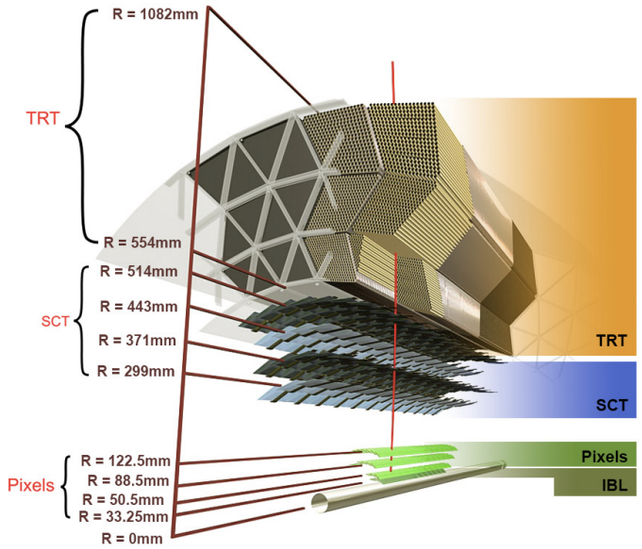
hard hadronic interactions

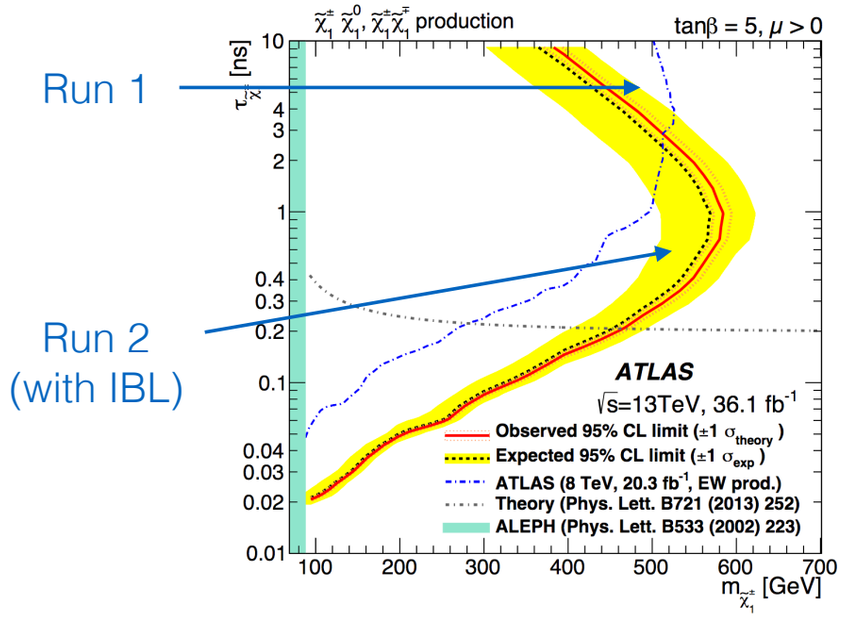
Could something similar be conceived at ATLAS/CMS?

ATLAS, CMS and LHCb

✦ Detector related developments

- ➡ New developments at ATLAS/CMS/LHCb are already/ will impact LLP searches
- ➡ **ATLAS**: Disappearing tracks IBL helped enable reconstruction of shorter tracks than in Run 1 → shorter sensitivity to shorter lifetimes





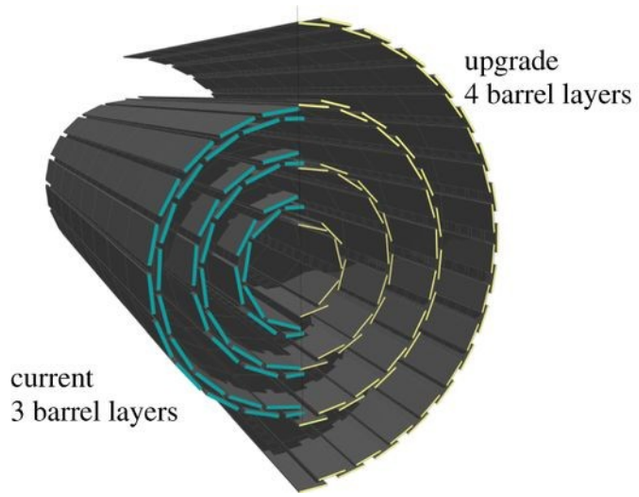
Roloff

ATLAS, CMS and LHCb

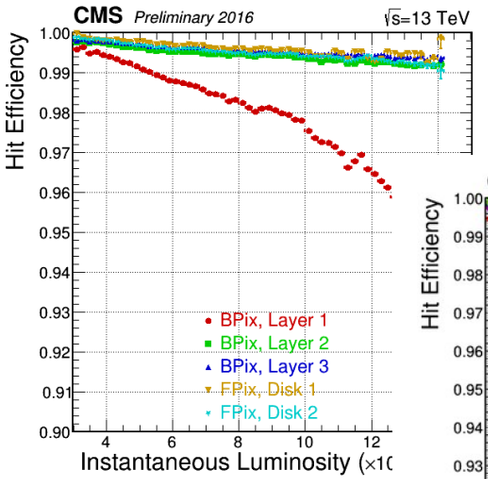
Detector related developments

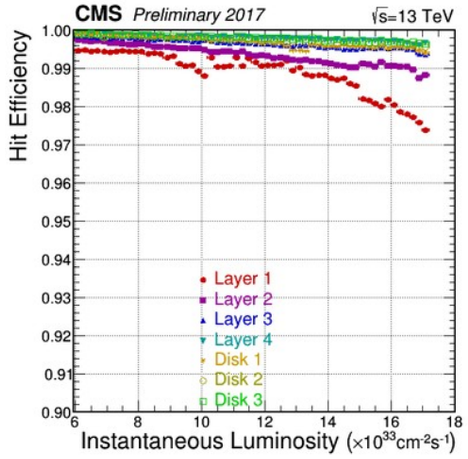
- New developments at ATLAS/CMS/LHCb are already/ will impact LLP searches

- **CMS**: 4 instead of 3 barrel layers, and more endcap coverage, first layer at 3cm from the beamline, 4th layer closer to first strip layer



for LL searches even more important, tracking inefficiency as function of luminosity correlates tracking and vertexing efficiencies within events





Lowette

ATLAS, CMS and LHCb

- **Detector related developments**
  - New developments at ATLAS/CMS/LHCb are already/ will impact LLP searches
  - **LHCb**

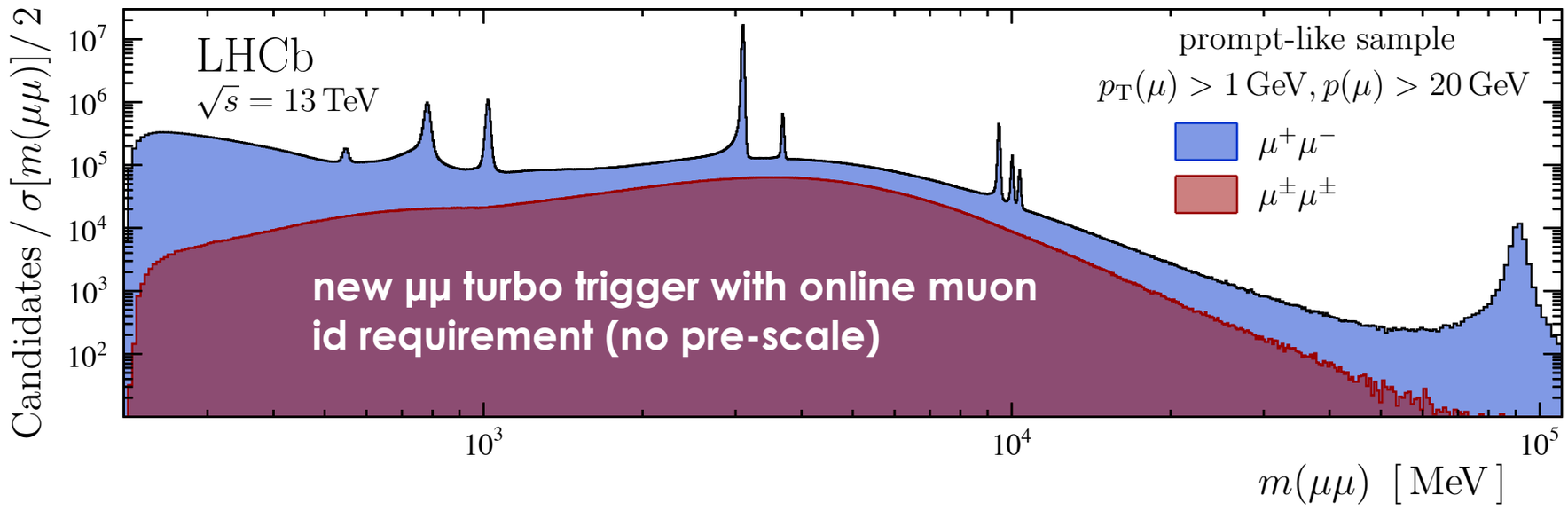
new **turbo** lines since 2015:

- online reconstructed particles stored
- lower level info discarded reducing event size
- output can be directly used for analysis

excellent for light dimuons (prompt and detached)

online μ id reduces rate of double misid from π

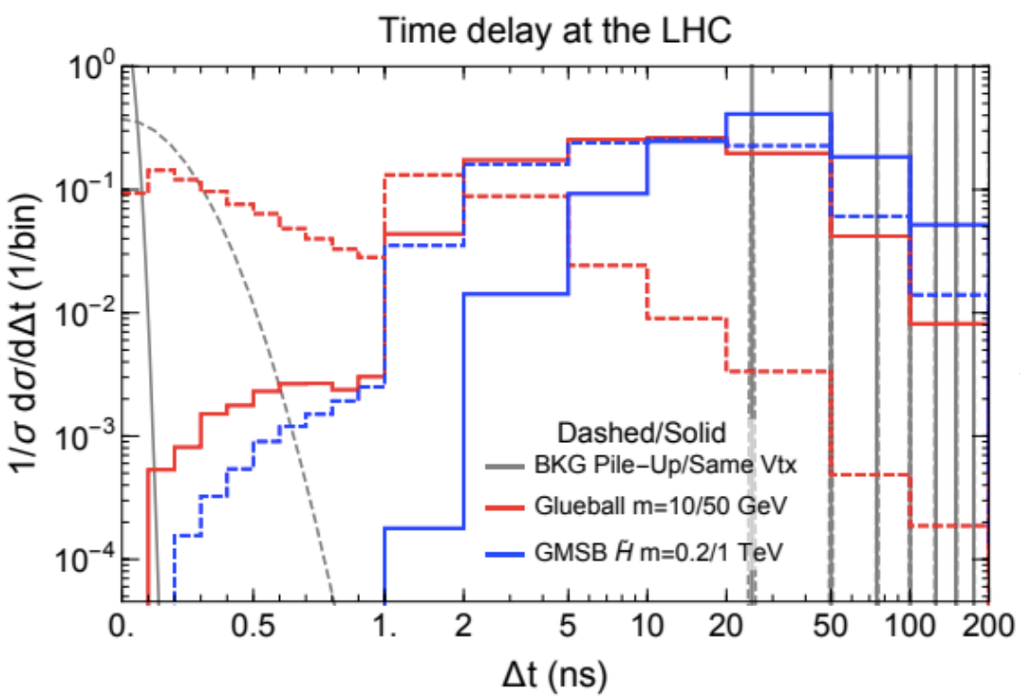
Phys. Rev. Lett. 120, 061801 (2018)

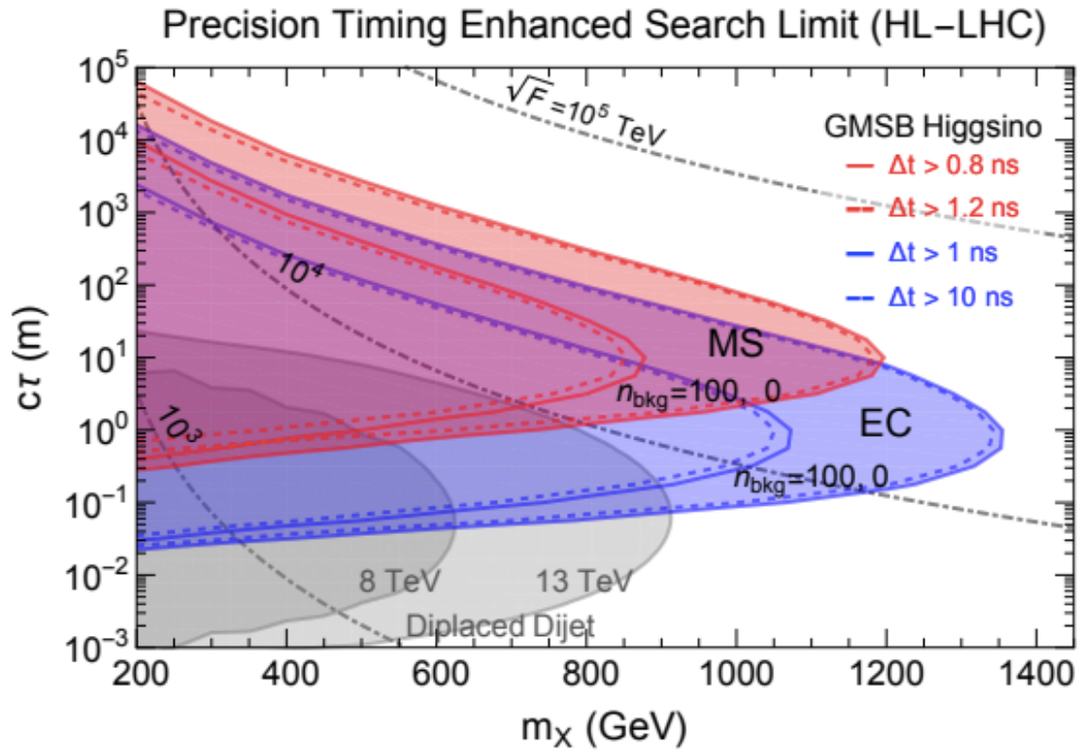


Dall'Occo

ATLAS, CMS and LHCb

- More in the long term: Brand new proposal to make use of timing! Heavy LLPs are slower…
  - Great discrimination against background → enhanced sensitivities

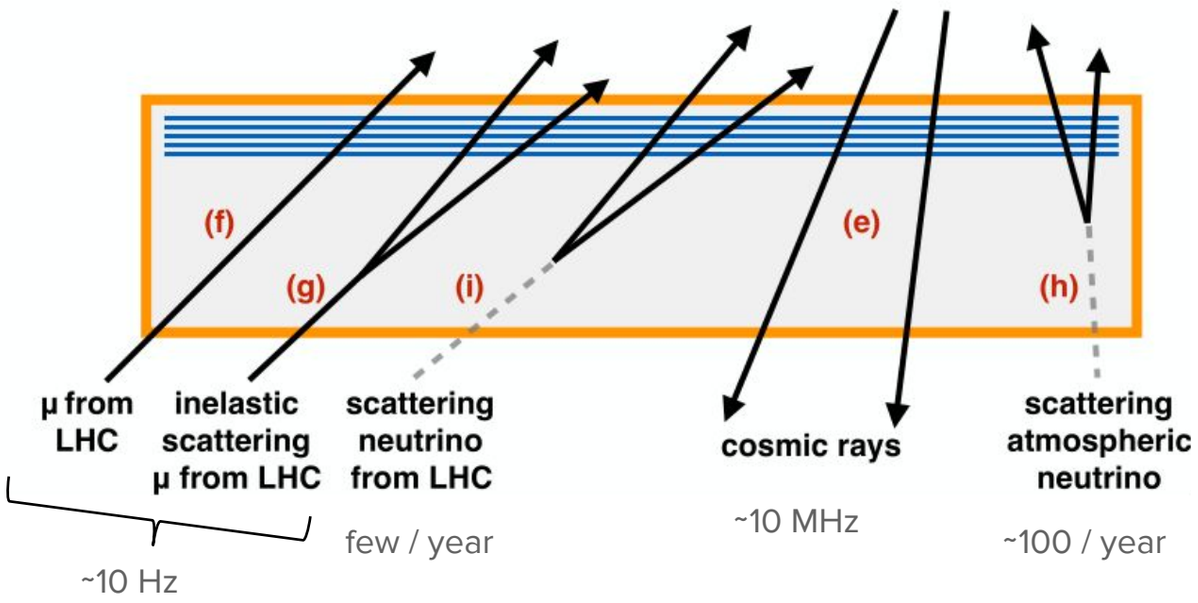




Liu

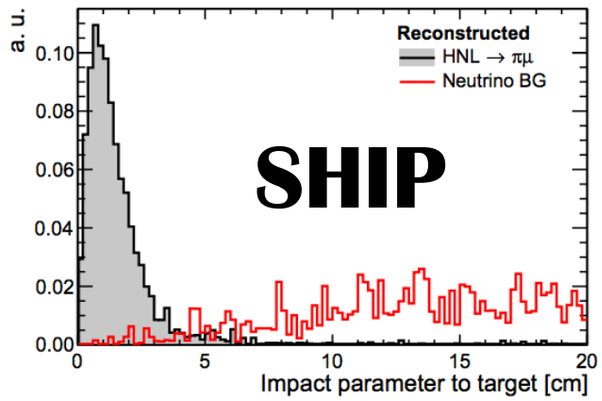
Dedicated experiments

- We've seen a lot of ~~fight~~ useful and lively discussion about the reach of new LLP experiments at the workshop
  - Key element: background. How realistic is the 0-background assumption?



Mathusla

Curtin, Proffitt, Reddi



Very simple selection reduces the bkg to only a few in 5 years:
- Fiducial volume
- DOCA
- IP wrt target
- Vetos

Realistic to reach 0.1 expected bkg events for all channels we have been studying

Dedicated experiments

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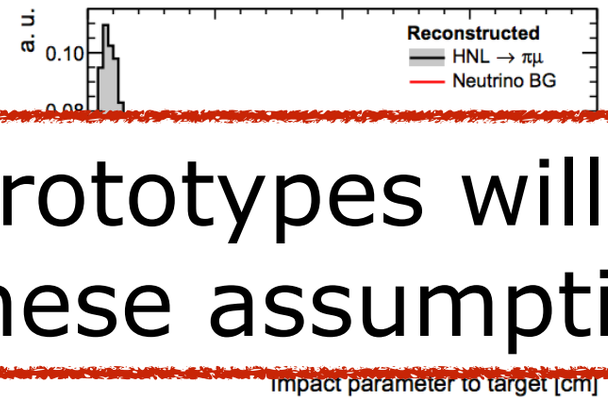
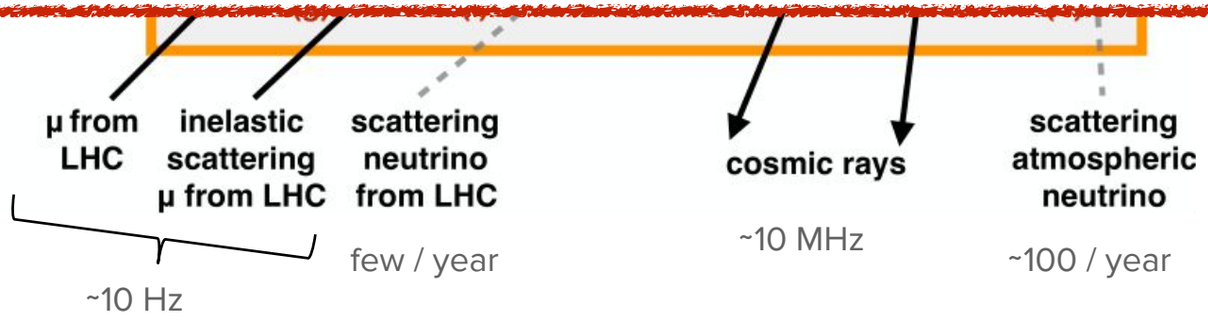


In general, on-site tests with prototypes will be very helpful to verify how realistic these assumptions are!



Mathusla

Curtin, Proffitt, Reddi

Very simple selection reduces the bkg to only a few in 5 years:
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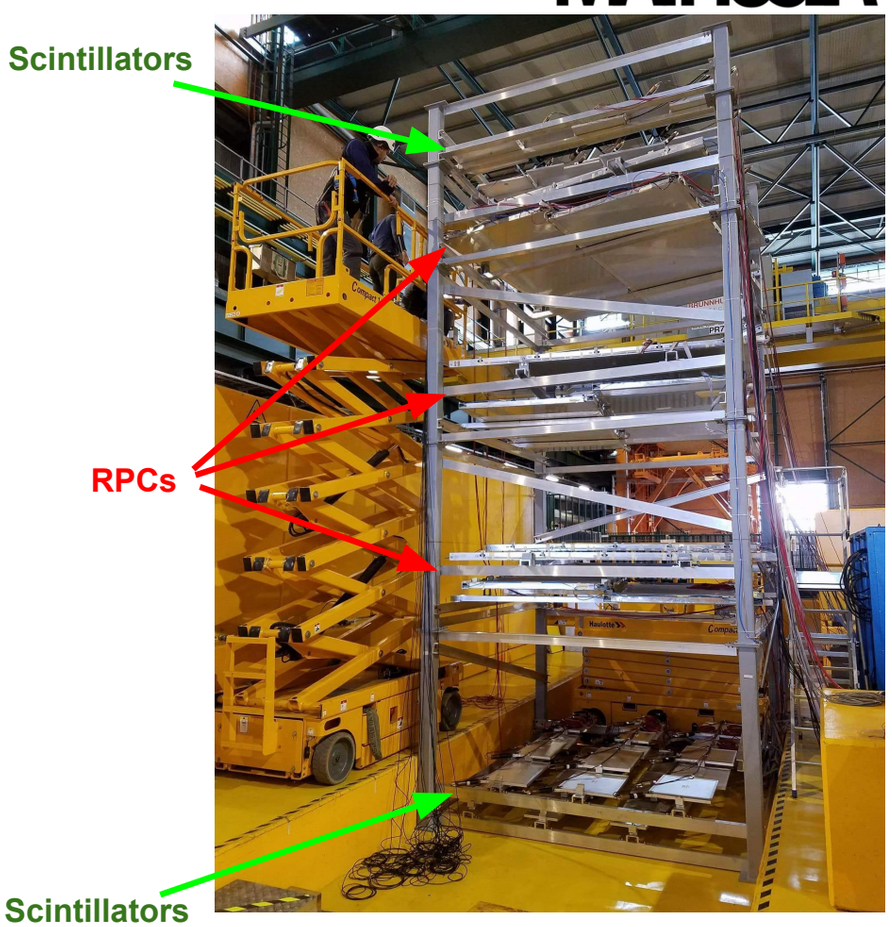
Dedicated experiments

- Great news: in several cases, first tests already starting!

MATHUSLA



Proffitt, Hill, Dey

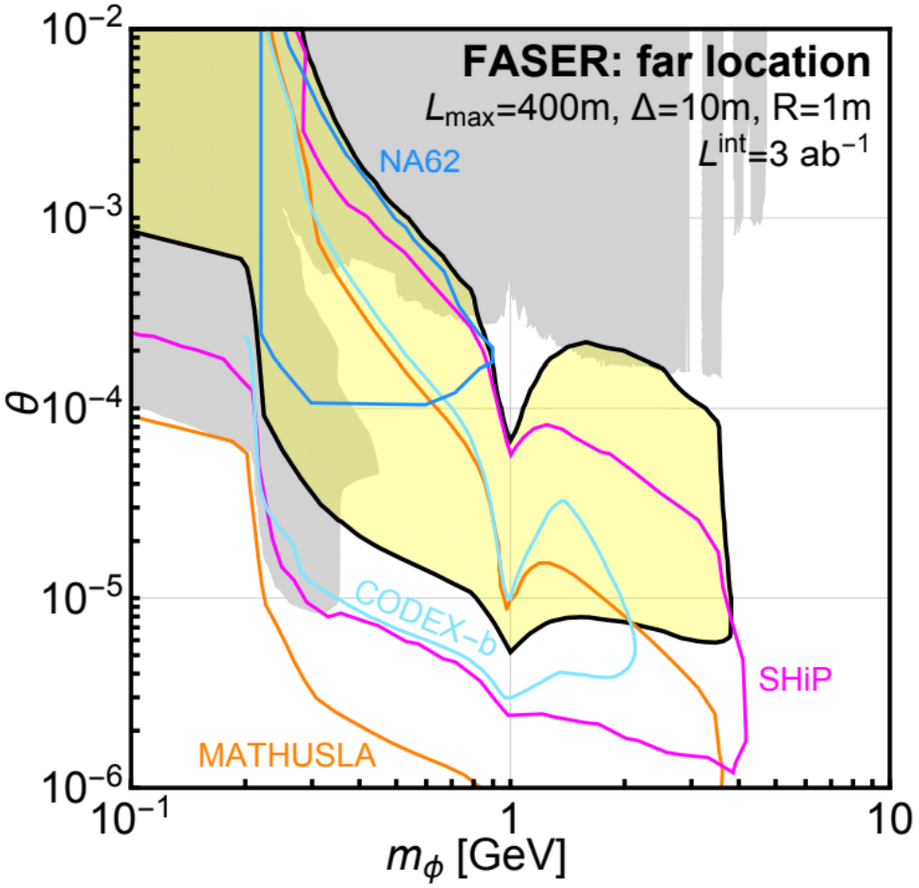
MilliQan

CODEX-b

Dedicated experiments

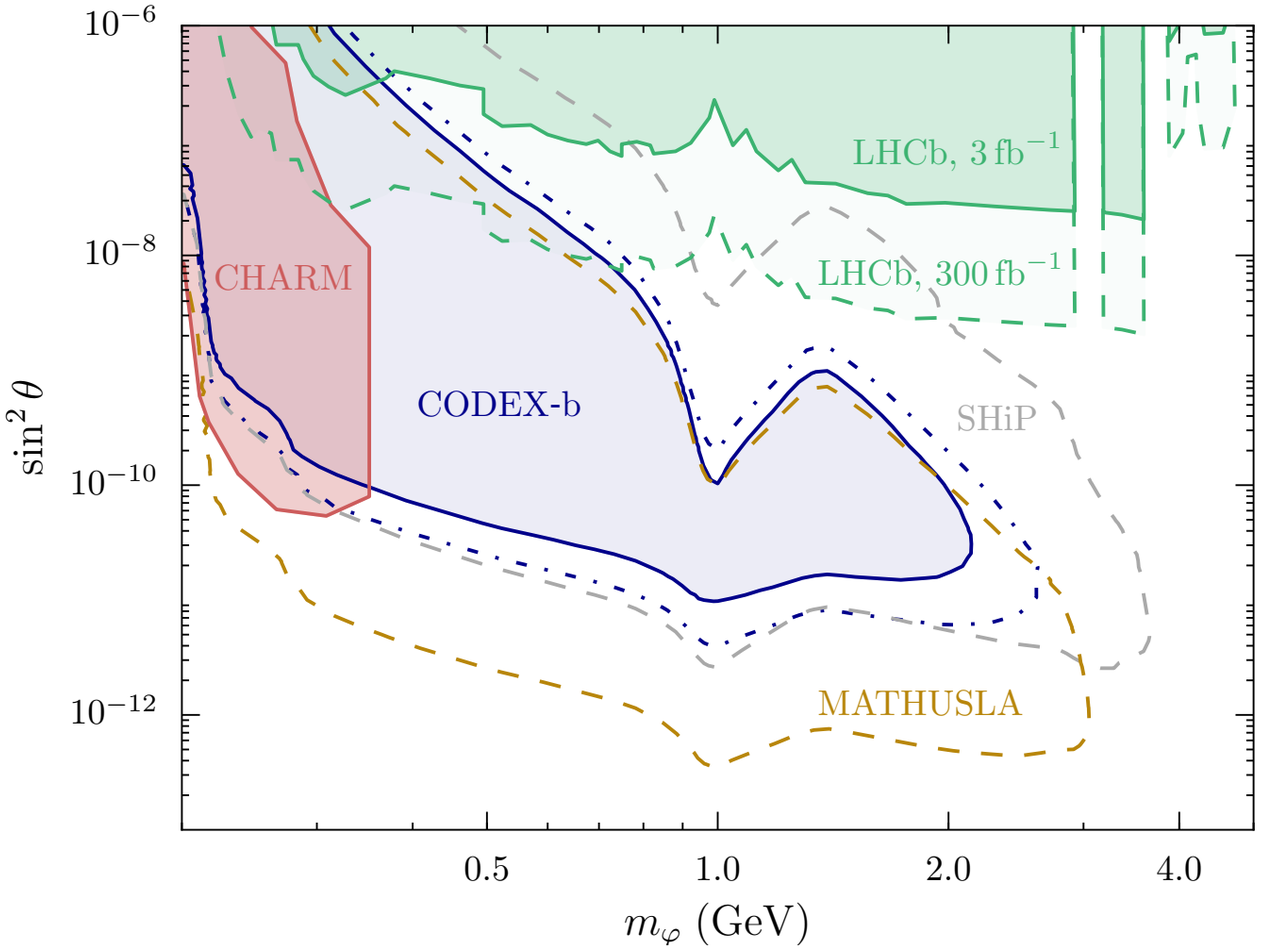
- Which one should be build?
  - Ideally, all of them… But if not, trade between reach/ funding needed

SM+S scenario



Curtin, Dey

$B \to Xs\varphi$



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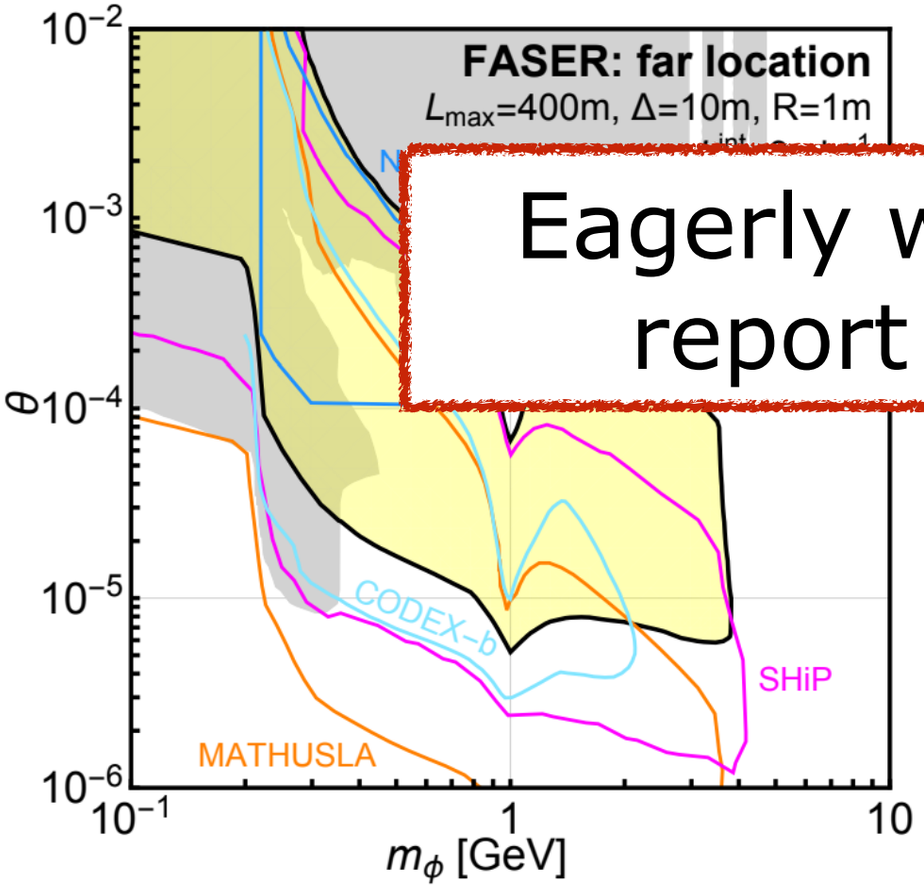
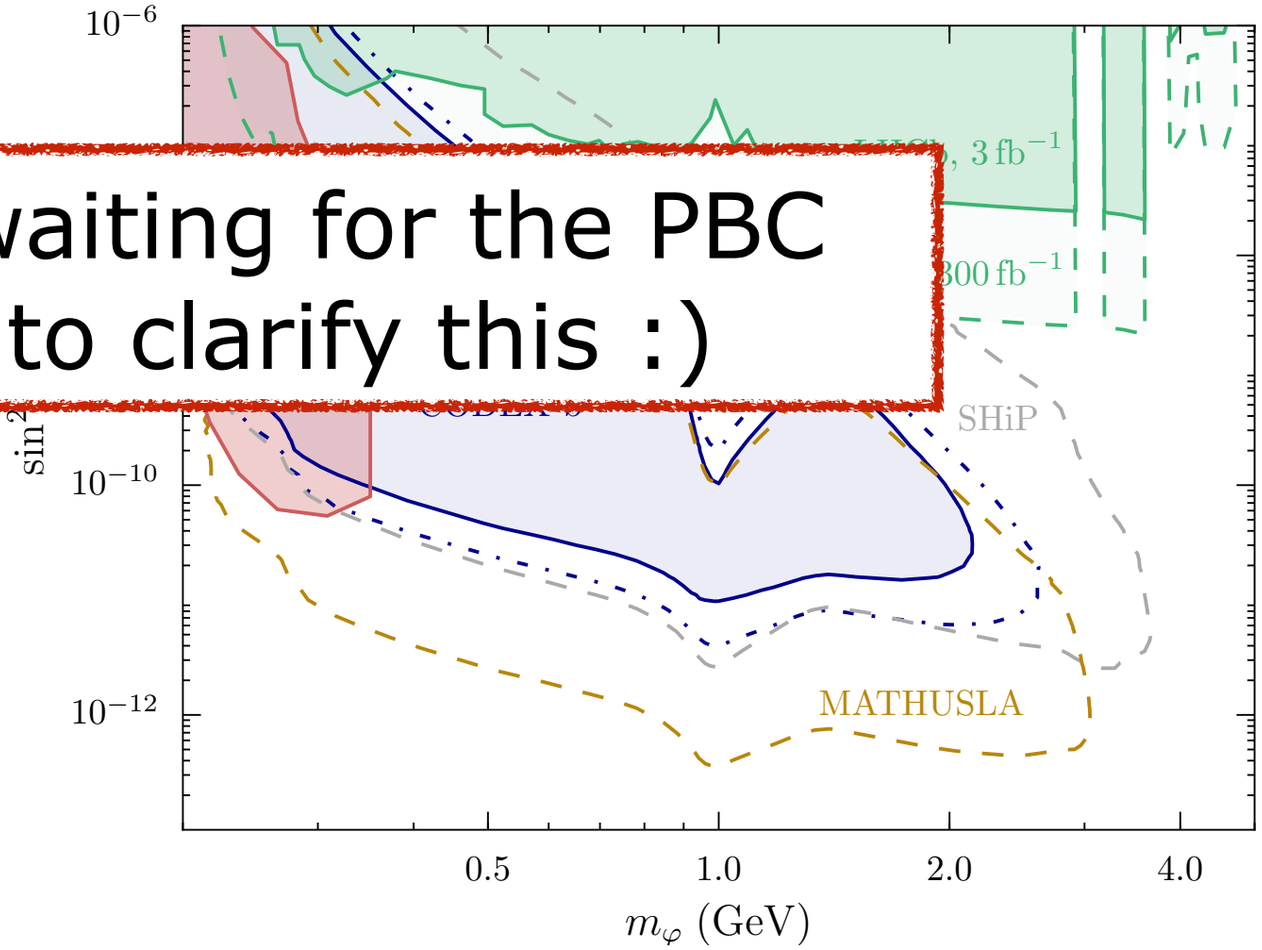


$B \rightarrow Xs\varphi$



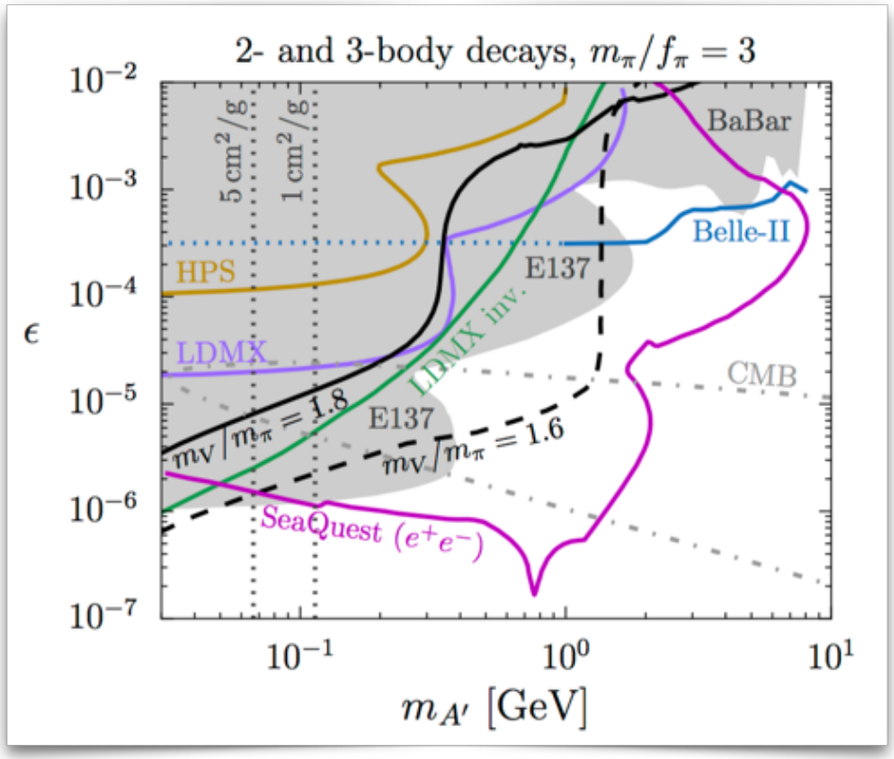
Eagerly waiting for the PBC report to clarify this :)

Curtin, Dey

Dedicated experiments

- Heard for the first time at the workshop

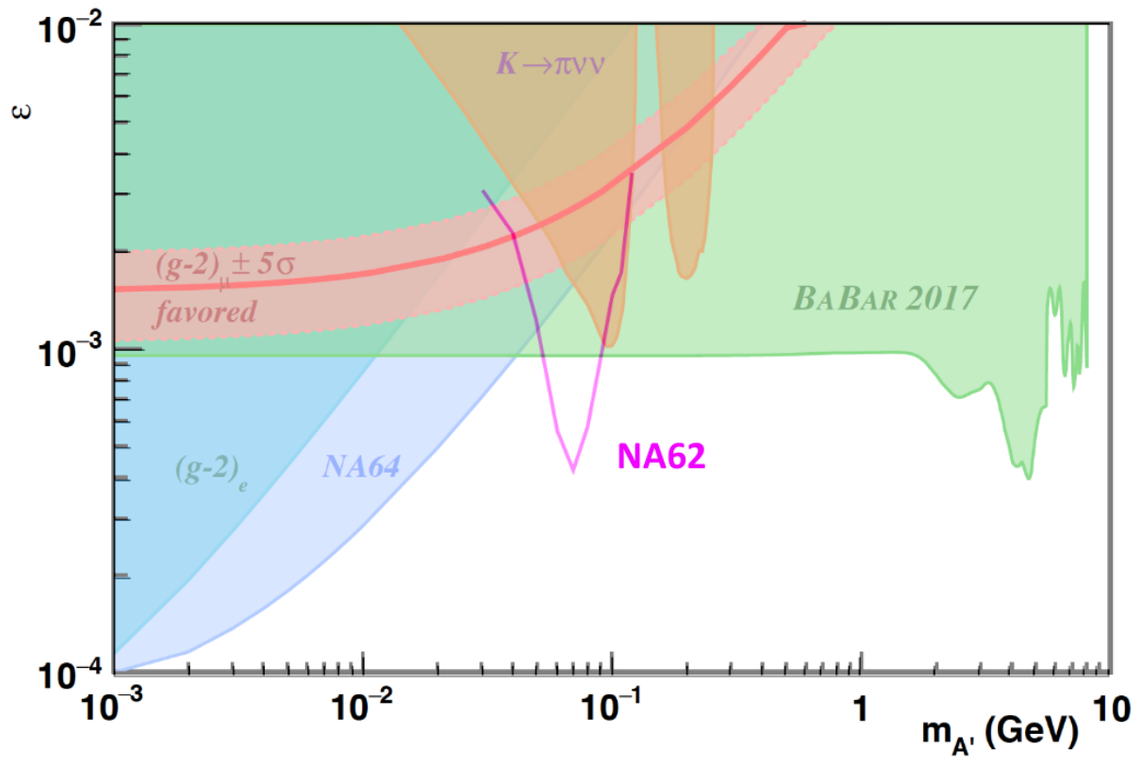
SeaQuest



SIMPS

Gori, Dobrich

NA62

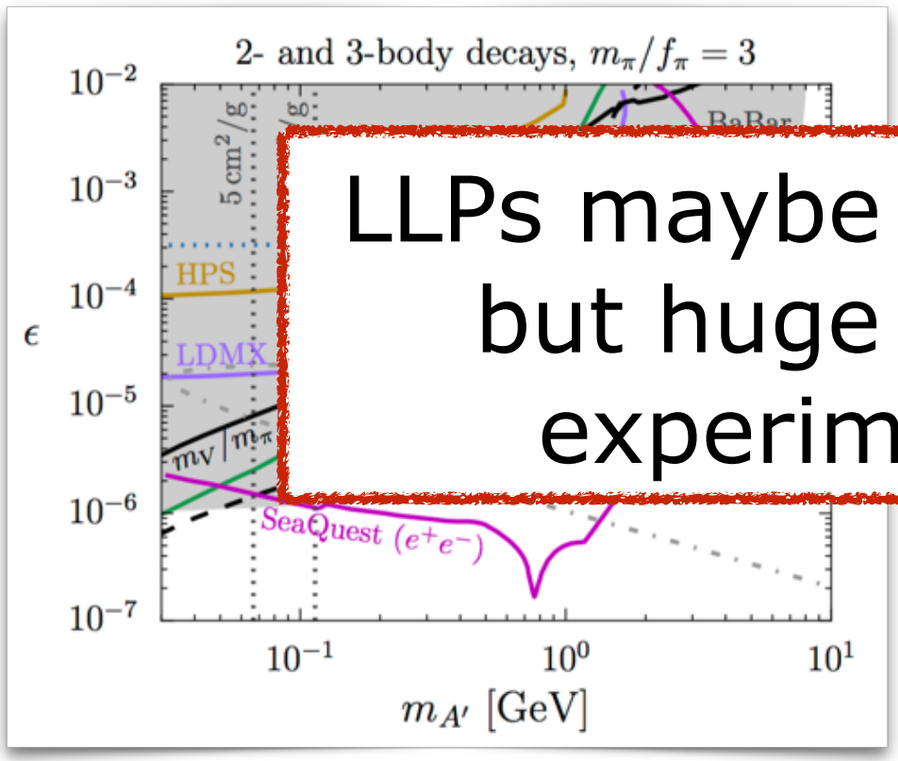


invisibly decaying Dark Photon
$K^+ \to \pi^0\pi^+$ with $\pi^0 \to A' + \gamma$

Dedicated experiments

- Heard for the first time at the workshop

SeaQuest



SIMPS

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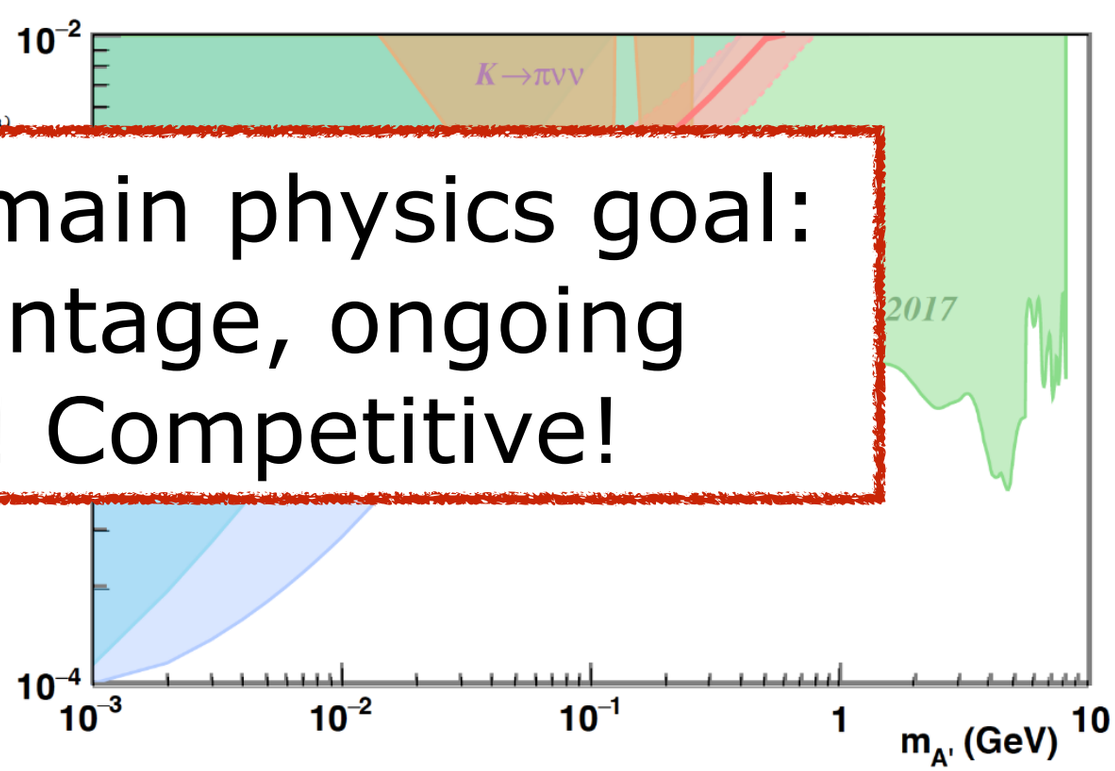


invisibly decaying Dark Photon
$K^+ \to \pi^0\pi^+$ with $\pi^0 \to A' + \gamma$

LLPs maybe not main physics goal: but huge advantage, ongoing experiments! Competitive!

Gori, Dobrich

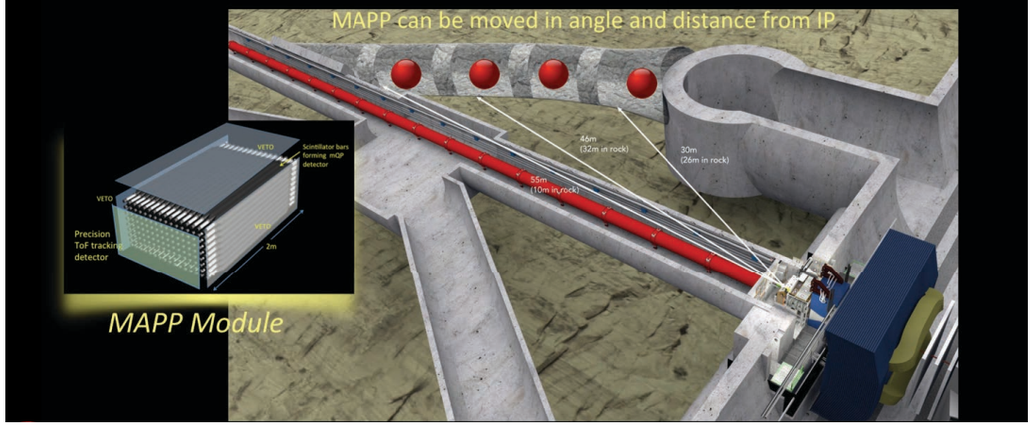
Dedicated experiments

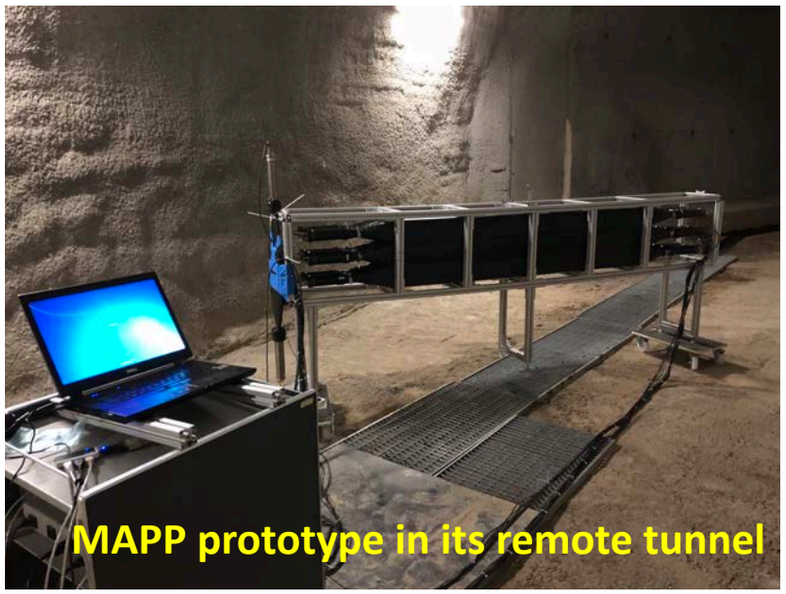
- **MOEDAL** already producing results, but not only

Exciting competition with ATLAS!

MAPP – MoEDAL Apparatus for Penetrating Particles

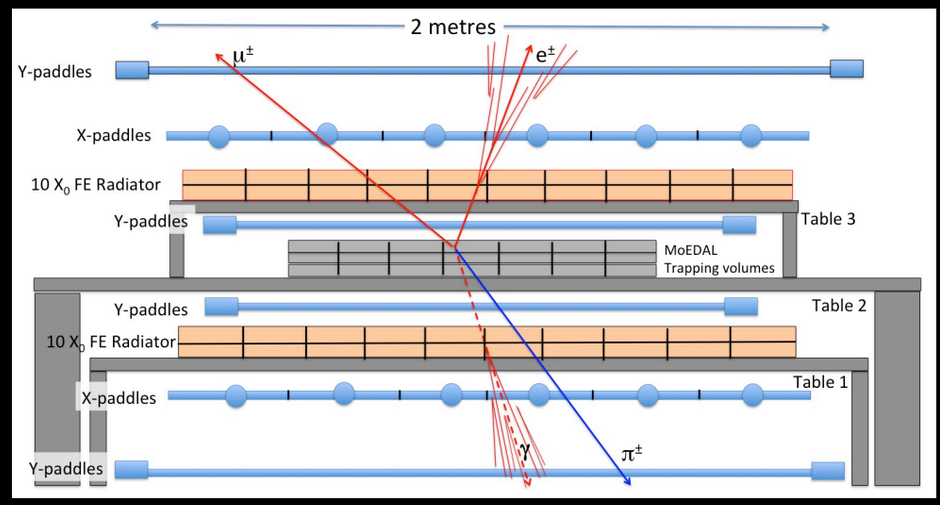
In prototyping phase





MALL (MoEDAL Apparatus for very Long Lived Particles)

A project in the development stage



After exposure trapping volumes will be monitored underground for the decays of trapped very long-lived particles using the scintillator detector sketched above.

Pinfold

Reinterpreting

- Reinterpretations' **main goal**: Where are the gaps? What other searches could we do?
  - For this we do not need completely accurate results.
  - But it’s probably not worth it to "compete" with full experimental analysis
- Other important goal (to me), compare results from different experiments in similar models. Two examples: **disappearing tracks** (see GAMBIT & CheckMATE) and **dark photons**
- But what ingredients do we need for this?
  - **At least** provide efficiency maps in every analysis: also useful from the point of view of data preservation

Reinterpreting

Reinterpretation Challenges

- One model can generate many different **signatures**
- One signature can come from many **models**

- LLP searches are challenging because:
  - "Standard" objects (electrons, muons, tracks) are not so standard if they come from LLP decay or stable LLP
  - Signal efficiencies hard to model with publicly available simulation
  - Efficiencies can have strong dependence on kinematics, LLP decay position, etc.

Shuve

+ efficiency tends to be model dependent…

Reinterpreting

Reinterpretation Challenges

- **Software: MA5 v1.6 + Delphes 3.4.1_Tracks with 8 TeV CMS tracking performance**

Region	$c\tau_{\tilde{t}}$ [cm]	MA5	CMS	Difference [%]
SR-I	0.1	3.89	3.8	2.30
	1	4.44	5.2	14.51
	10	0.697	0.8	12.84
	100	0.0610	0.009	$> 100\%$
SR-II	0.1	0.924	0.94	1.71
	1	3.87	4.1	5.61
	10	0.854	1.0	14.58
	100	0.0662	0.03	$\sim 100\%$
SR-III	0.1	0.139	0.16	12.84
	1	6.19	7.0	11.59
	10	4.45	5.8	23.56
	100	0.497	0.27	$\sim 100\%$

- LLP
- not so
- LP
- vailable
- Efficiencies can have strong dependence on kinematics, LLP decay position, etc.

+ efficiency tends to be model dependent…

Shuve, Conte

Reinterpreting

- More work needed on our (experientalist) side
  - Challenging, but we should try

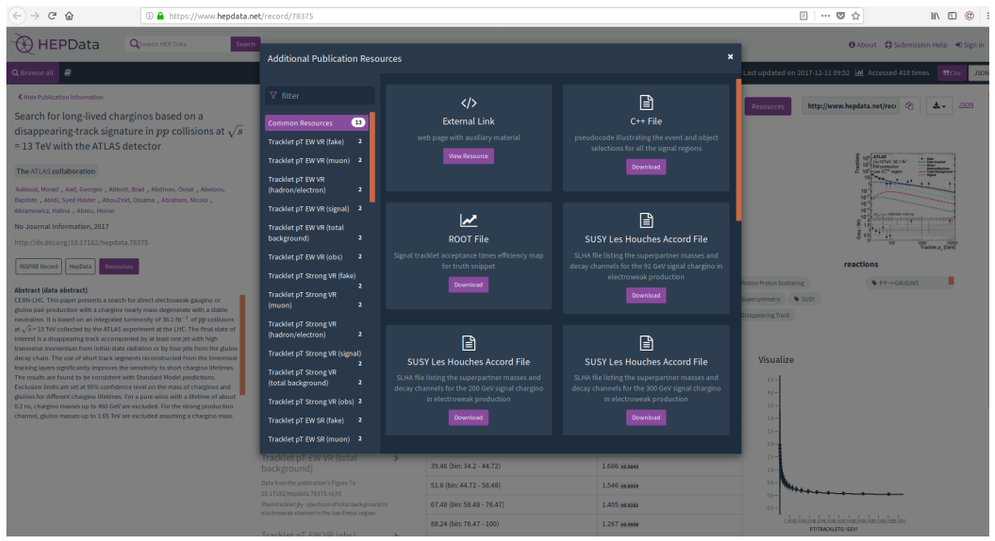
List of cuts

Preselection
Event passes standard FilterOutScraping cuts
One good primary vertex
generator electron coming from stop
generator electron with η < 2.5
generator electron with v0 < 4 cm
generator electron with vz < 30 cm
generator electron with pT > 25 CMS.GeV
⋮

Requires CERN login

Don't know, but probably 100%

Hmm..



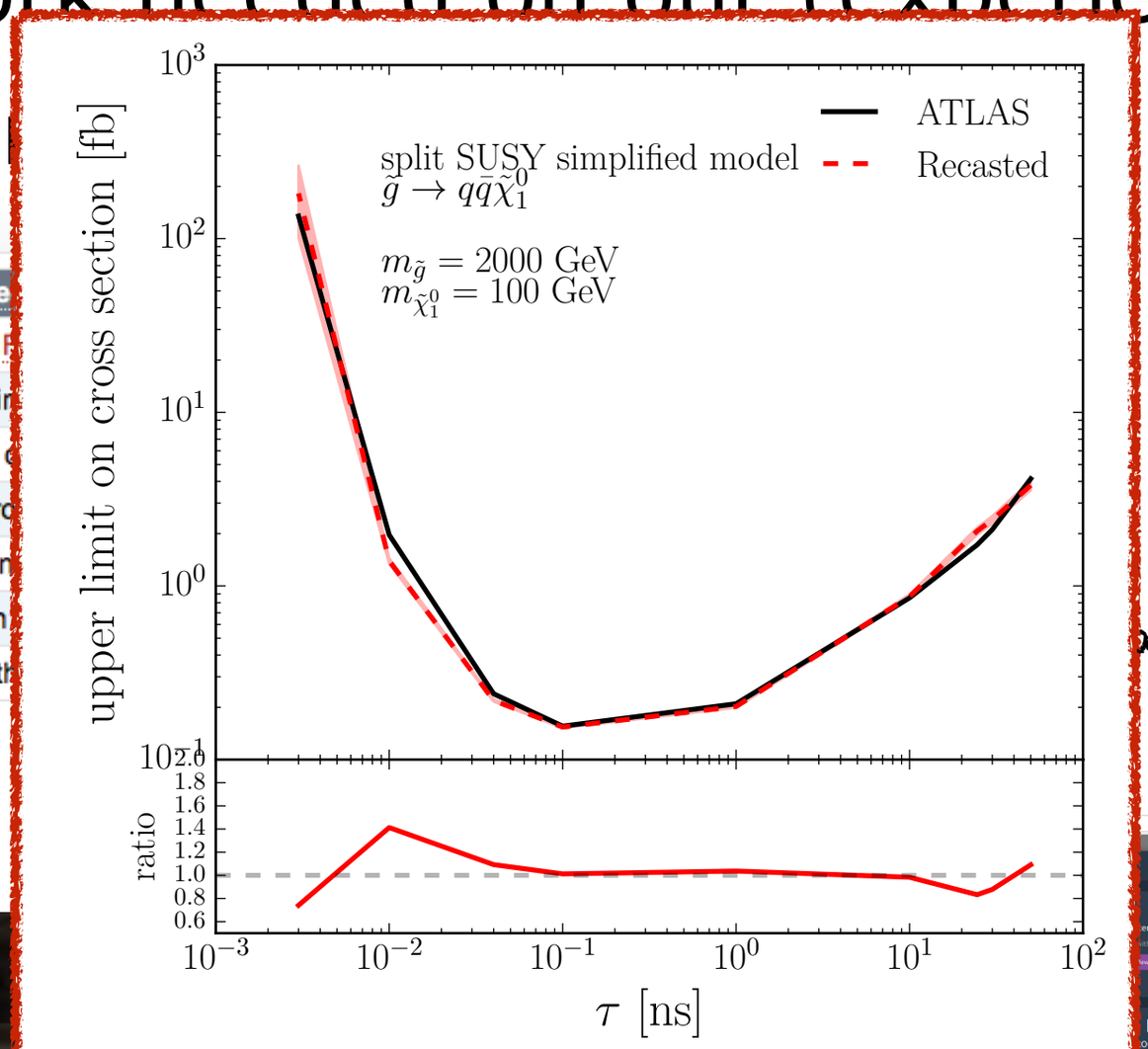
Desai, Kim

Reinterpreting

- More work needed on our (experientalist) side
  - Challe

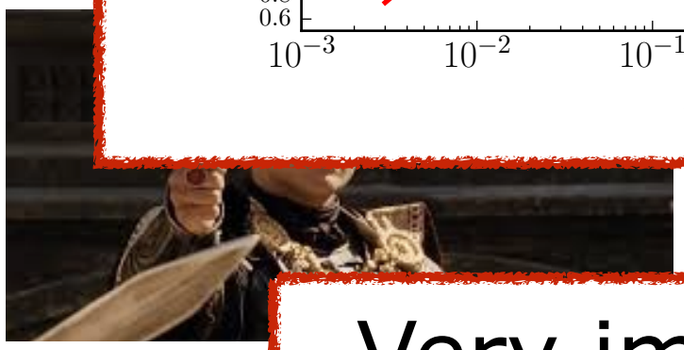
List of cuts

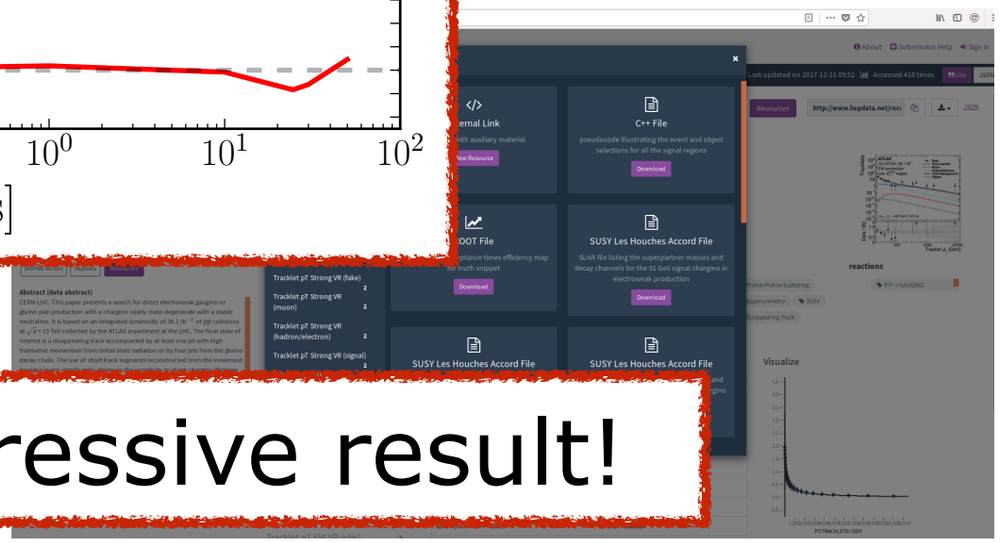
Presele
Event passes standard
One good prir
generator electron
generator electro
generator electron
generator electron
generator electron with



CERN login

ably 100%



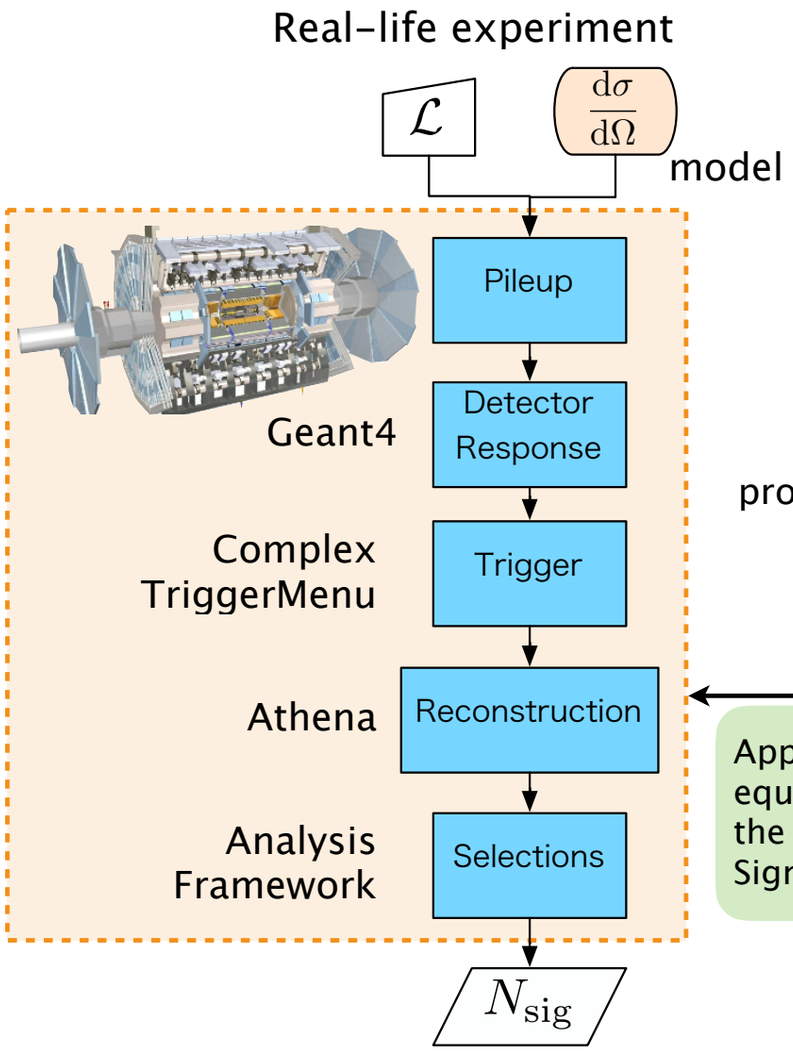


Very impressive result!

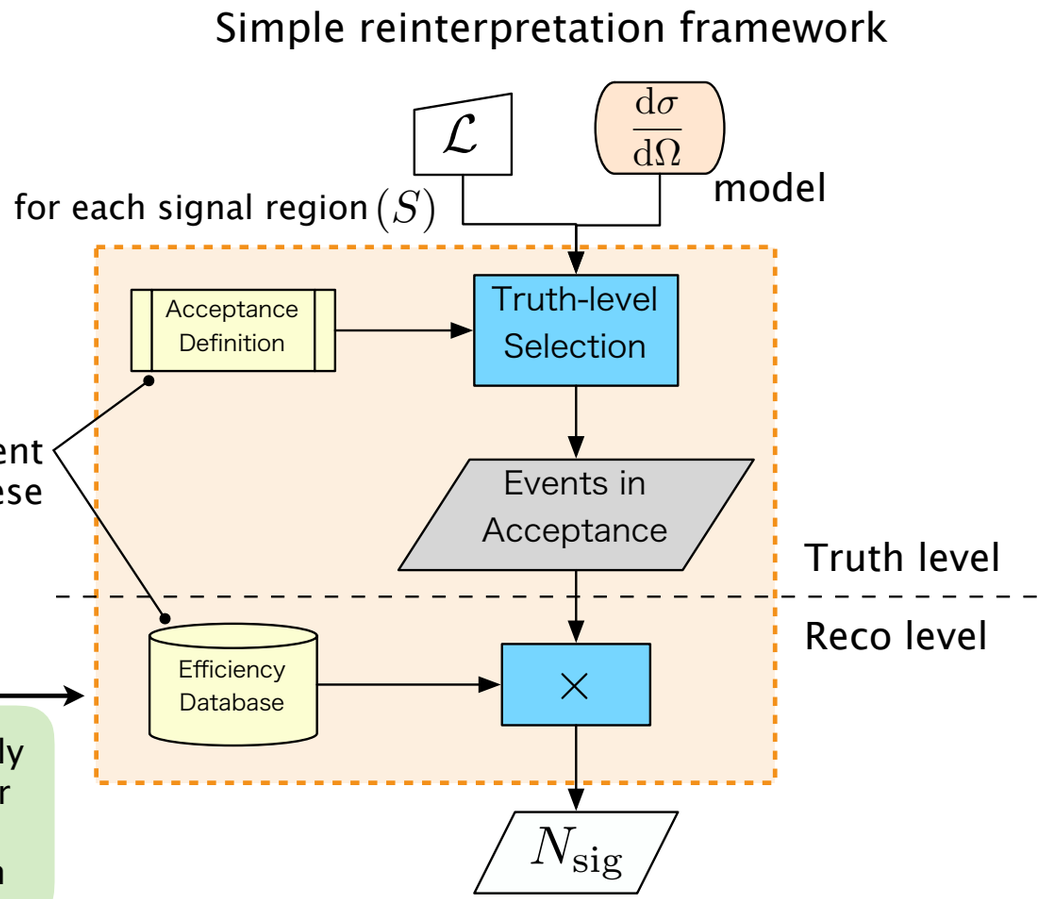
Desai, Kim

Reinterpreting

- Therefore crucial to provide tools! First step, reinterpretation of own results?



Approximately equivalent for the given Signal Region

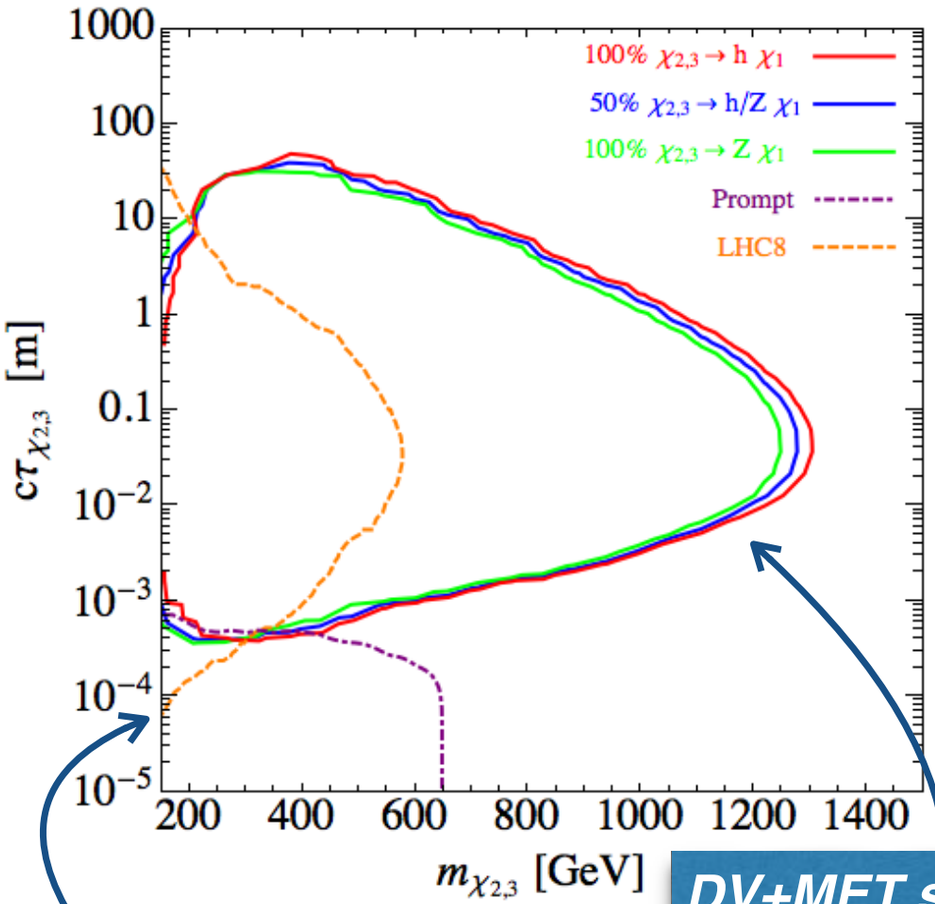


$$N_{\mathrm{sig},i}^{(S)} \simeq \left(\mathcal{A}_i \cdot \langle\varepsilon\rangle\right)^{(S)} \cdot \left(\mathcal{L} \cdot \sigma_i^{\mathrm{tot}}\right)$$

Oide, Alimena

Reinterpreting

- Example: Freeze-In Dark Matter
  - Freeze in: alternative mechanism to obtain dark matter abundance
  - It naturally involves small couplings (long-lived particles)
  - Several recasts done: example DV+MET ATLAS



8TeV limits
Z.Liu, B.Tweedie, '15
CMS PAS EXO-12-038

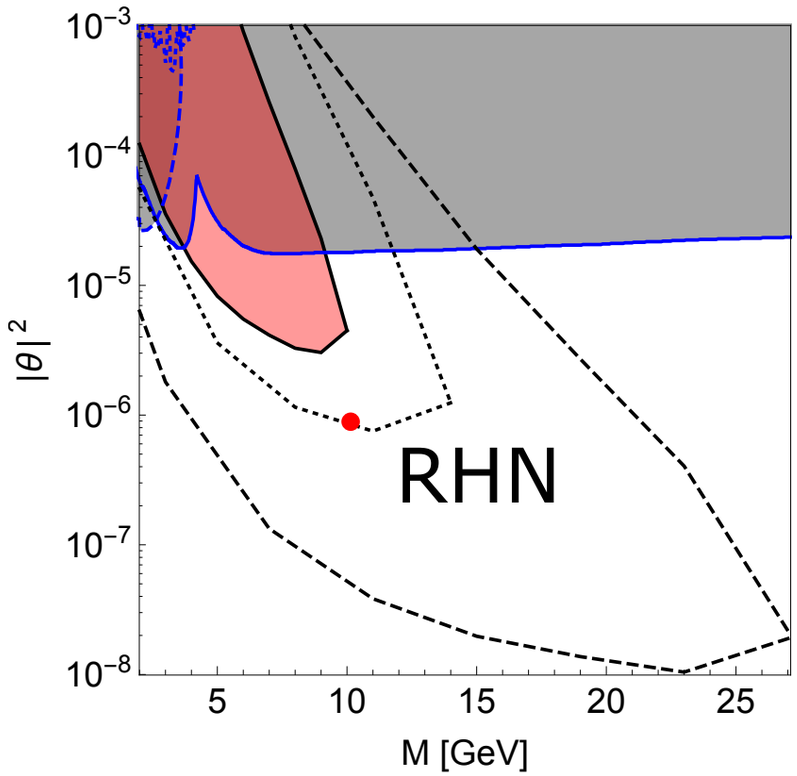
DV+MET search has strong reach on EW states in SD-FI

Mariotti, Zaldívar

Other interesting examples: Cottin, Lara, Vogl, Popara, Heisig, DiPetrillo…

Reinterpreting

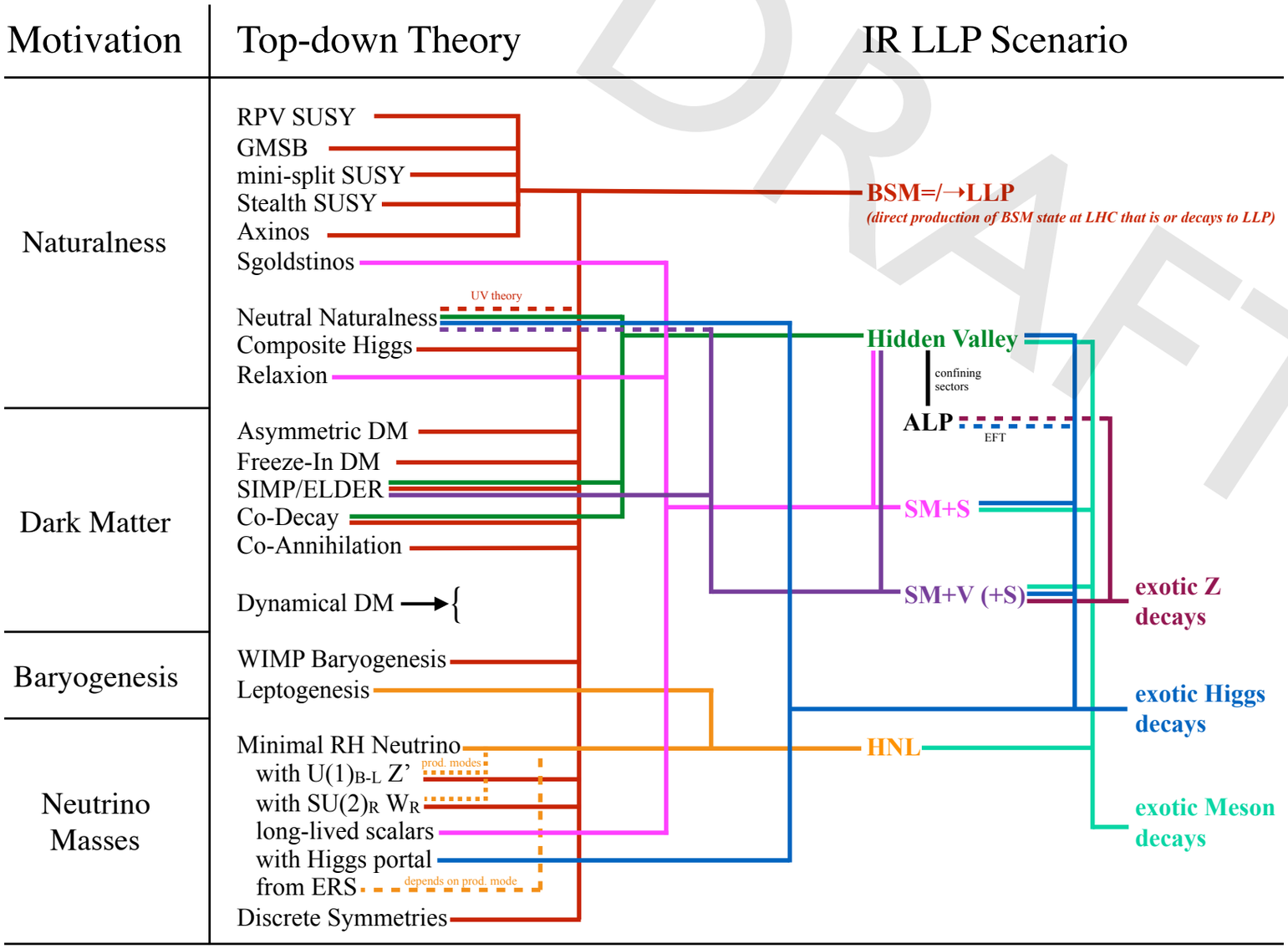
- I have the feeling that LHCb is behind ATLAS/CMS in providing this kind of tools
  - Modest effort, but more work needed!
  - Still, some courageous dared to give it a try



Fischer, Xue

New (and not so new!) theory ideas

- Now I wonder, why didn't we look for LLPs from the very beginning?



Curtin

New (and not so new!) theory ideas

- Now I wonder, why didn't we look for LLPs from the very beginning?

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*

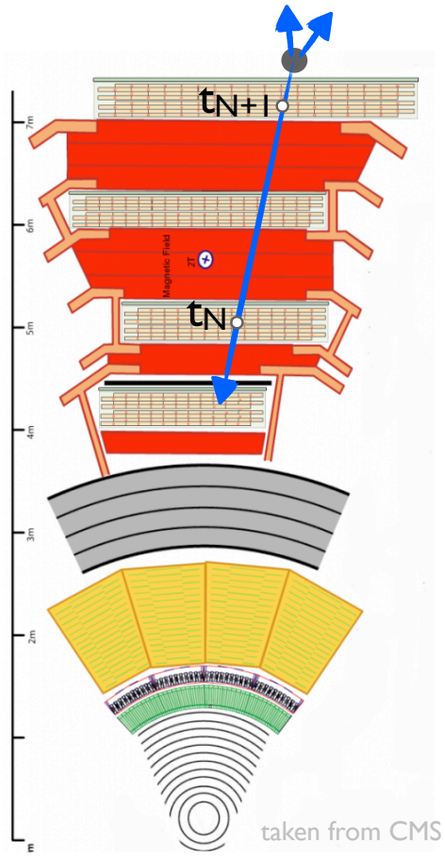
Shuve

New (and not so new!) theory ideas

- **Novel signatures** for long-lived particles

Very exotic, unconventional signature

- not yet searched for?
- experimentally challenging?



Decay outside detector

- Extreme scenario
- Only backward-moving particle enters the detector
- Identify backward moving particle by timing
- Potential background is cosmic ray
  - Use only lower half of barrel ?

➡ Really enjoy this approach, no matter how crazy these signatures may look like!

Mukherjee

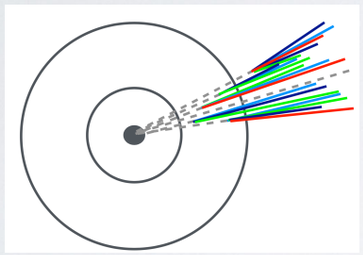
New (and not so new!) theory ideas

- **Novel signatures** for long-lived particles

FLAVOURED DARK SECTOR

LHC

Emerging jets for dark pions above about 20 GeV



Different characteristic length scales for different hadron flavours to emerge

Fixed Target

Hadronically-decaying dark pions with masses 1-5 GeV

Common decay modes:

$$\pi_D \to \pi\pi\pi$$
$$\pi_D \to K\pi$$

Both NA62 and SHiP will probe interesting parameter space

- Really enjoy this approach, no matter how crazy these signatures may look like!

Renner

New (and not so new!) theory ideas

✦ Hidden Sectors are Diverse!

- In the majority of theories, we cannot calculate what will happen
  - At best we can learn a few facts that will help guide our searches
  - There are surely some phenomena that we don't yet suspect

Implications for LLPs

- Multiplicities (total and by particle type) are often unknown
  - Low multiplicity (1!) a big issue for LLPs; need searches covering this case
- Energy distributions for non-perturbative processes are rarely known
  - Slow LLPs raise special concerns; could this dominate??
- Angular distributions are often unknown
  - This is not always a problem for LLPs
  - Except maybe (in limited cases) when typical LLP is inside prompt decay

- Soft spherical SUEP is not entirely well-defined, needs more nuance
  - Need more details, or at least more clarity on what is not known

Strassler

New (and not so new!) theory ideas

✦ Hidden Sectors are Diverse!

- In the majority of theories, we cannot calculate what will happen
  - At best we can learn a few facts that will help guide our searches
  - There are surely some phenomena that we don't yet suspect

- Therefore: **we must search for LLPs in general ways,** not reliant on
  - QCD-like hidden sector dynamics
  - Unreliable and unvalidated MCs
- **LLP searches need a model-independent approach!**

- Angular distributions are often unknown
  - This is not always a problem for LLPs
  - Except maybe (in limited cases) when typical LLP is inside prompt decay

- Soft spherical SUEP is not entirely well-defined, needs more nuance
  - Need more details, or at least more clarity on what is not known

Strassler

New (and not so new!) theory ideas

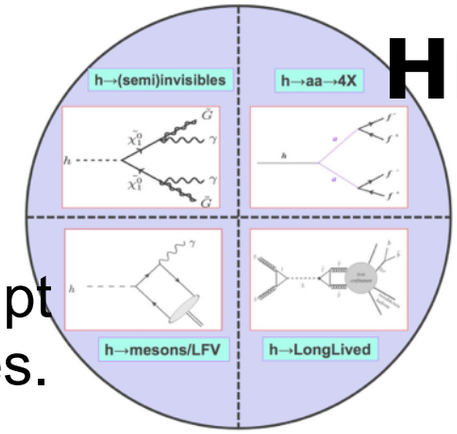
- The days of "guaranteed" discoveries or of no-lose theorems in particle physics are over, at least for the time being ....
- .... but the big questions of our field remain wild open (hierarchy problem, flavour, neutrinos, DM, BAU, ...)
- This simply implies that, more than for the past 30 years, future HEP's progress is to be driven by experimental exploration, possibly renouncing/reviewing deeply rooted theoretical bias

Michelangelo Mangano

Reddi

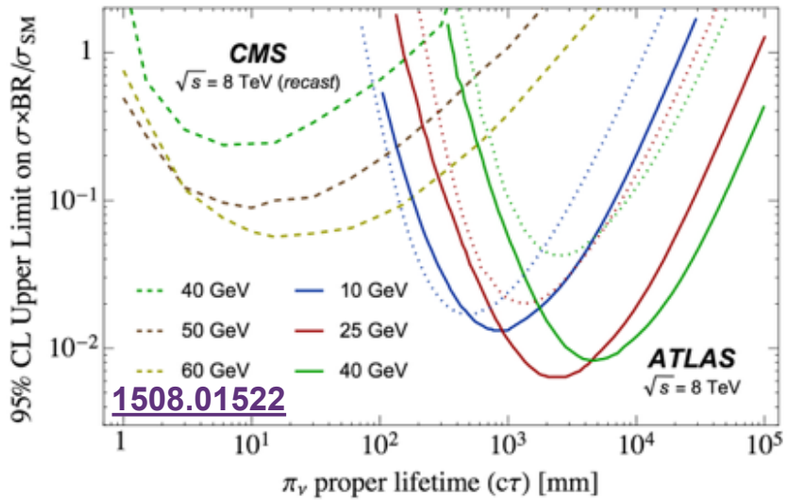
Synergies

Higgs XS WG



Ongoing work and new ideas

- From the Higgs Exotic Decay group we are encouraging analyses to **re-interpret** their prompt searches in terms of slightly displaced signatures.



- Probe a region of the phase space “in between” prompt and LL.
- Coordinate the transition between long-lived and prompt searches.

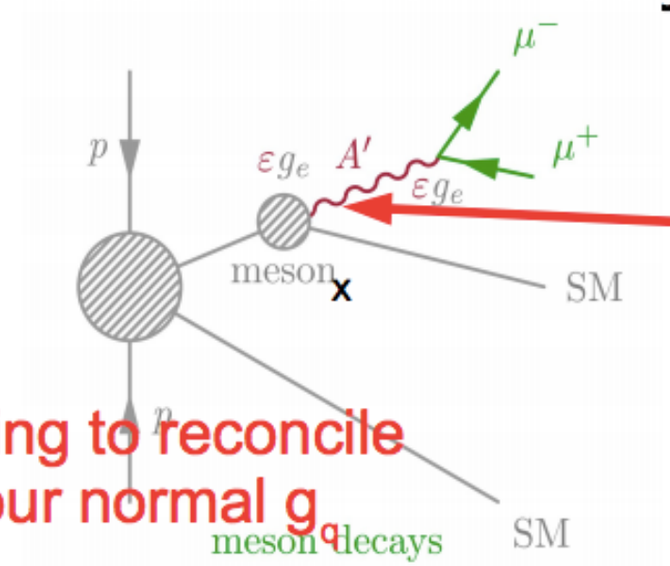
- Big effort ongoing to provide final recommendations on the several fronts and feasibility studies for final states not currently being studied.
- As it has been done for prompt h→aa searches, centralize the different benchmark models and provide recommendations to generate MC, if they don’t exist.

Caminal

Synergies

DM WG

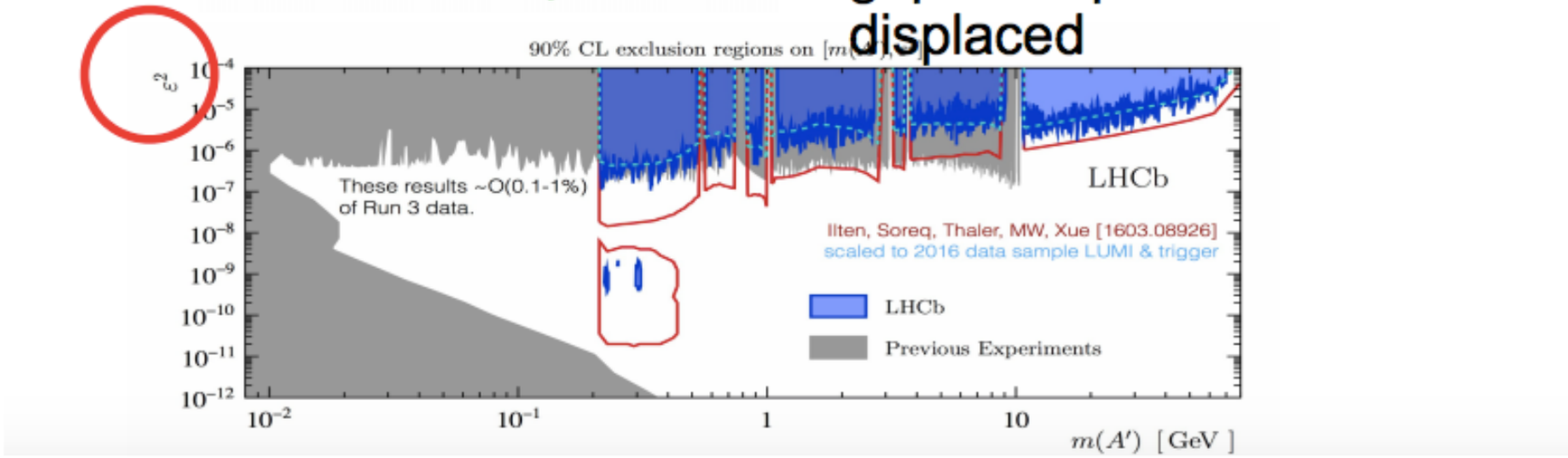
- Dark sector search through the visible decays



Can also be displaced

Working to reconcile with our normal g

Dark photon model is one of these models that bridge the gap of displaced and non-displaced

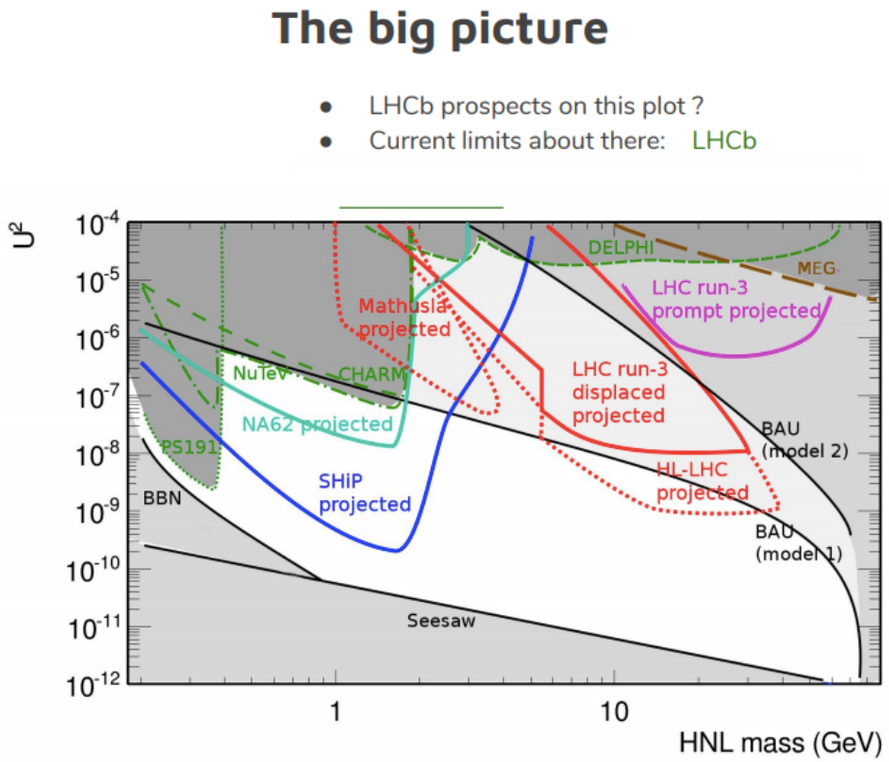


Harris

Next meeting on dark photons: June 22nd, 14:30

WG breakout

- Lively discussion in the breakout sessions + elevator pitch session!
  - **Blue Sky ideas**. Example of idea: use of new potential crossing points? Infinite money: let’s instrument Geneva's sky!
  - **Simulation** (+example from elevator pitch): stop very heavy particles in the calorimeter, very high ionization, doesn’t rely on the stopped particle to decay
  - **HNL**: a lot of interest, Formation of HNL@LLP group should definitely take place!



Fischer, Zurita, Shuve, Buttinger

LLP white paper

- Don’t forget it: **we’re writing a paper**!
  - Huge effort from many people, now very close to the end!

https://github.com/jbbeacham/LHCLLP

LLP white paper

- **Experimental gaps**: Very good state, but discussion on *taxonomy*…

Proposals for exotics taxonomy

Proposal I

2) Highly ionizing tracks:
- a- calo decays: HSCP
- b- HIPS: monopoles
- c-quirks

3) anomalous tracks:
- b1-disappearing/kinked tracks
- b2-emerging tracks: SIMPS, emerging jets

4) Out of time decays: SP

Proposal II

2) Highly Ionizing/Calorimeter Signatures:
- a- Large dE/dx: HSCP
- b- Out-of time decays: SP
- c- Trackless signatures: SIMPS, emerging jets

3) Unconventional Track Signatures :
- a- Highly-Ionizing tracks: monopoles and quirks models
- b- disappearing/kinked tracks

Proposal III

2) In-time exotic long-lived signatures:
- a- Slow and/or anomalously ionizing tracks (HSCPs, fractionally charged, quirks, monopoles)
- b- disappearing/kinked tracks
- c- Trackless jets
- d- Emerging jets

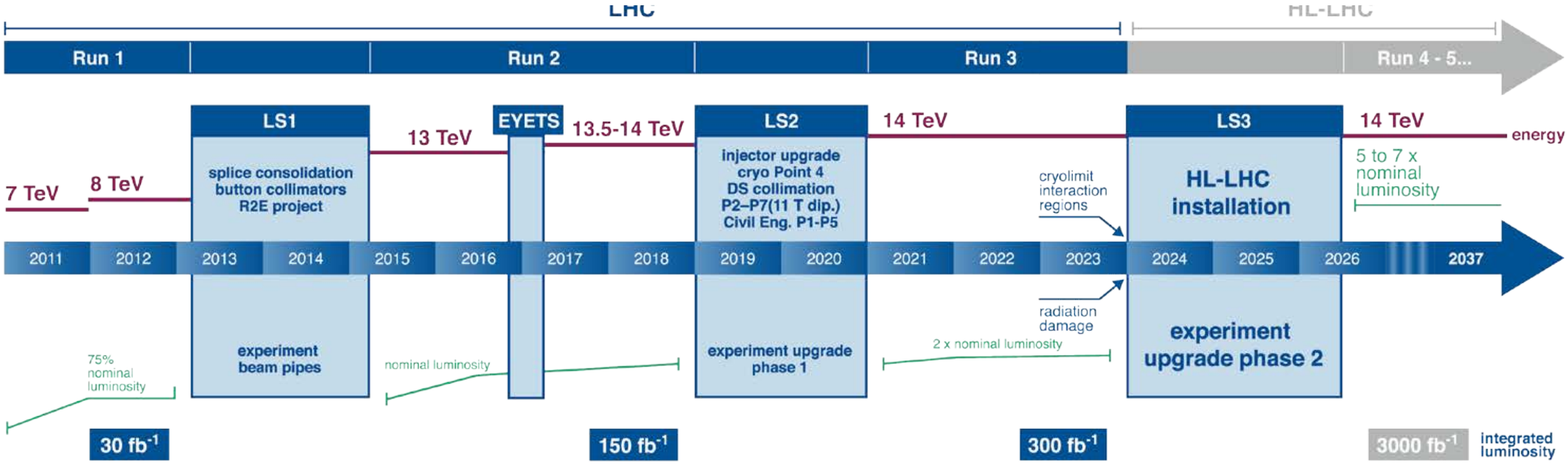
3) Out-of-time long-lived signatures:
- a) OoT calo
- b) OoT muons

2a) could be broken into a bunch of options:
- a- Slow & highly ionizing tracks (HSCP & quirks)
- b- Low dE/dx (fractional)
- c- Extremely high ionization (Monopoles)

Zurita

LLP white paper

- **Trigger and detector upgrades**: very good progress, some *external* review probably needed



- Important for dedicated detectors: if you want to be in the paper, please contribute

Can we actually fit ep collider, CLIC here?

Cheng

Conclusions

After our first look at 13 TeV, our traditional motivation paradigms are fading or dead

The Higgs discovery only answered one open question — does the SM Higgs exist? — and raised a bunch of others!

But these other questions a~~re no longer accompanied by guaranteed discoveries~~ where they ever? :-)

~~Scary~~: Where do we look? Exciting!

Freedom: Everywhere! We have one of the most sophisicated devices ever built at our disposal, and our job is to push it to its limits, to map out all available experimental object space

This means bold new ideas involving LLPs. 2018 is the perfect time to be bold!

Beacham

See you in Nikhef !