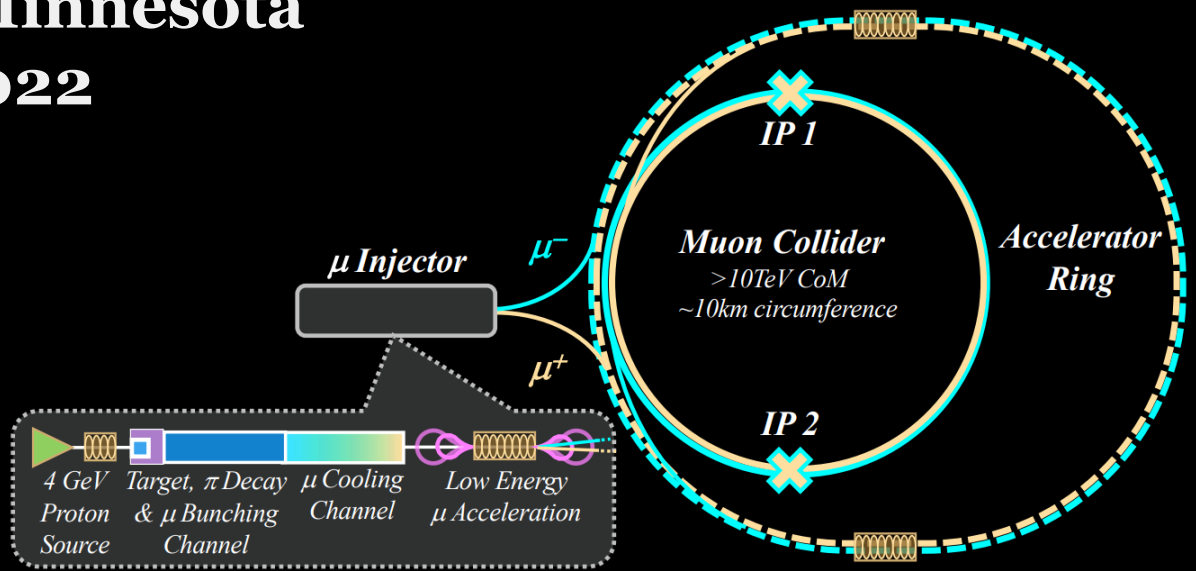
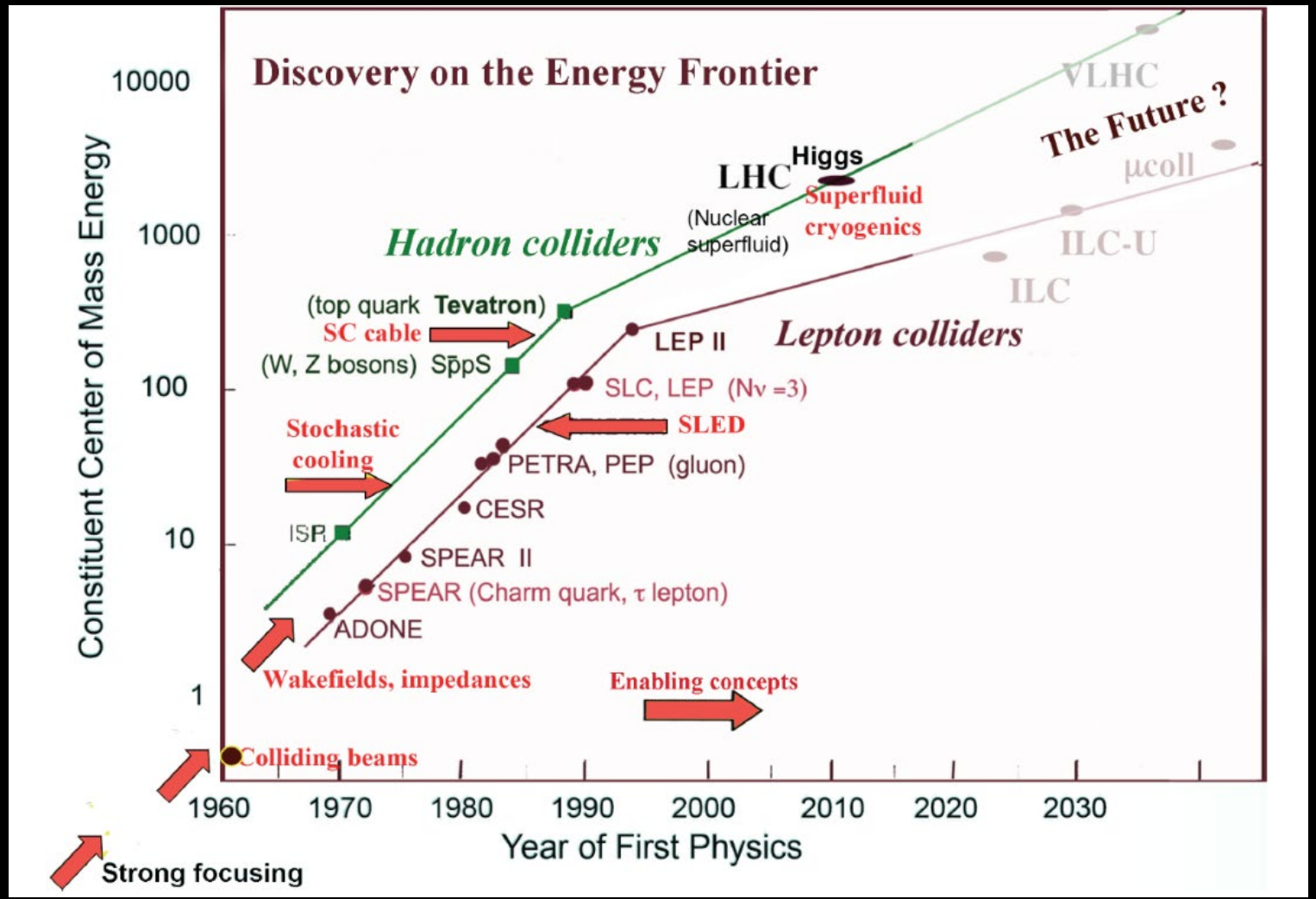
Muon Collider Physics and Detector workshop

Physics Demands (on detectors)

Zhen Liu
University of Minnesota
12/16/2022



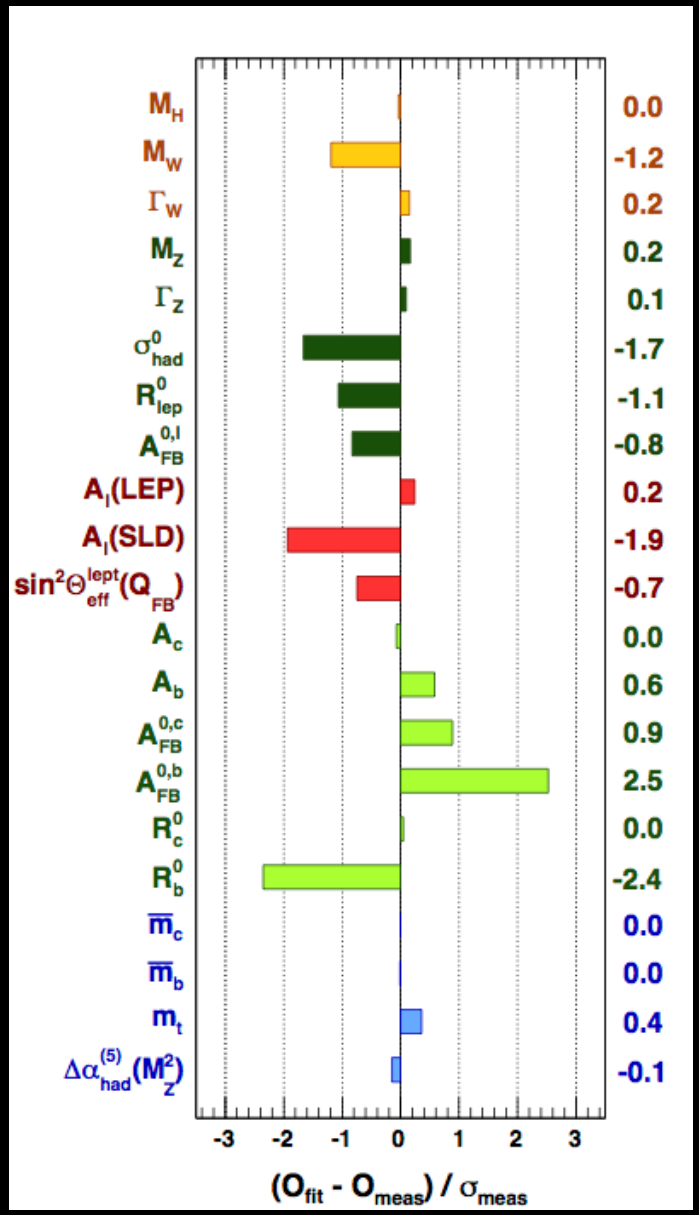
High Energy Rules



Snowmass Report: [1401.6114](1401.6114)

The power of cleanness

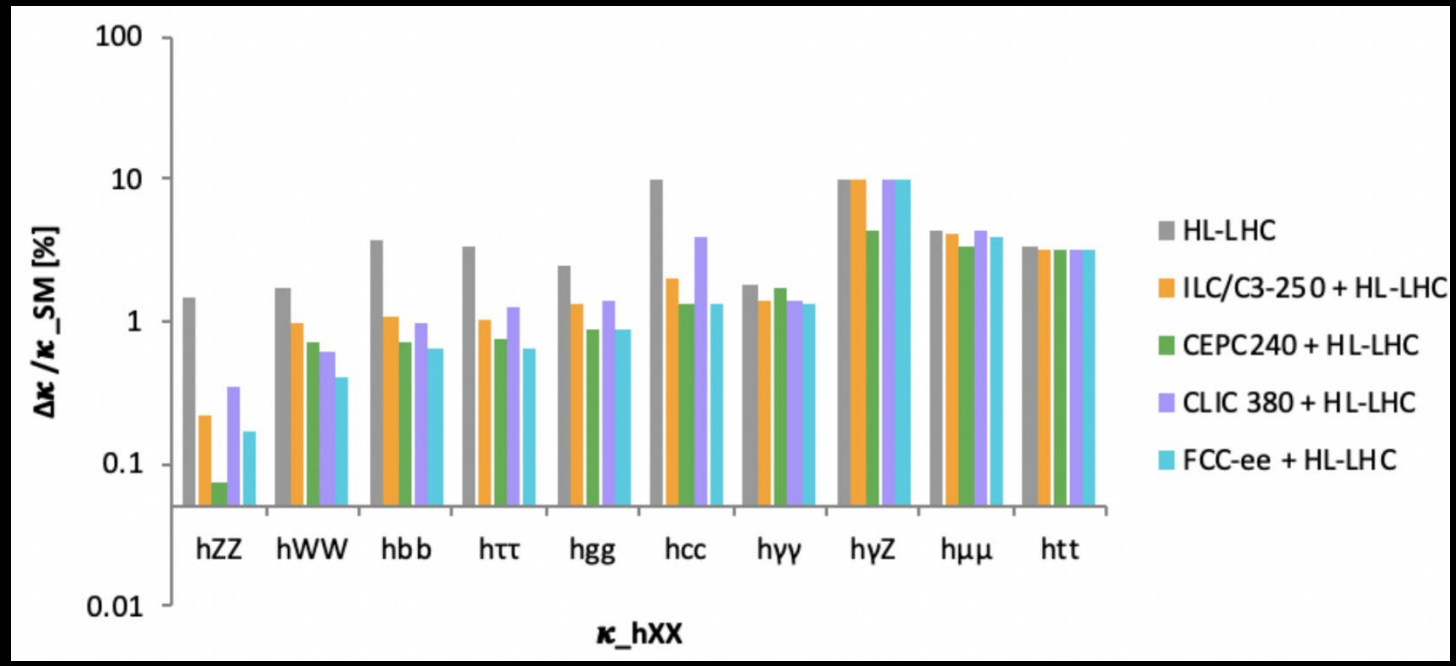
- LEP still is a headache/treasure of theorists



Dawson et al, 2209.07510

The power of cleanness

- LEP still is a headache/treasure of theorists
- 1M Higgs Higgs factory v.s. 0.5B Higgs HL-LHC



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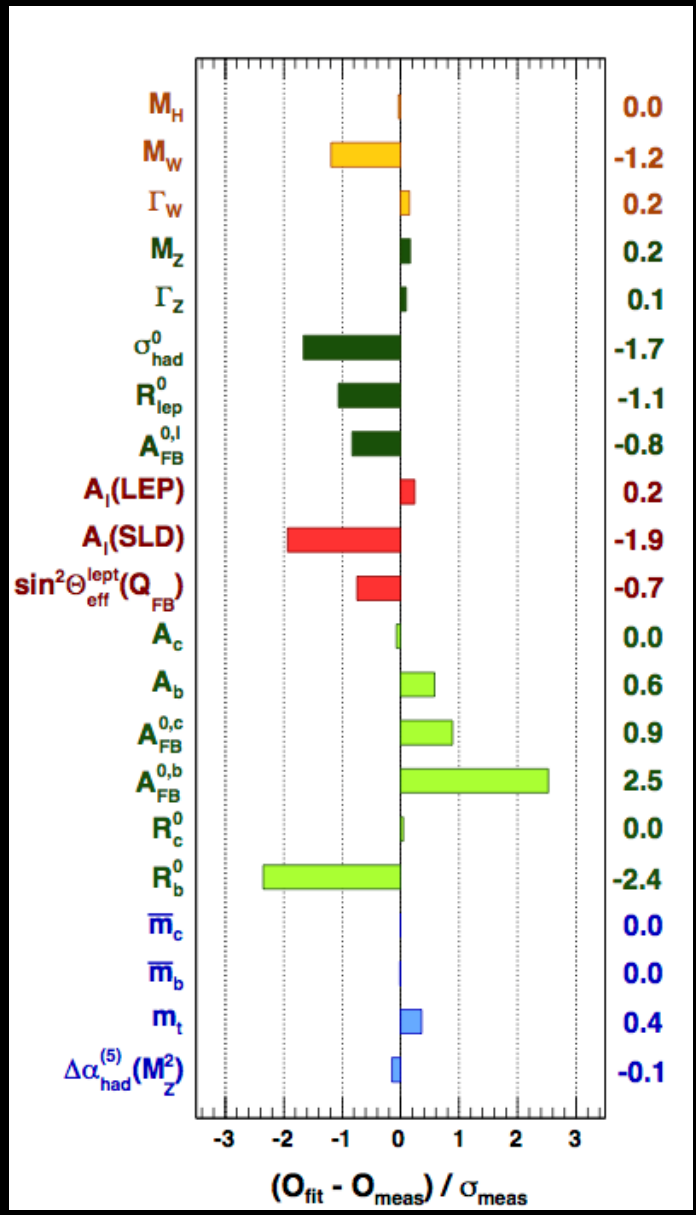

Zeroth Order

Let's get a high-energy muon collider running!

- Energy Resolution (comparable to current)
- Granularity (comparable to current)

(Any reasonable detector performance would deliver baseline physics goals: dive deeply into the 10~TeV realm.)

We are very excited!

Interplay between Accelerator and Detector design
Speaker: Donatella Lucchesi (INFN-Padova)
MuonWorkshop-FN...

9:00 AM **Overview of FullSim Framework**
Speaker: Nazar Bartosik (INFN Torino)
2022_12_16_bartosi...

9:25 AM **Framework to do : from 3 to 10 TeV**
Speaker: Federico Meloni (Deutsches Elektronen-Synchrotron)
FrameworkToDo.pdf

9:50 AM **FastSim with Delphes**
Speaker: Massimo Casarsa (INFN-Trieste)
casarsa_FastSim.pdf

0.5^{th}-1^{st} Order

There are various good features to have,
some are urgent
some are less urgent.

0.5^{th}-1^{st} Order

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Pheno Demands? (solutions are not unique).

Demands? (randomly ordered)

- 0) great energy resolution for all SM precisions;
- forward muon;
- additional long-lived particles trigger;
- dark showers;
- triggerless data possible? At least a triggerless readout?
- disappearting track (low threshold and low bkg);
- good missing energy measurements?
- anomaly detection (lepton collider environment make it stand out more sharply, let's use the clean data!)
- precision timing
- On beam: high energy & high Lumi (also low energy s-channel with low beam energy spread).

The beam-induced background simulation

machine lattice & optics

Fluka Element DB

detector nozzle description

LineBuilder

Flair + new code

machine geometry

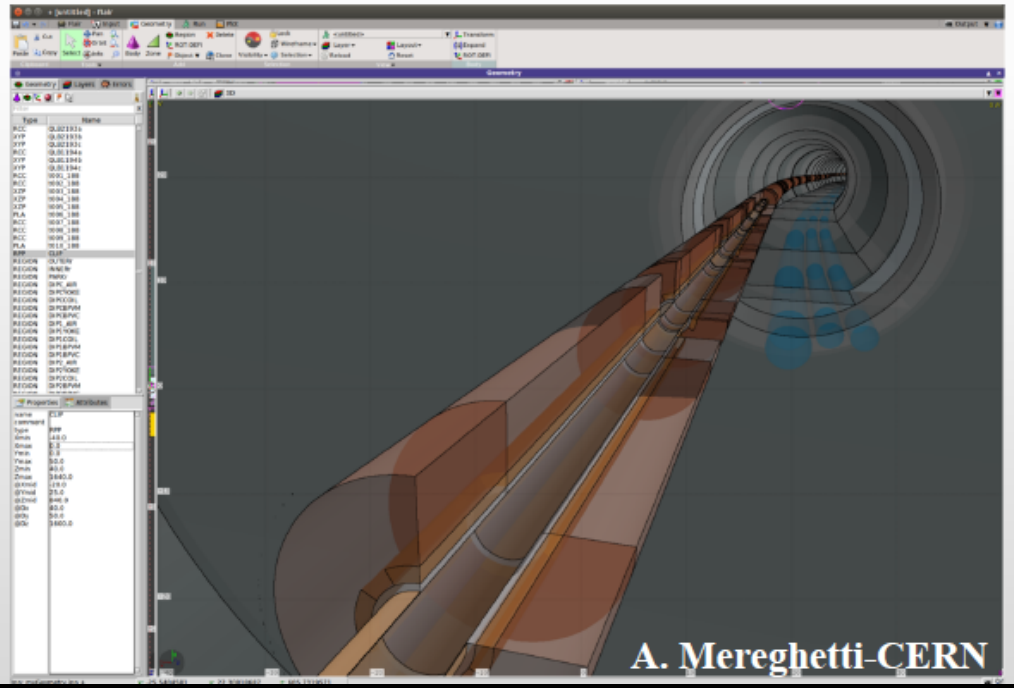
detector nozzle position

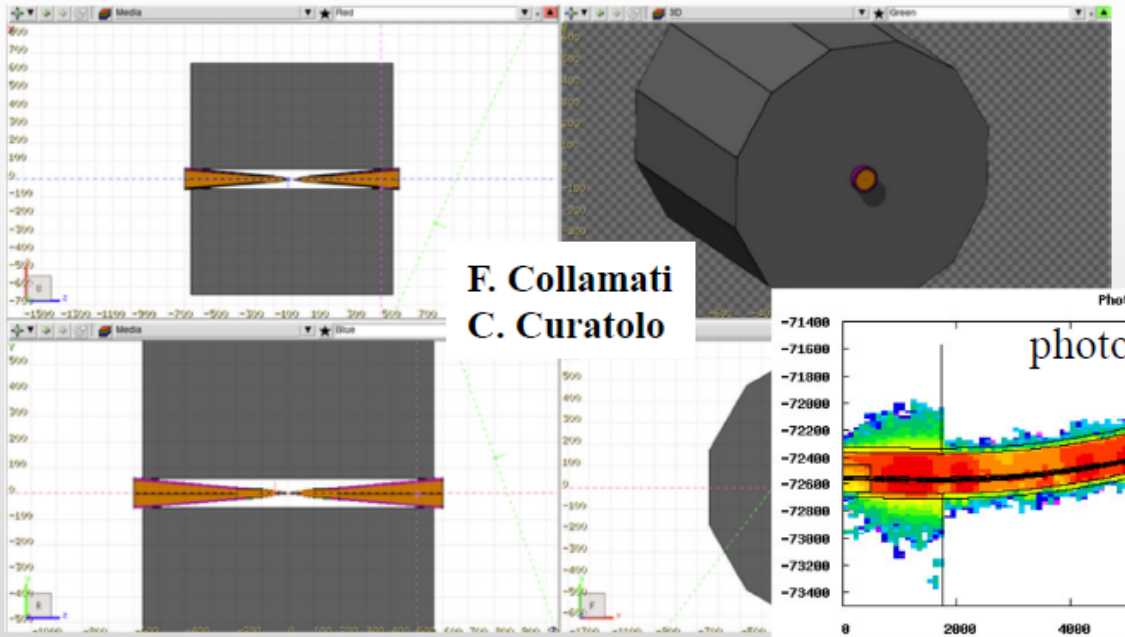
Fluka simulation muon decay & interaction with material

Background on detector envelope

See F. Collamati talk at ICHEP2020

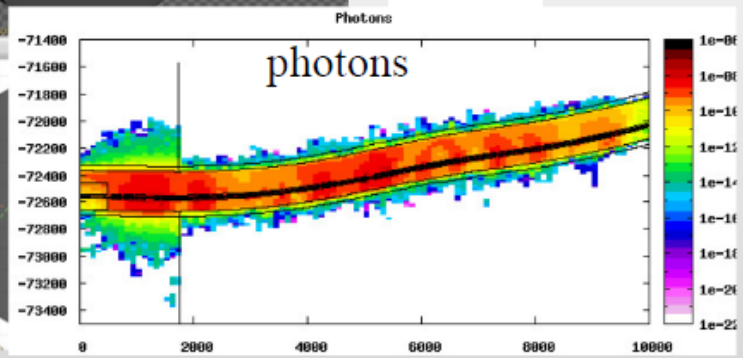
Input data
Output data
Software program



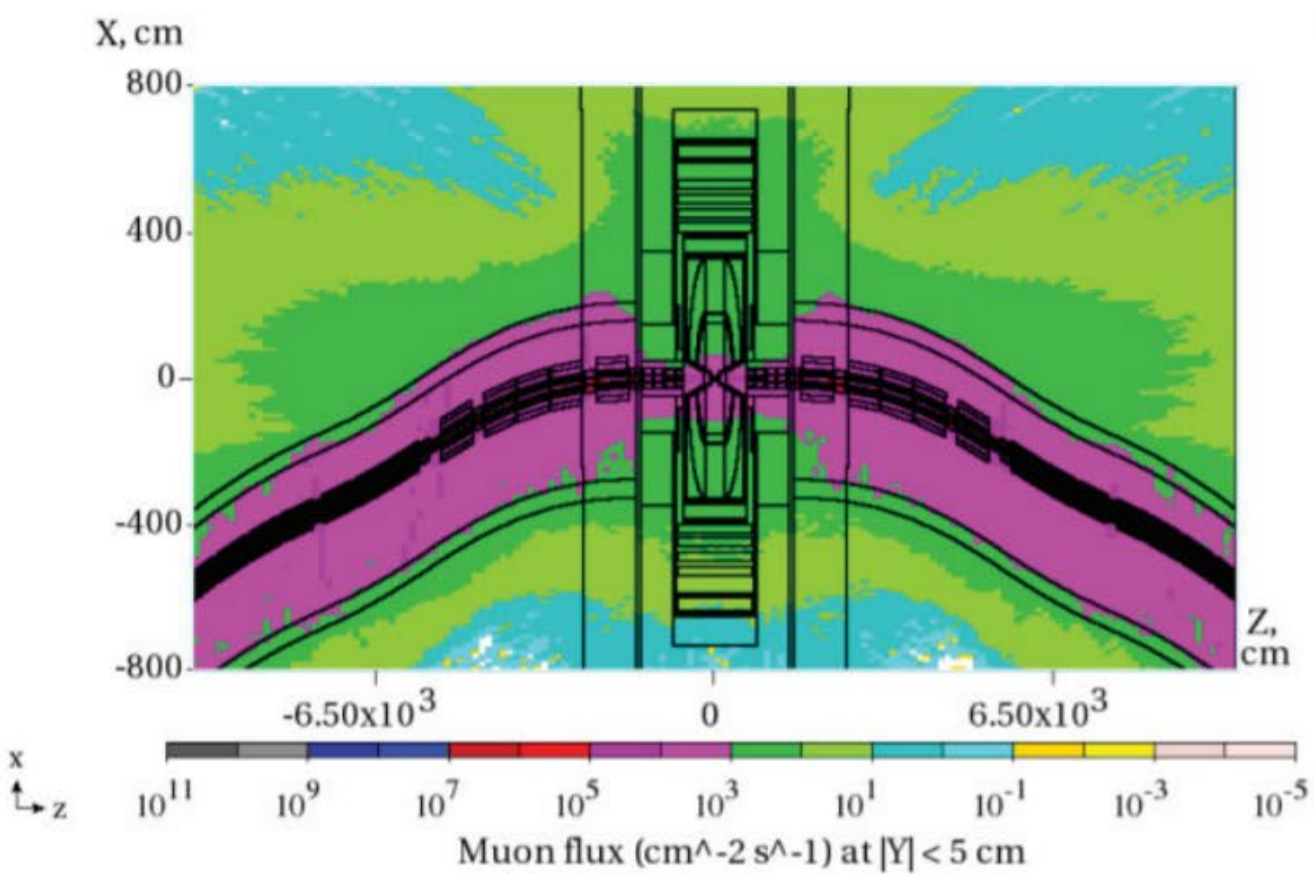


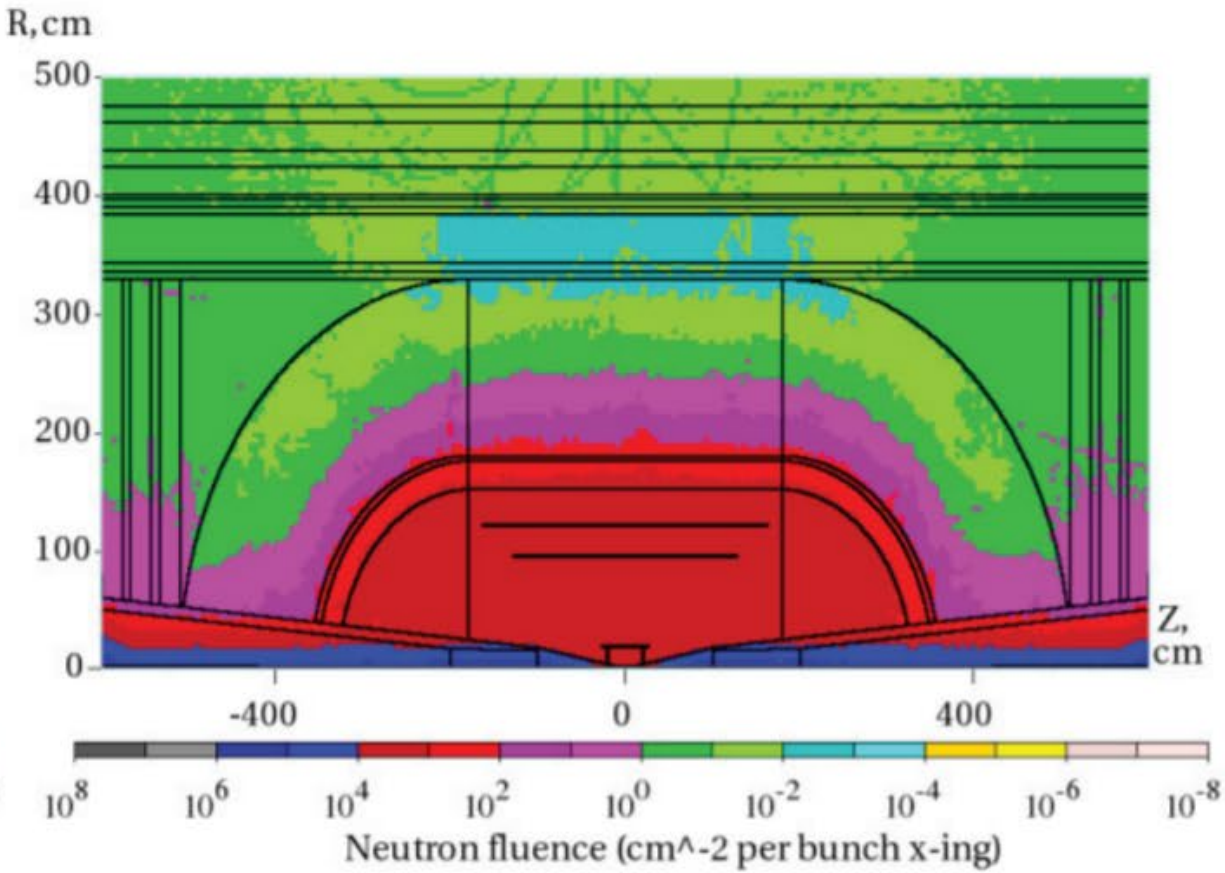
F. Collamati
C. Curatolo

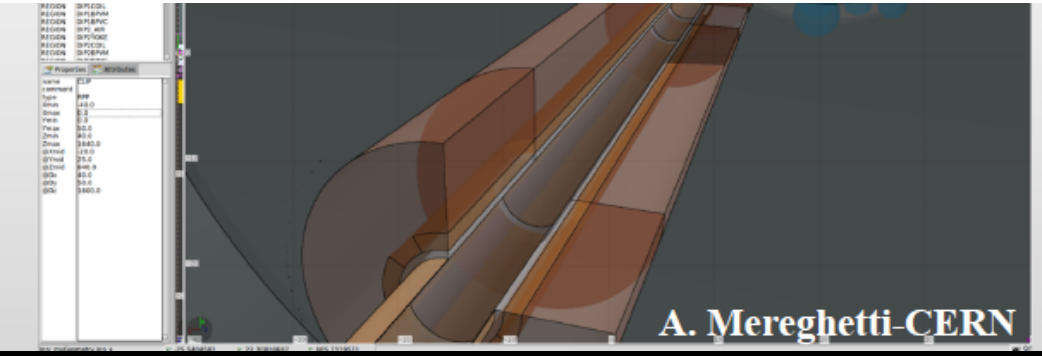
P. Sala

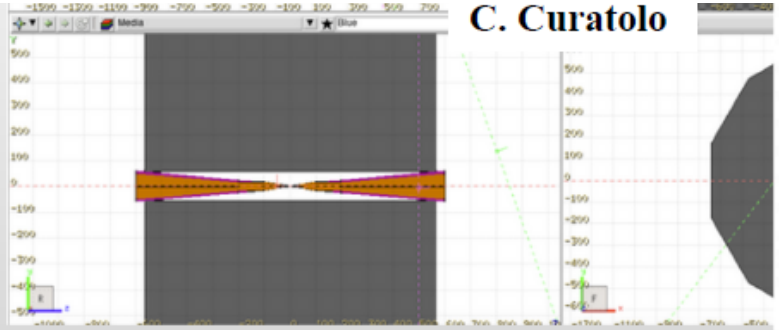


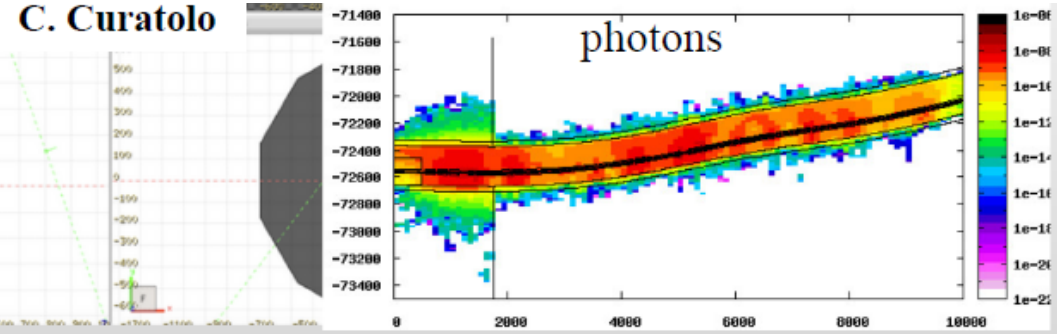
The beam-induced background simulation



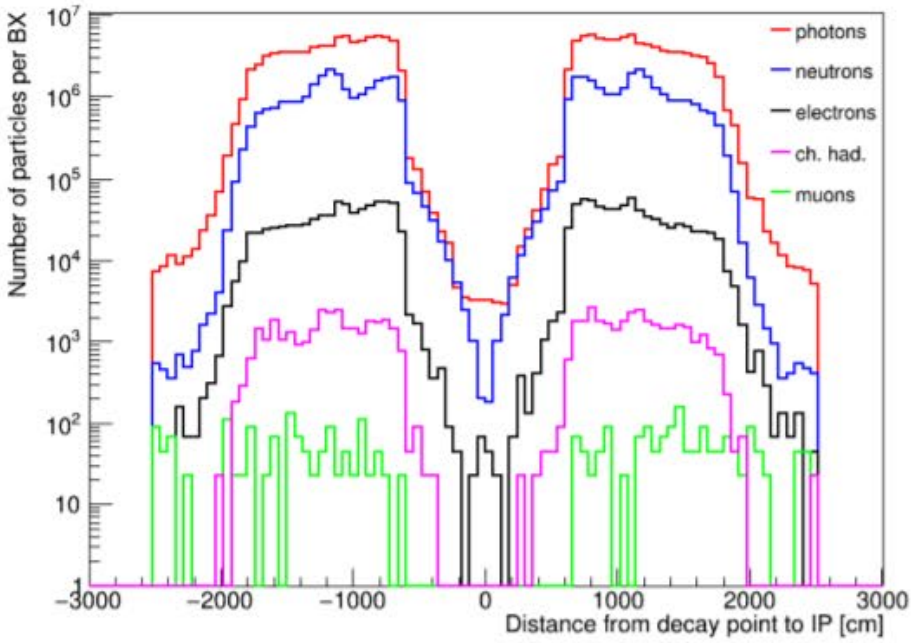




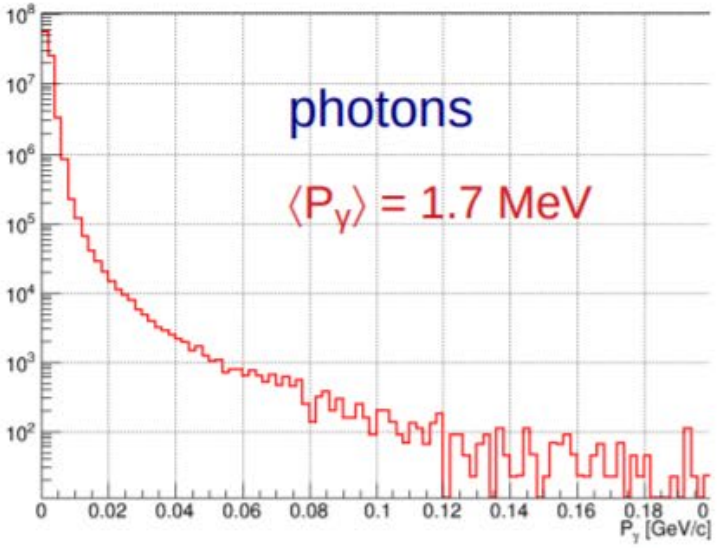


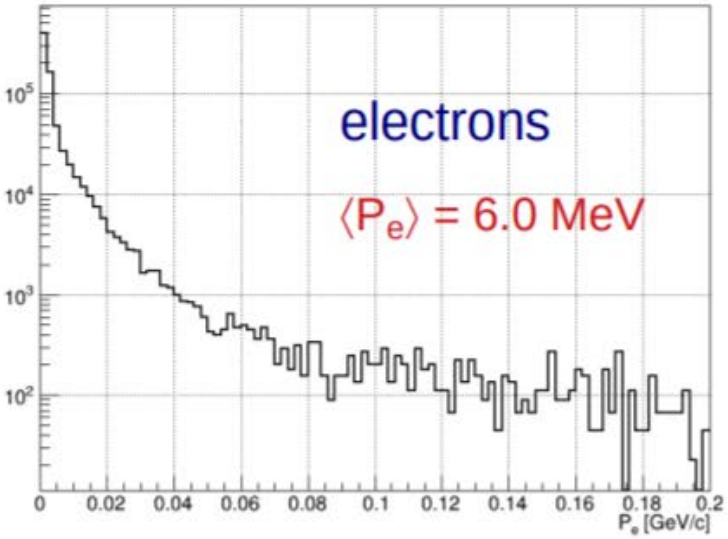


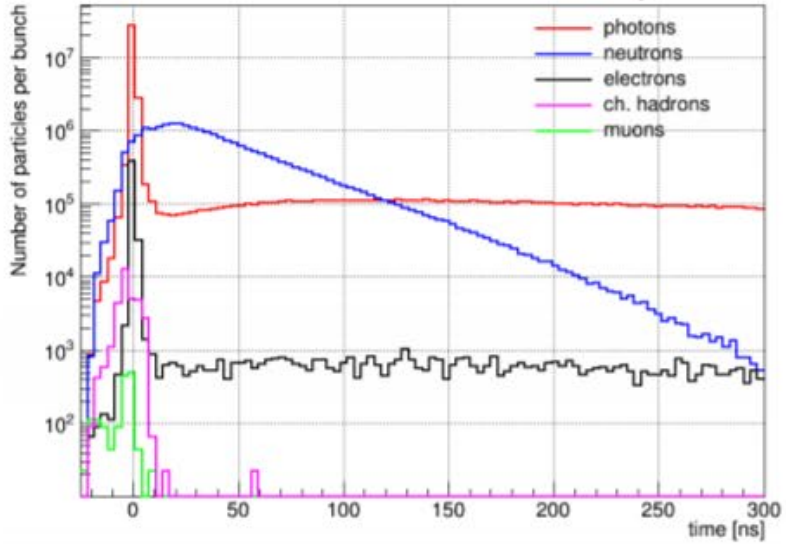
Beam-induced background Studies at $\sqrt{s}$ =1.5 TeV



Contributions form μ decays |z| > 25 m become negligible for all background species but Bethe-Heitler muons





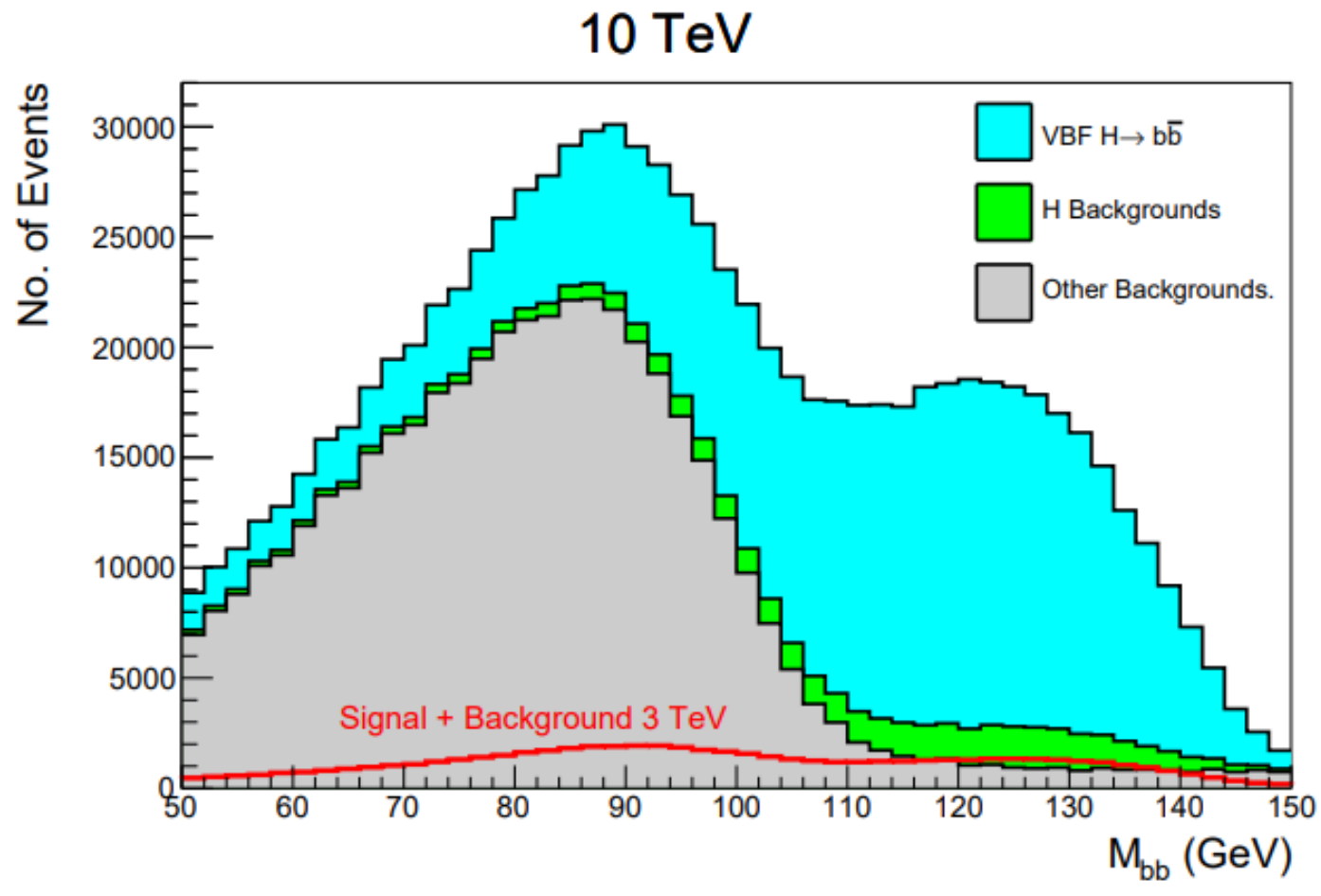


Secondary and tertiary particles have low momentum and different arrival time in the IP.

Precision Energy

Single Higgs Precision at a Muon Collider ¶

Speaker: Matthew Forslund (Stony Brook University)



Dominant background from Z-peak: distinguishing the two is crucial

3 TeV has also been done with fullsim: quite similar results (2209.01318)

The $c\bar{c}$ and gg channels are very similar, with mistagged $H \to b\bar{b}$ contributing a large background as well

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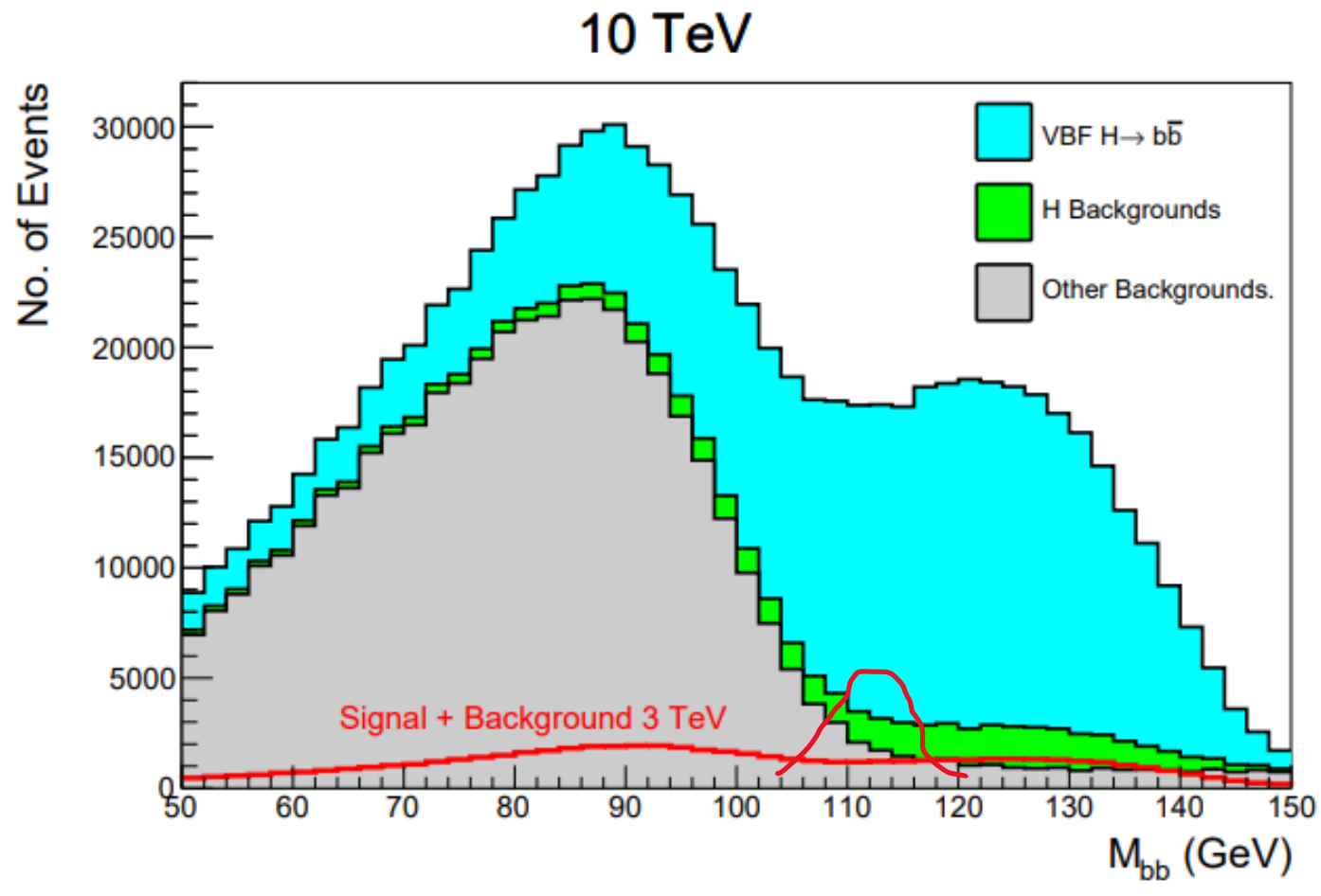

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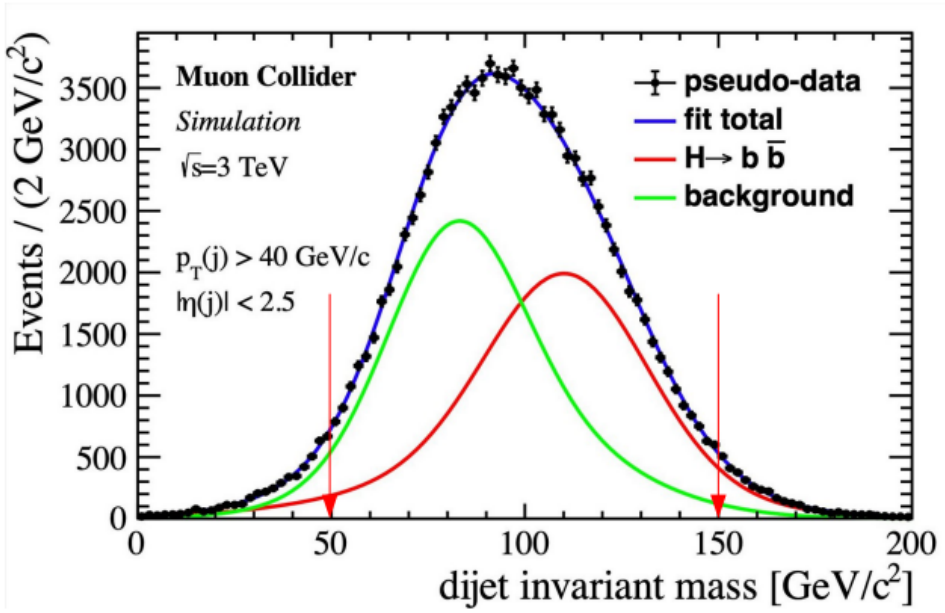
How about a new scalar?

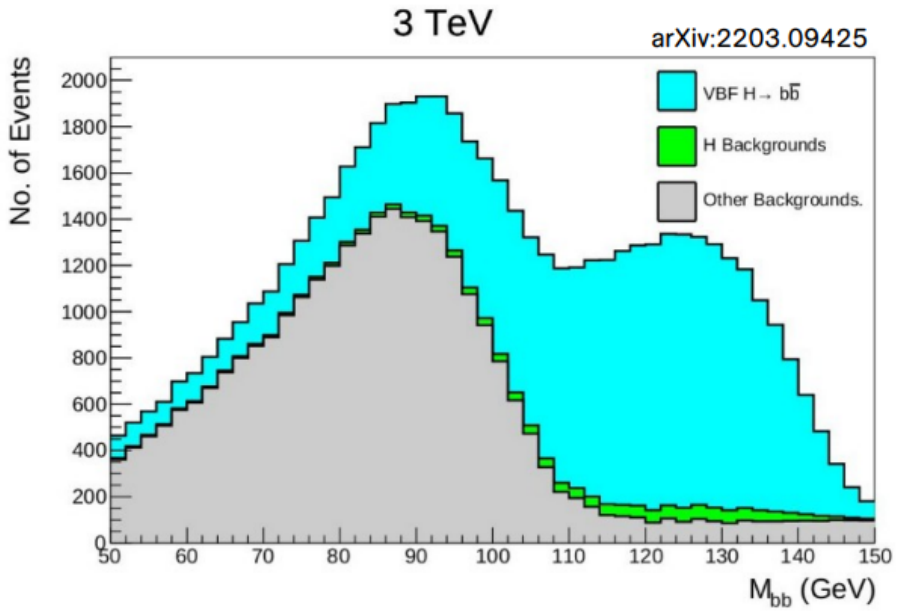
Precision Energy

Dijet invariant mass

FULL SIMULATION



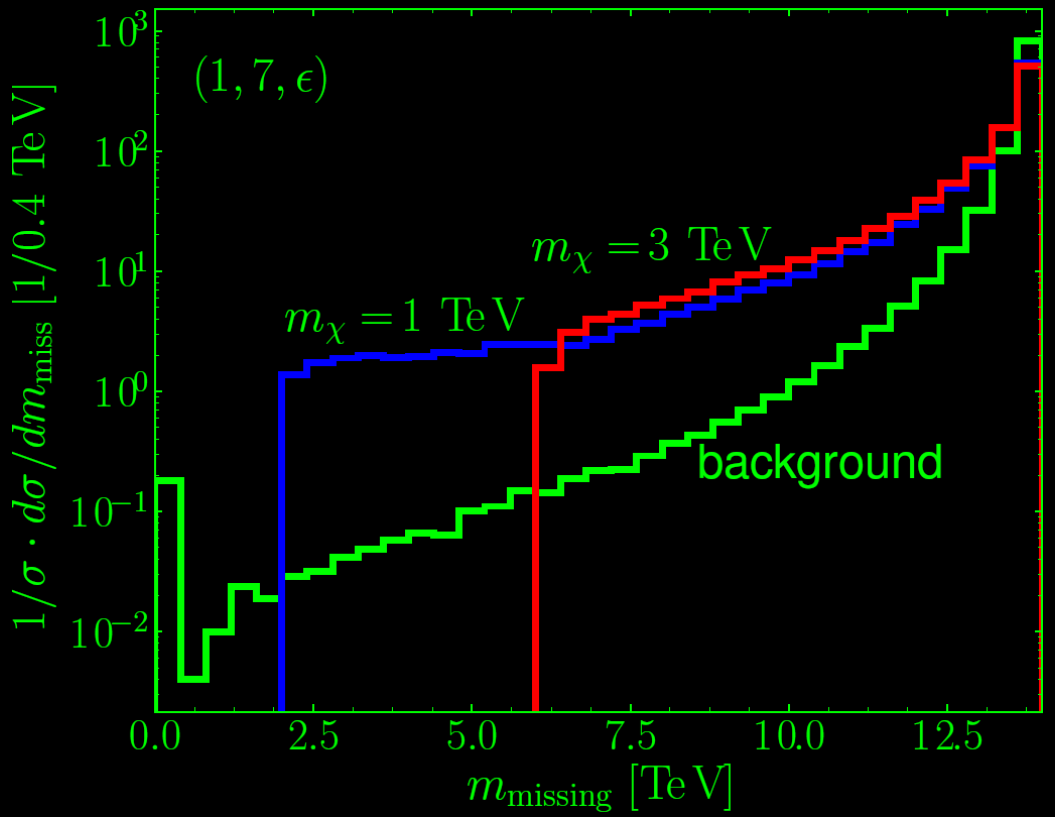
FAST SIMULATION



Missing Energy

Missing mass:

- Sharp kinematic features
- Signal-background separation
- Signal parameter determination



Han, ZL, Wang, Wang, 2009.11287, 2203.07351

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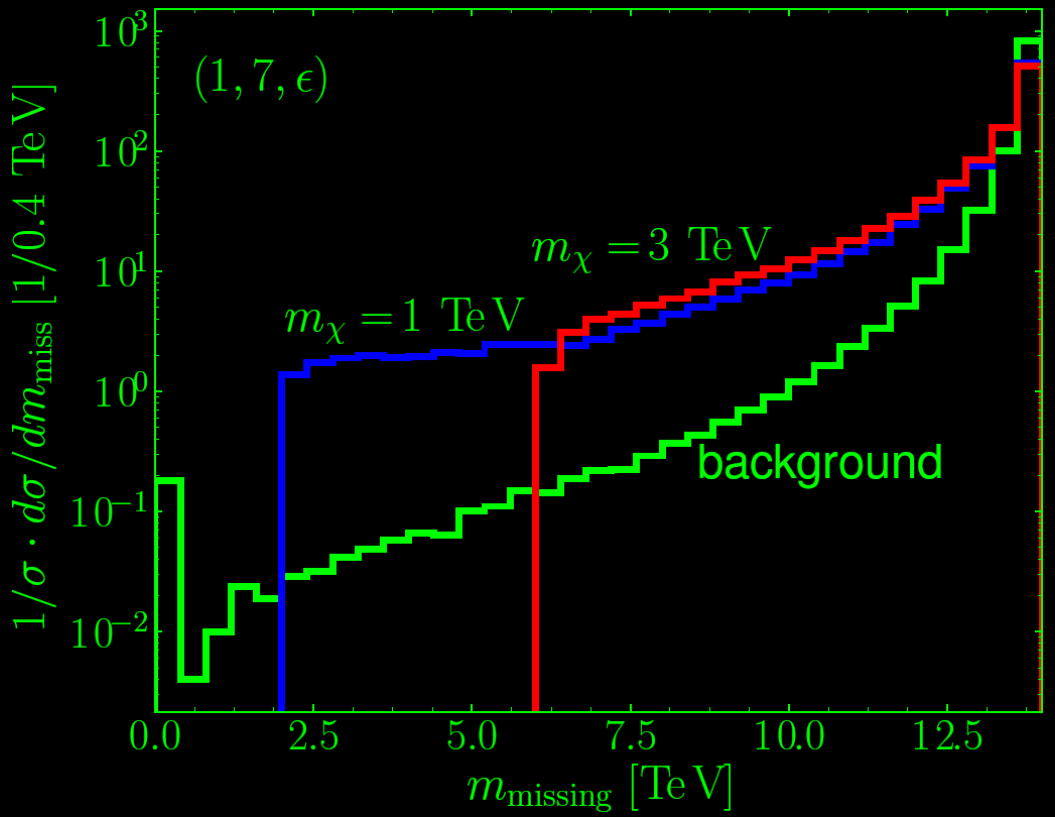
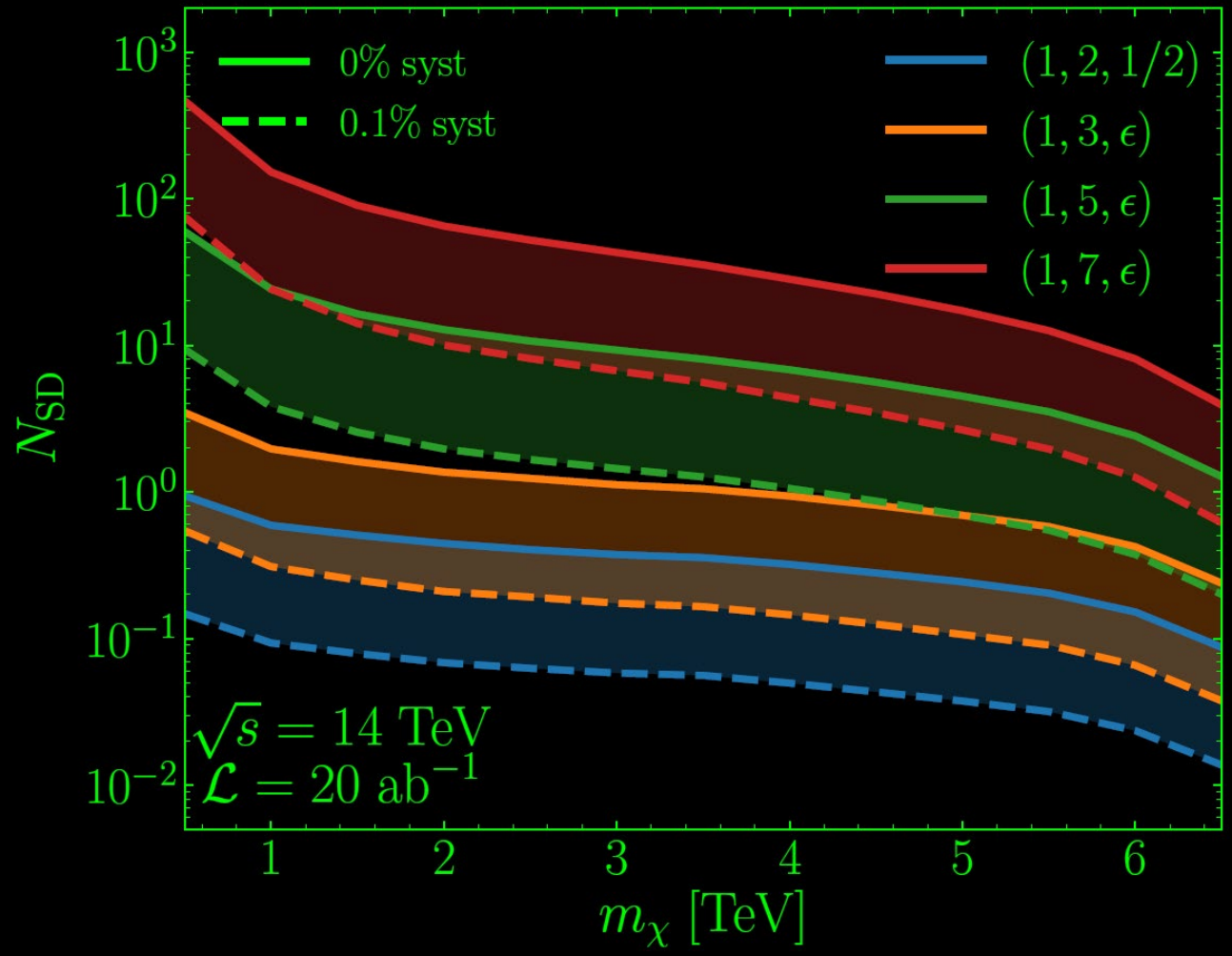


Signal-background ratio 10^-3
At lepton colliders systematics controlled to 0.1% level should be achievable but requires theory & experimental work



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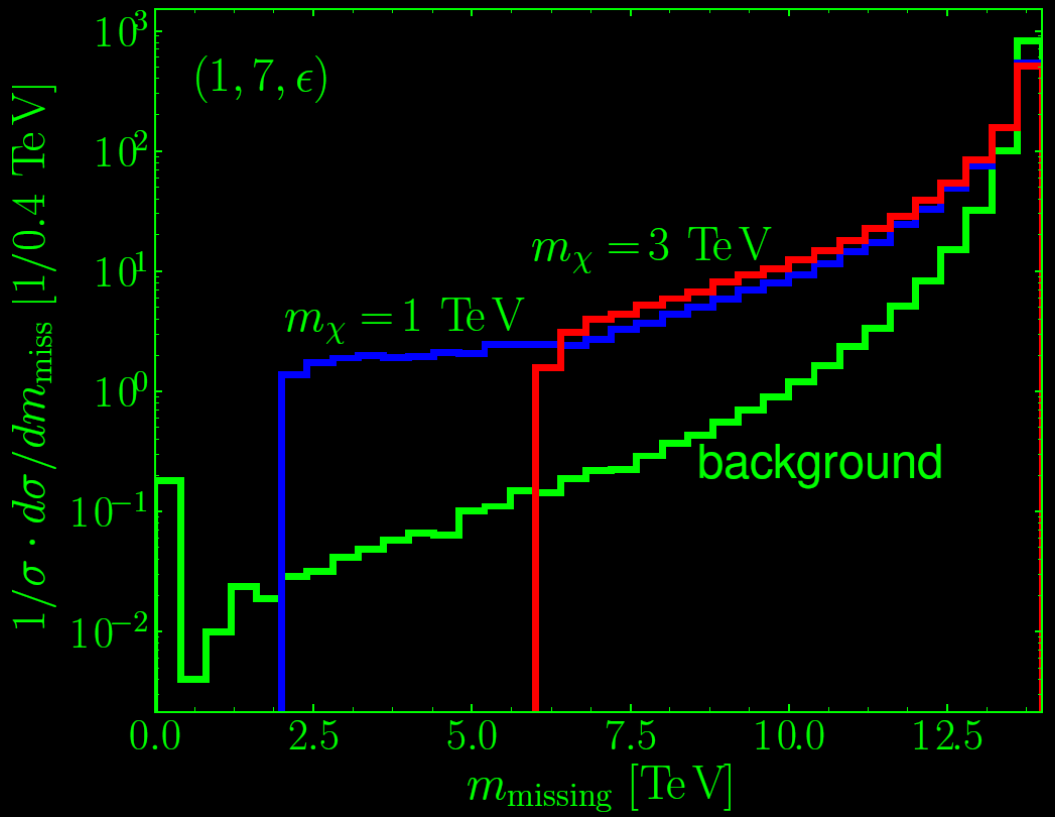

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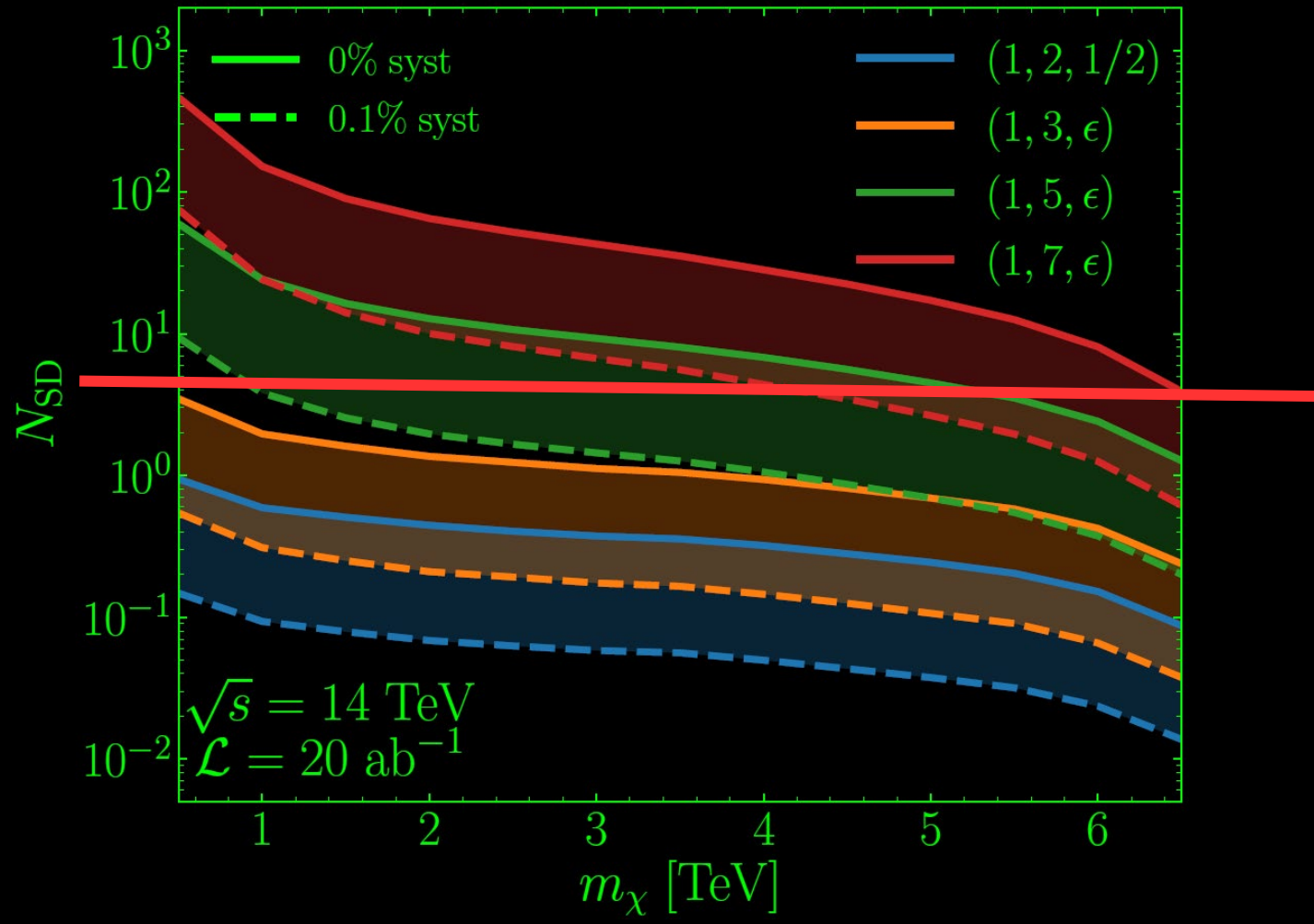

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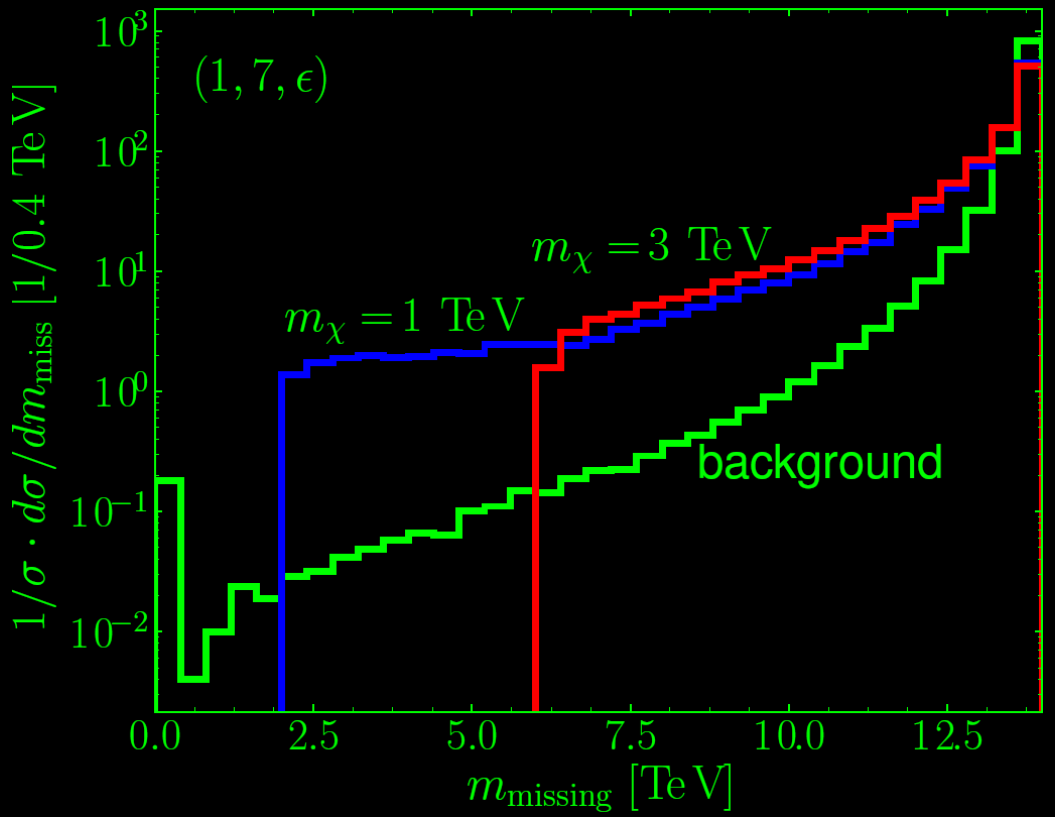

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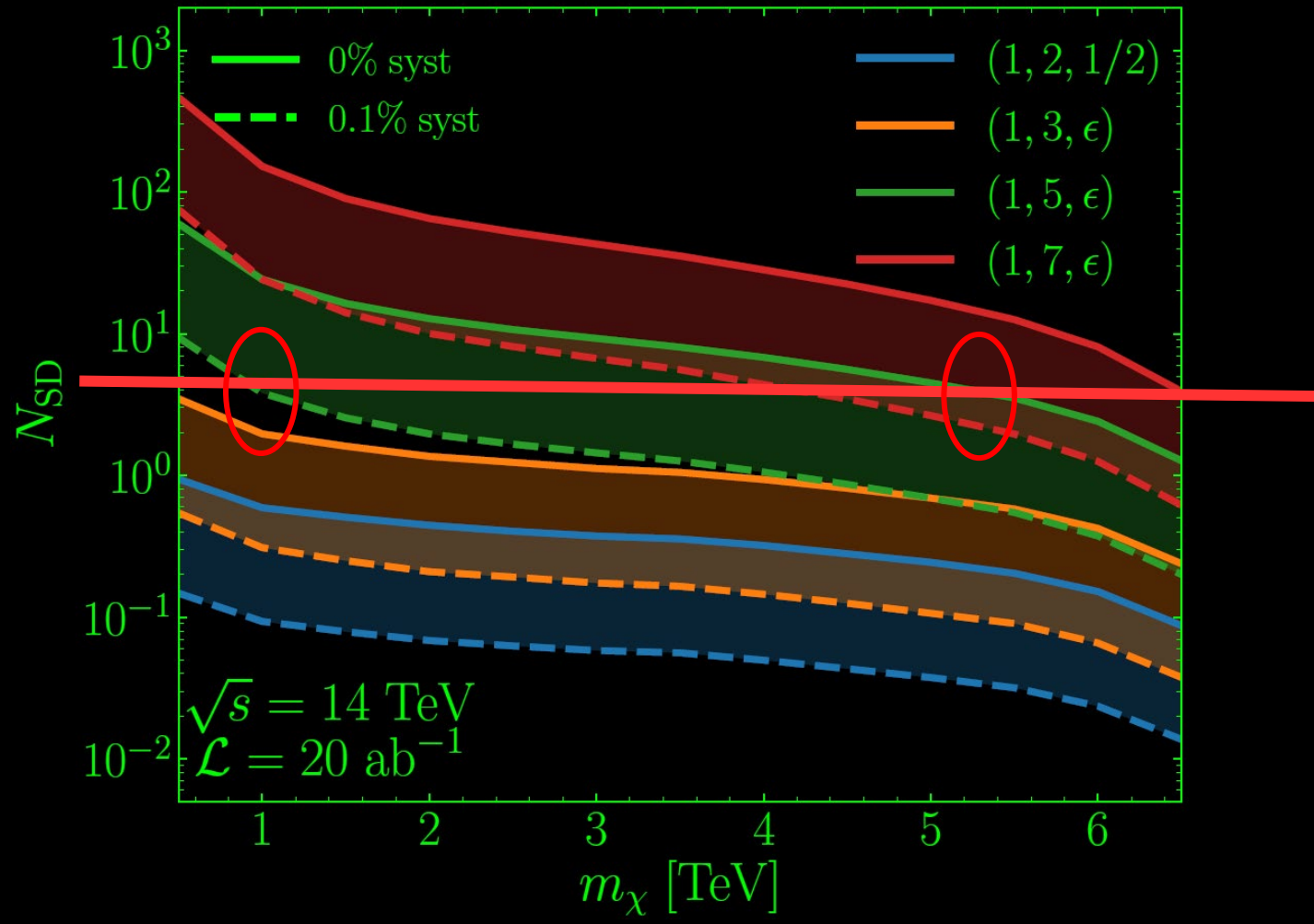
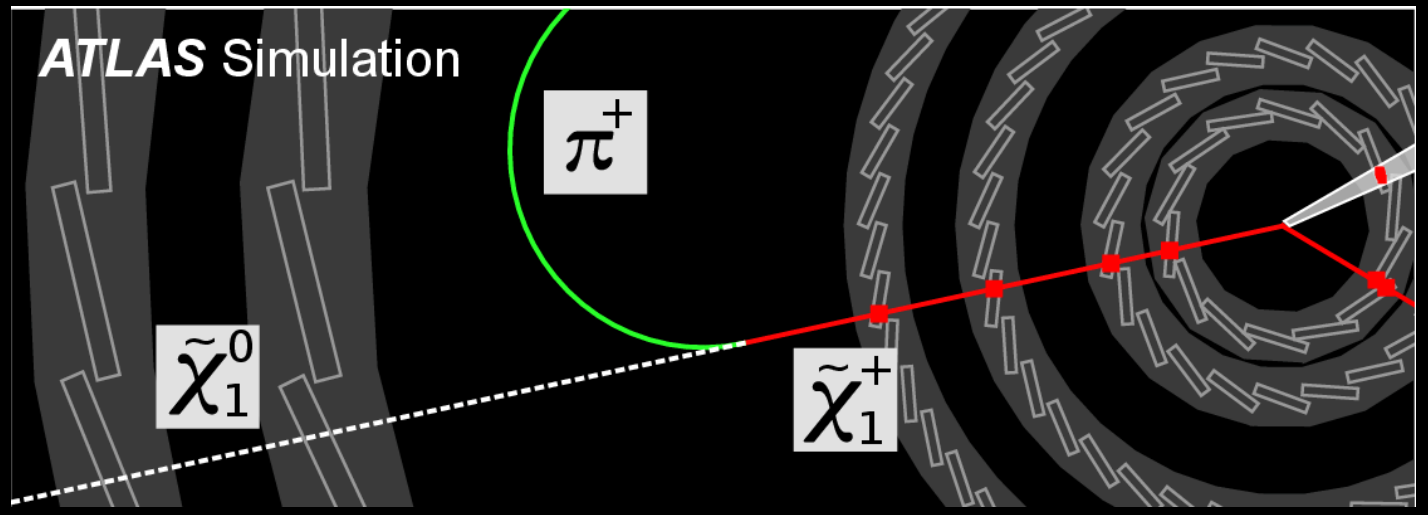
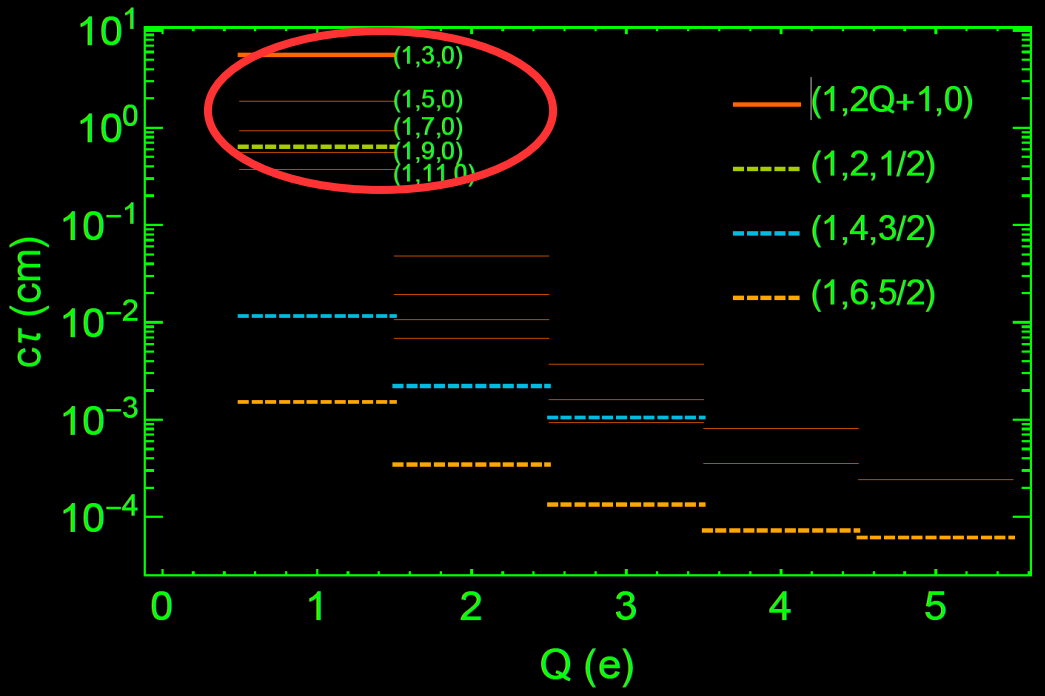


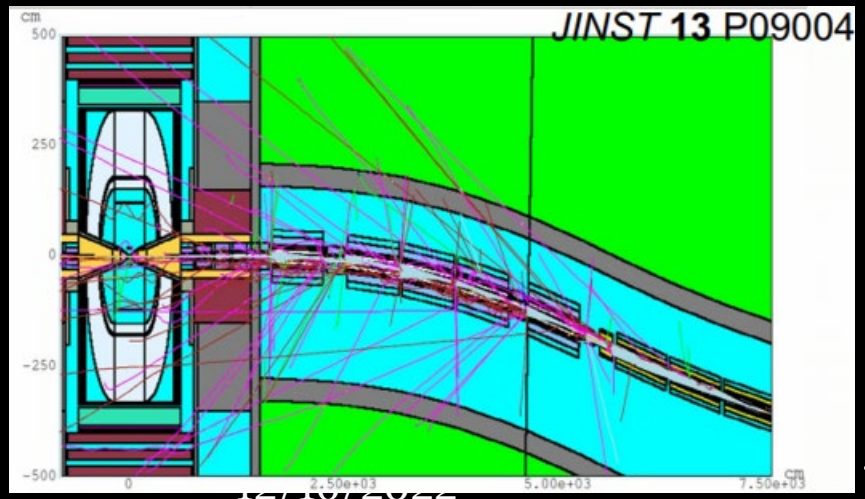
Han, ZL, Wang, Wang, 2009.11287, 2203.07351

Disappearing Tracks





- Only useful for searches using charge 1 states
- Still, all higher charged states will cascade back to charge 1 states promptly
- Use all the production rates of charged states
- Mono-photon+disappearing tracks
- Beam Induced Background

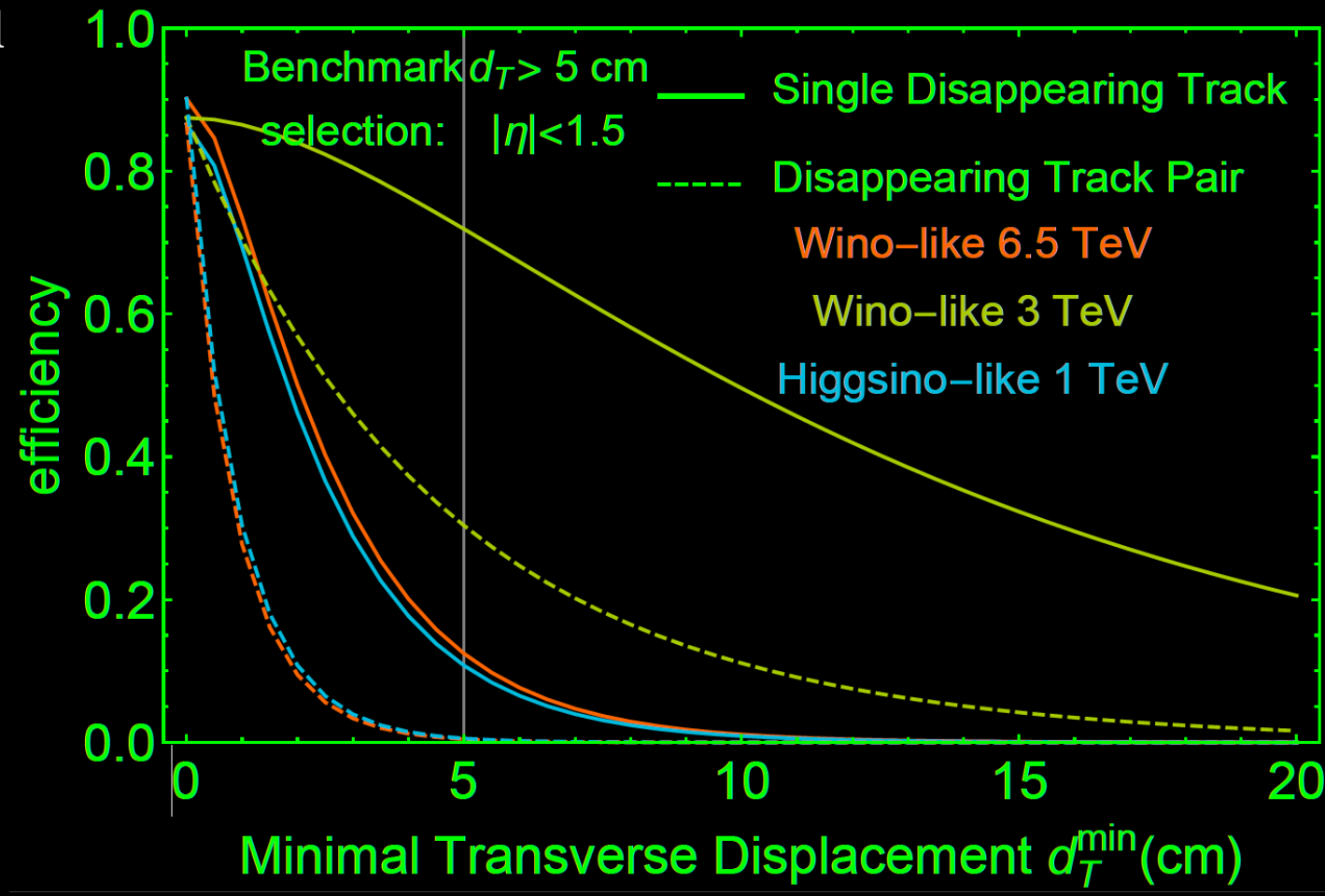


Disappearing Tracks

- Only use the central tracks, |eta|<1.5
- Current design have first layer of pixel detector at 3cm (new discussion about 2cm)
- We assume at least two-hits can be measured at 5cm
- Show both pair reconstruction or single reconstruction results
- Requiring 50 signal events for discovery

$$d_T^{\min} = 5 \text{ cm with } |\eta_\chi| < 1.5$$

$$\epsilon_\chi(\cos\theta, \gamma, d_T^{\min}) = \exp\left(\frac{-d_T^{\min}}{\beta_T \gamma c\tau}\right)$$



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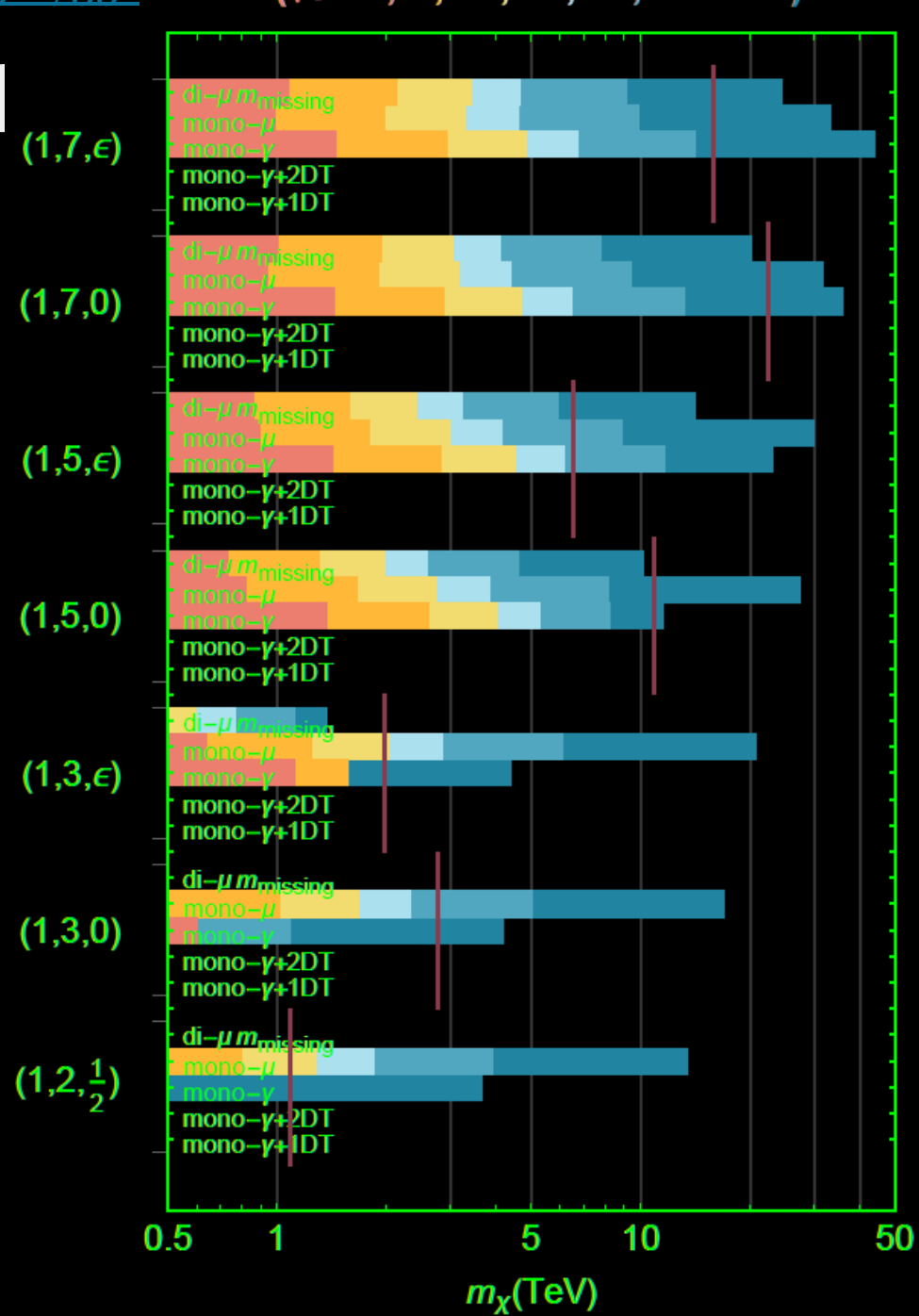
Impact of Disappearing Tracl

- Mono-photon powerful for high n-plets
- Mono-muon uniquely powerful low multiplets (Wino and Higgsinos)
- VBF dimuon large room to improve (we conservatively assumed |\eta mu|<2.5, losing lots of signals)



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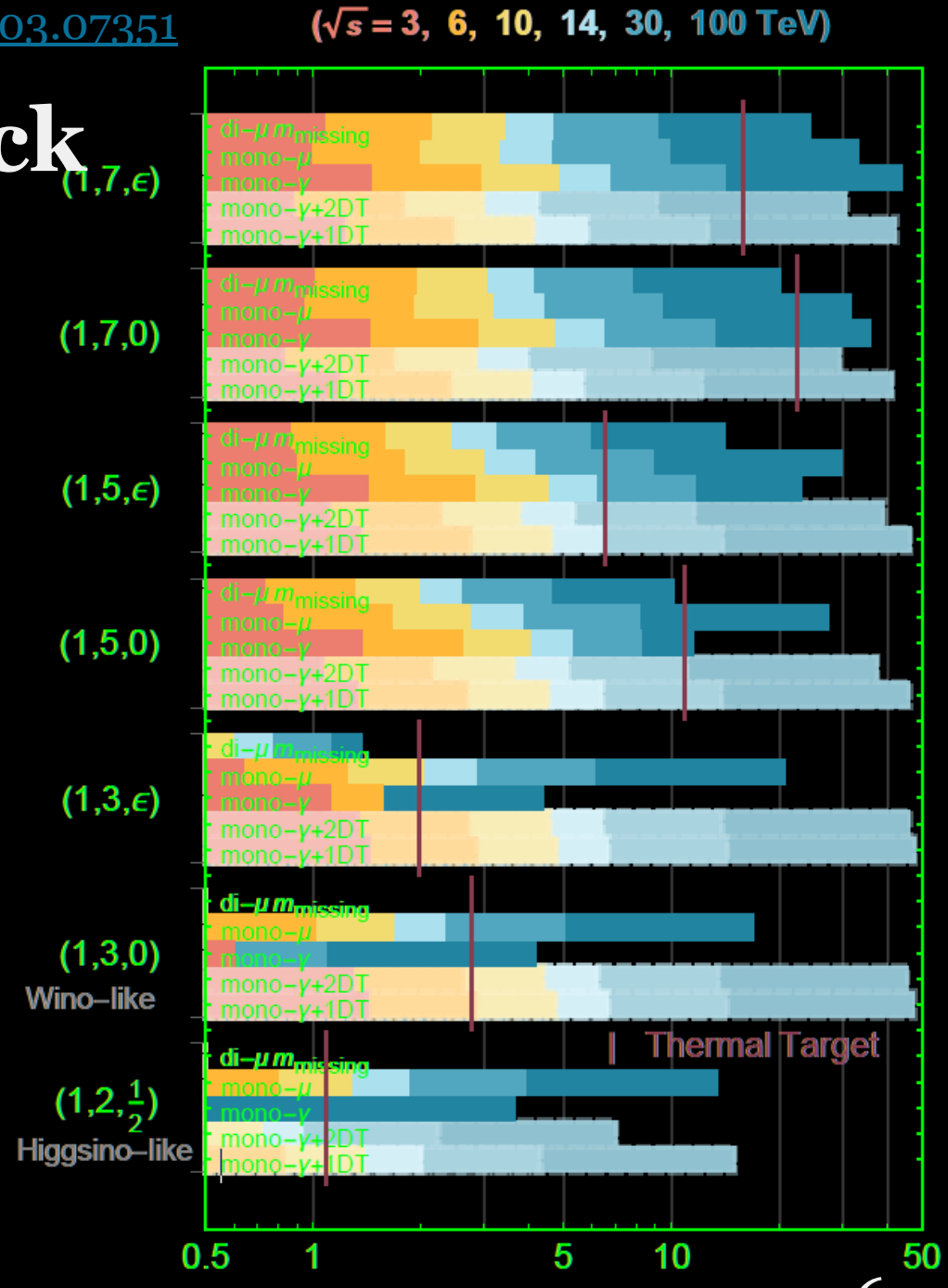
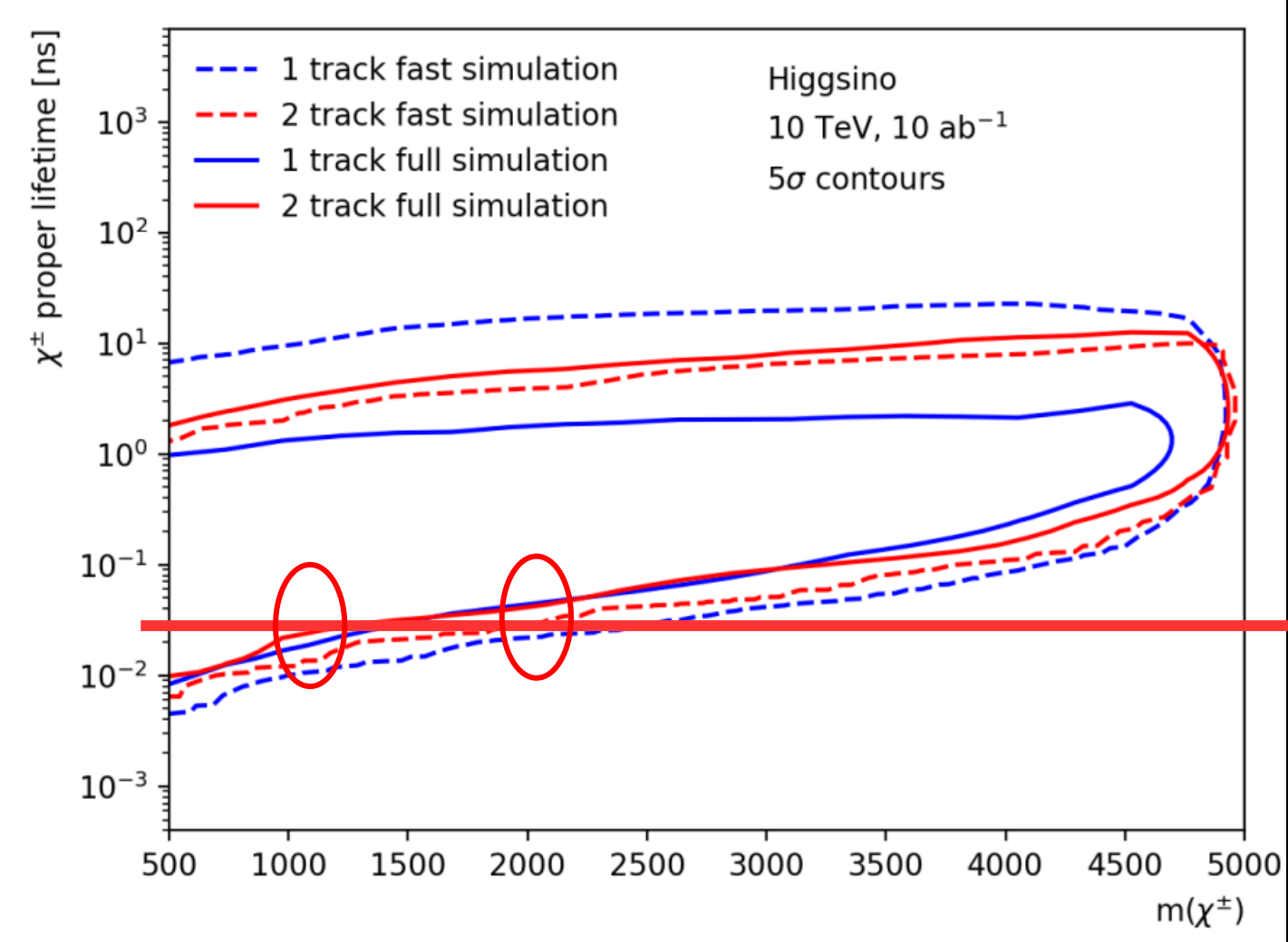
- VBF dimuon large room to improve (we conservatively assumed |\eta mu|<2.5, losing lots of signals)
- Disappearing track great potential (can push to the kinematic limit)!



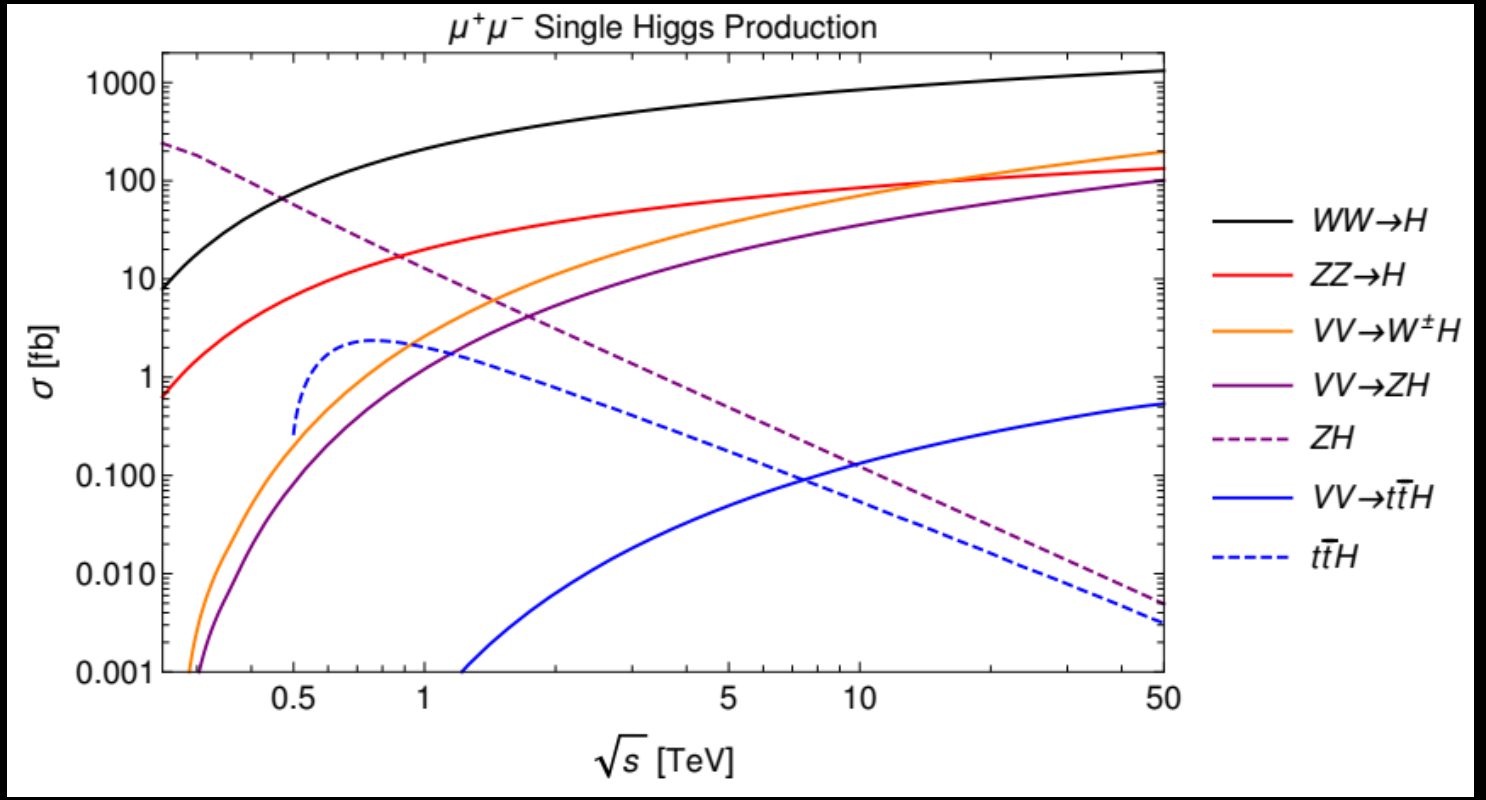
Another look: disappearing track



Taking the 2-track full v.s. fast simulation as an example
Same number of background but slightly different signal efficiency,
1 TeV-2TeV for a Higgisino

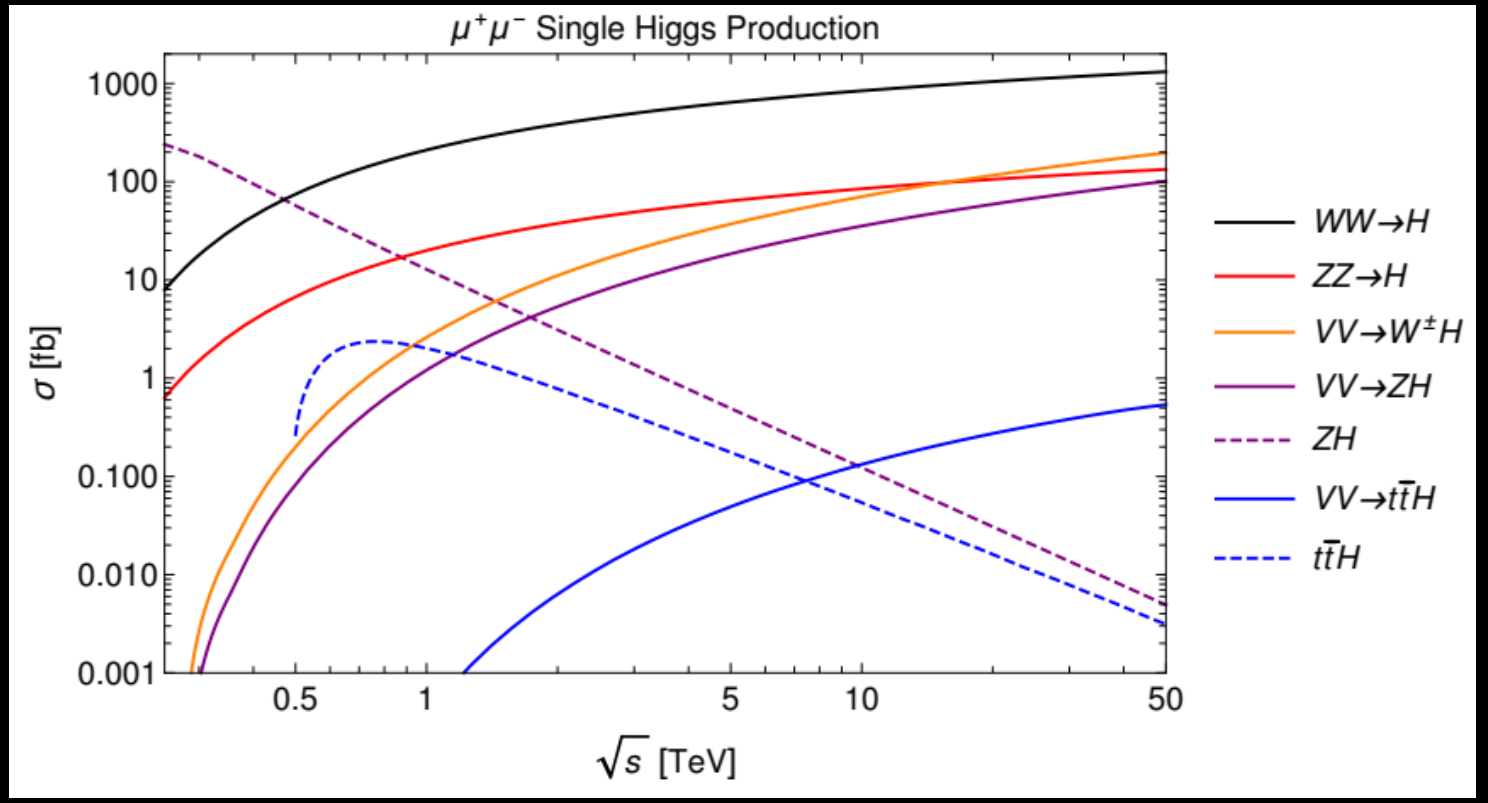
MuC Forum Report 2209.01318

Impact of Forward Muon



Impact of Forward Muon

Production	Decay	$\Delta\sigma/\sigma$ (%)	
		3 TeV	10 TeV
WW-fusion	bb	0.84	0.24
	cc	14	4.4
	gg	4.2	1.2
	$\tau^+\tau^-$	4.5	1.3
	$WW^*(jj\ell\nu)$	1.8	0.50
	$WW^*(4j)$	5.7	1.4
	$ZZ^*(4\ell)$	48	13
	$ZZ^*(jj\ell\ell)$	12	3.5
	$ZZ^*(4j)$	67	16
	$\gamma\gamma$	7.7	2.1
	$Z(jj)\gamma$	73	20
	$\mu^+\mu^-$	43	11
ZZ-fusion	bb	7.9	2.2
	bb, $(N_\mu \geq 2)$	2.6	0.77
	$WW^*(4j)$	49	12
	$WW^*(4j)$, $(N_\mu \geq 2)$	17	4.3
tth	bb	61	53



M. Forslund, P. Meade, 2203.09425

See also discussion in
Muon Smasher's Guide, 2103.14043
T. Han, Y. Ma, K.-P. Xie, 2007.14300;
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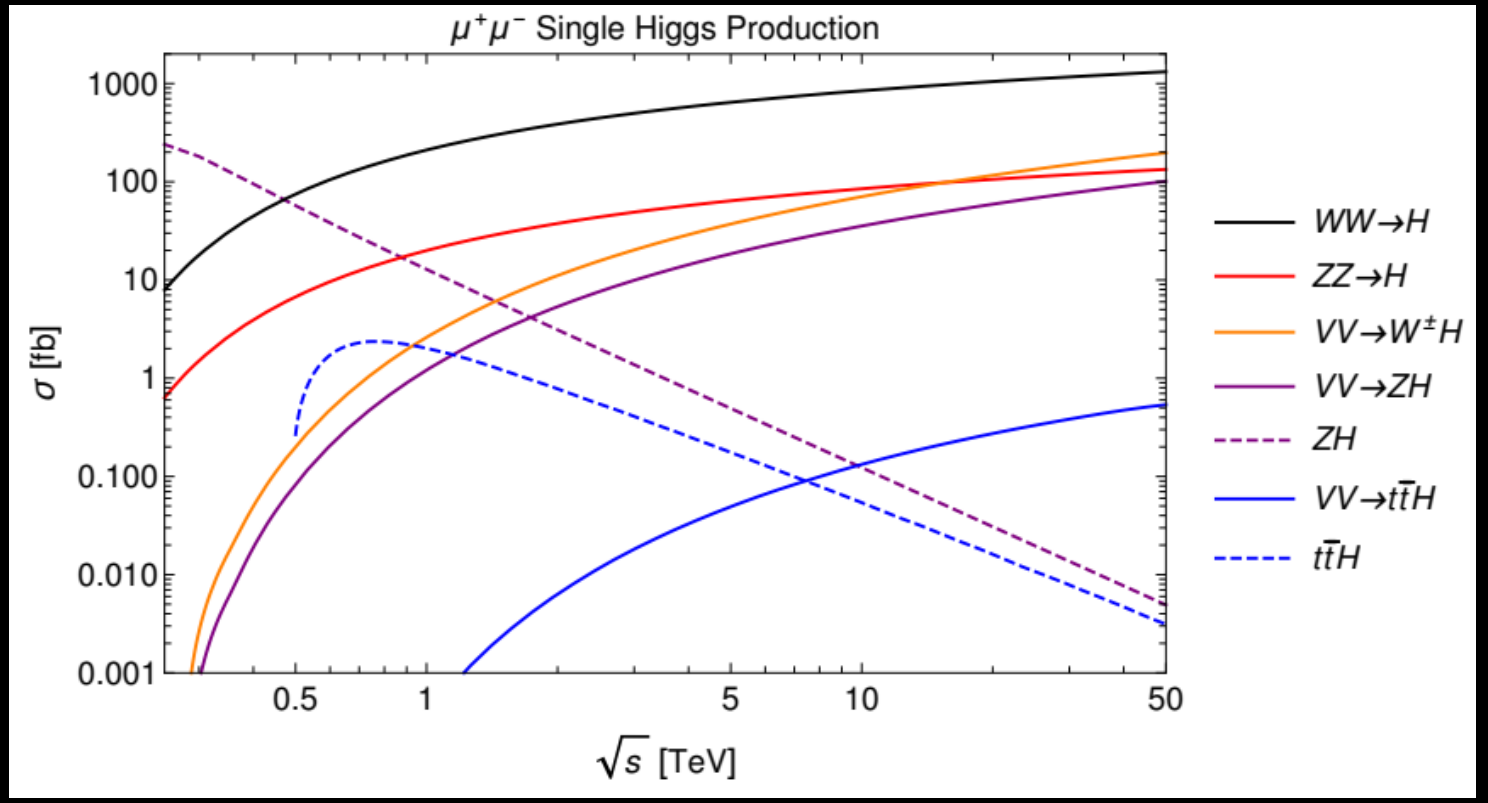

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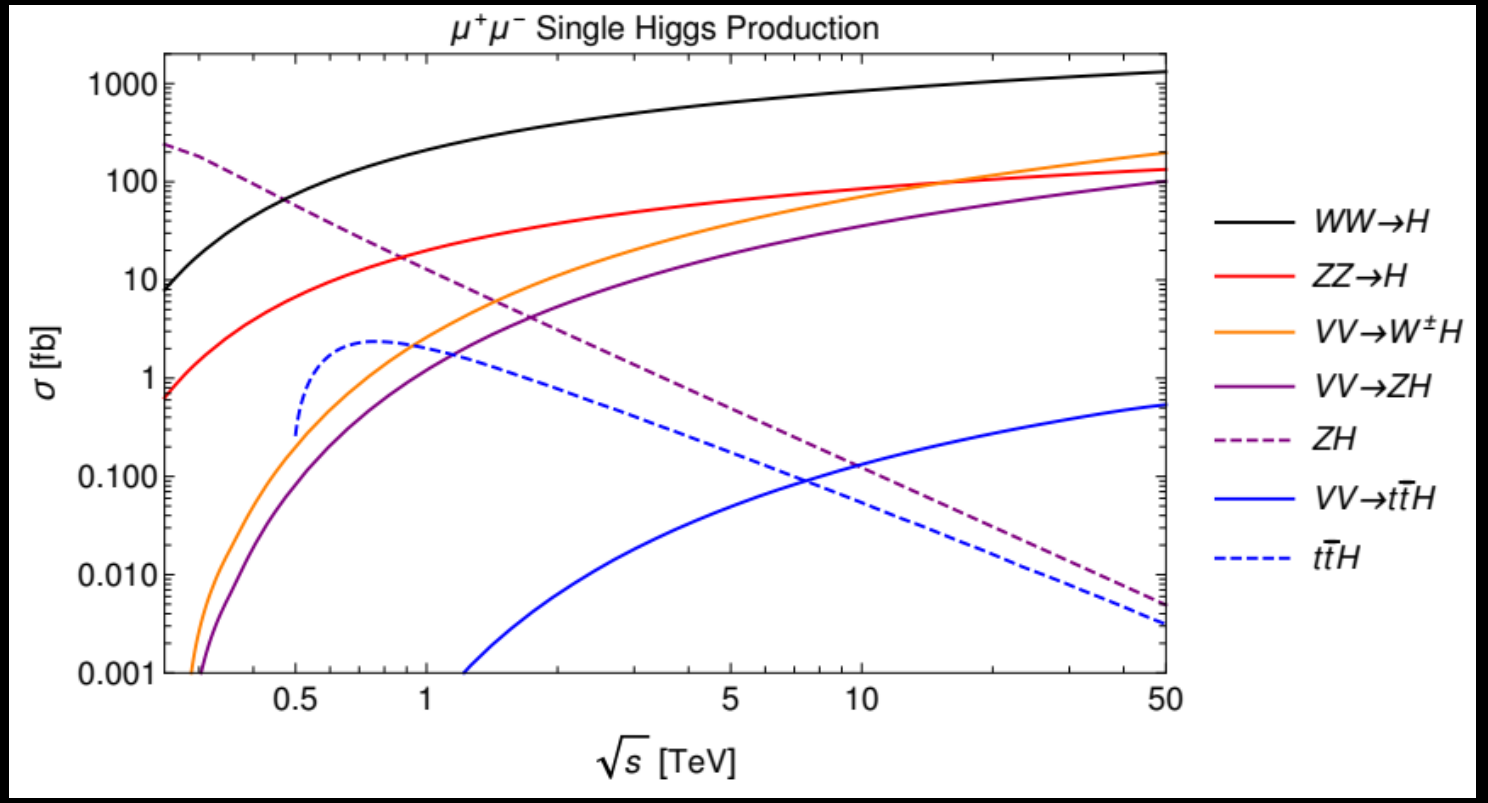

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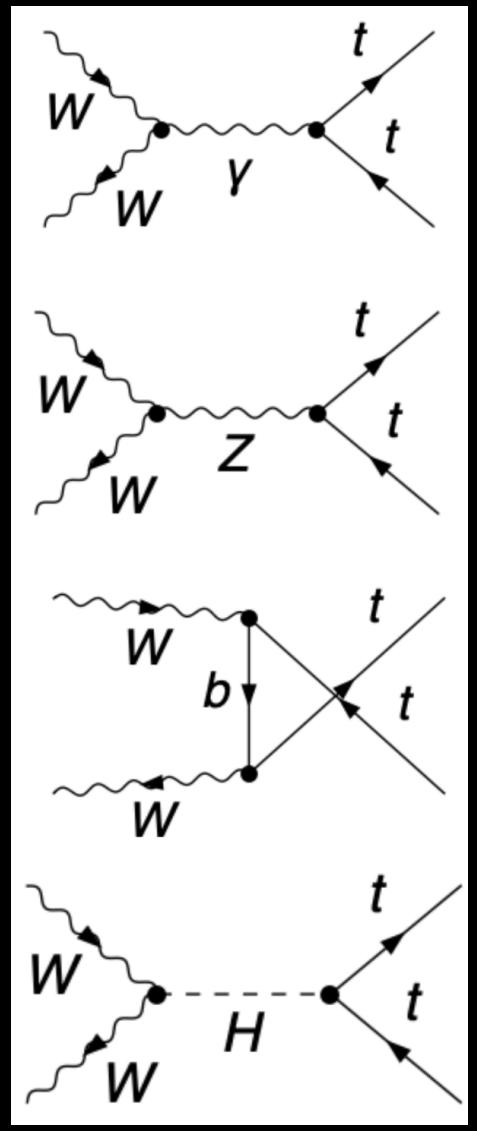
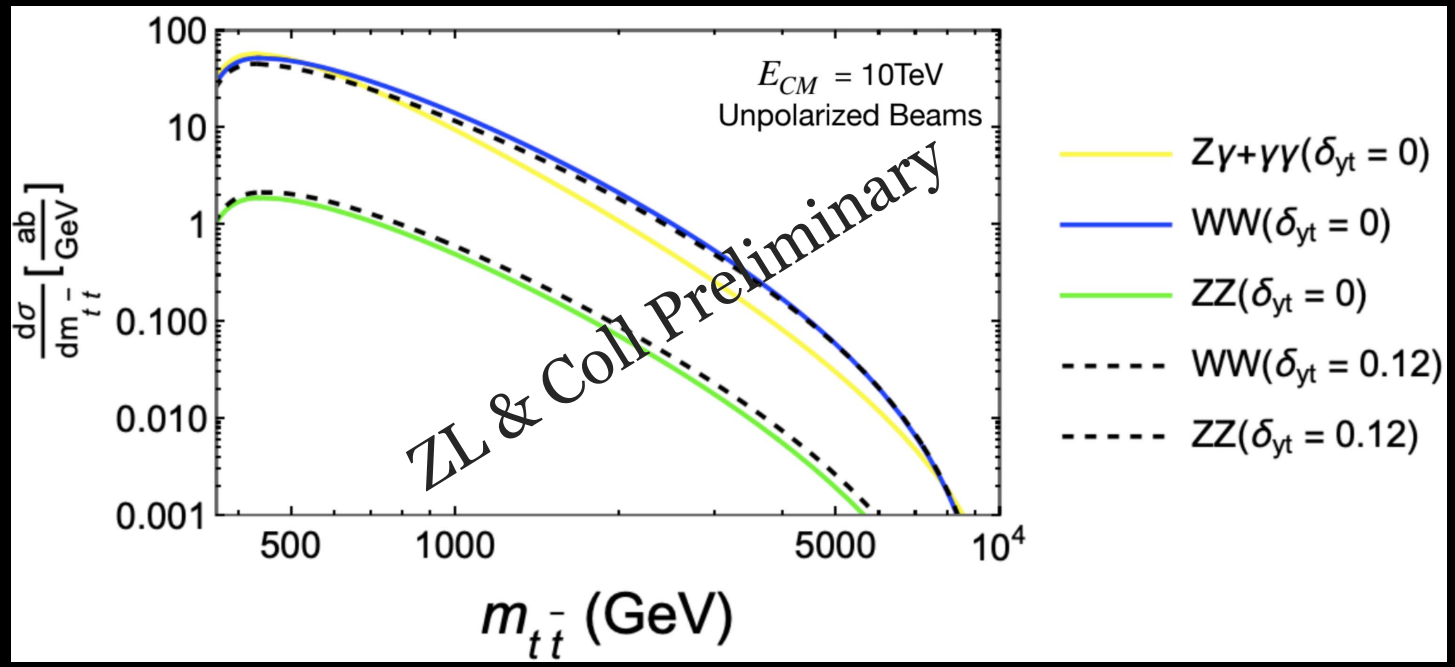
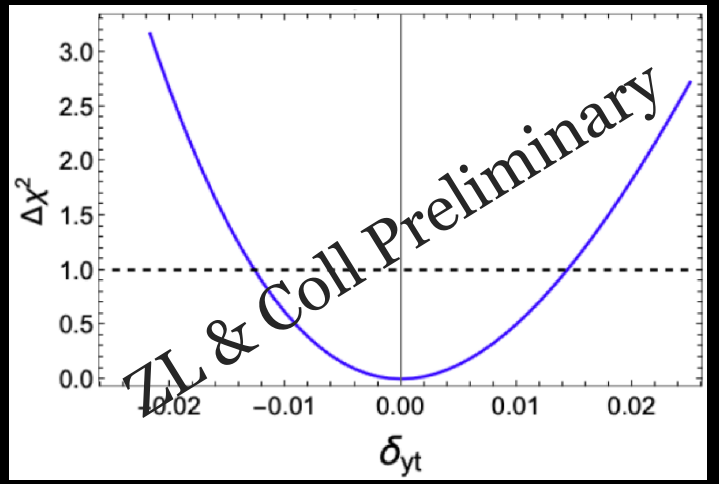
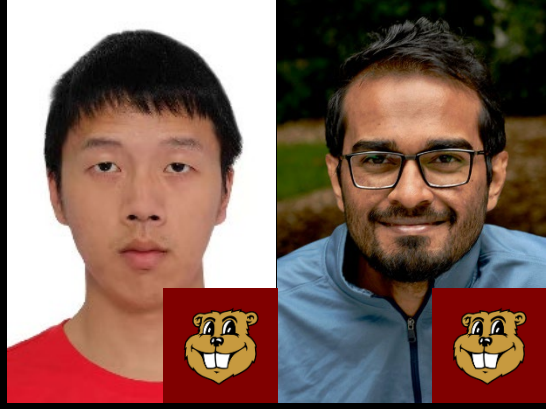
Measuring Top Yukawa





$$\mathcal{M}(t\bar{t} \to W_L^+ W_L^-) = \frac{m_t}{\nu^2}\delta_{BSM}\sqrt{s} \quad \sqrt{s} >> m_t, M_Z, M_W$$





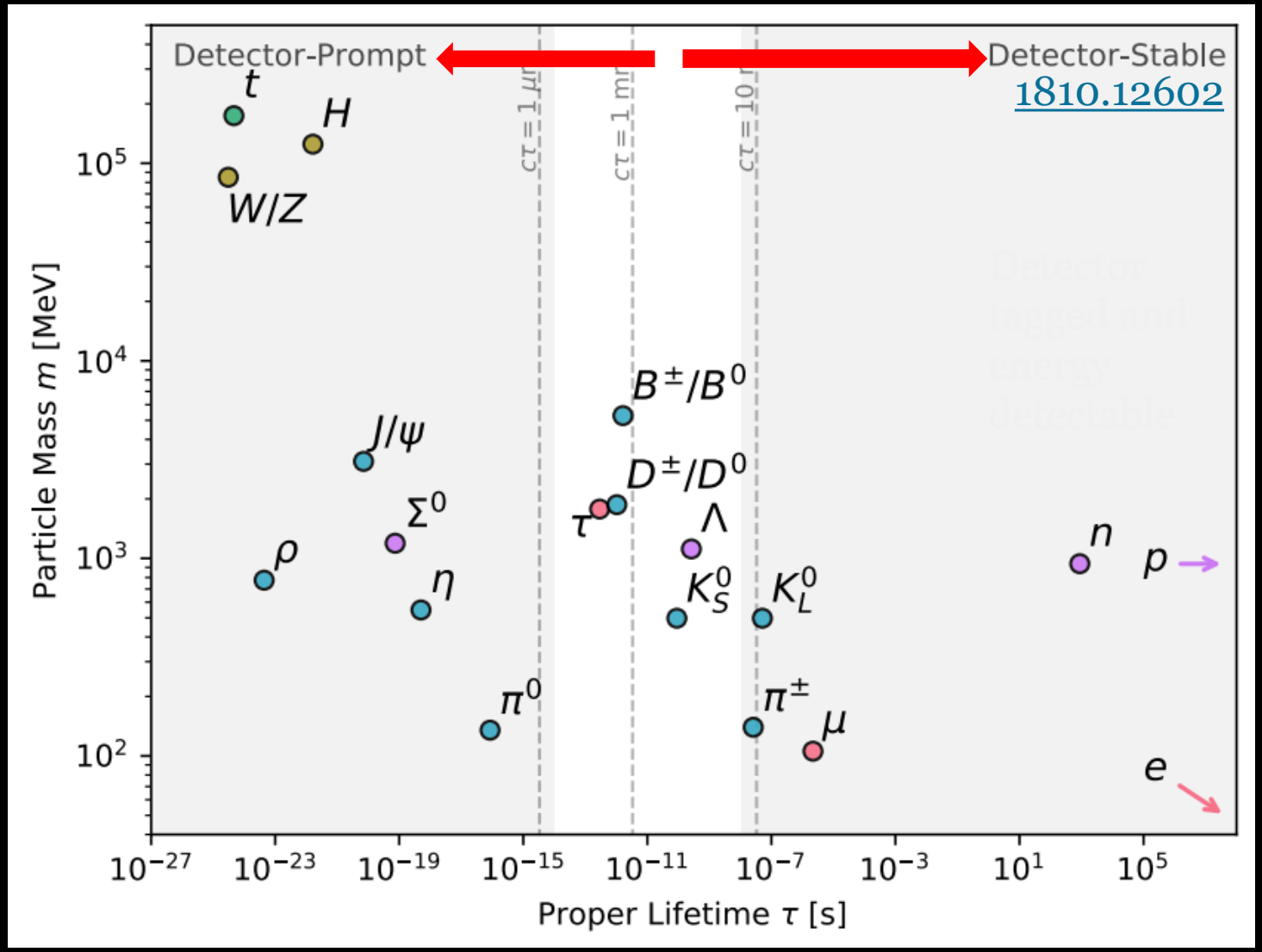
K.F. Lyu, I. Mahbub et al., in progress.

Also so see in MSG (2103.14043).

What is LLP & Why searching for them?

Long-lived particles in the standard model:

- approximate symmetries;
- kinematic suppressions;



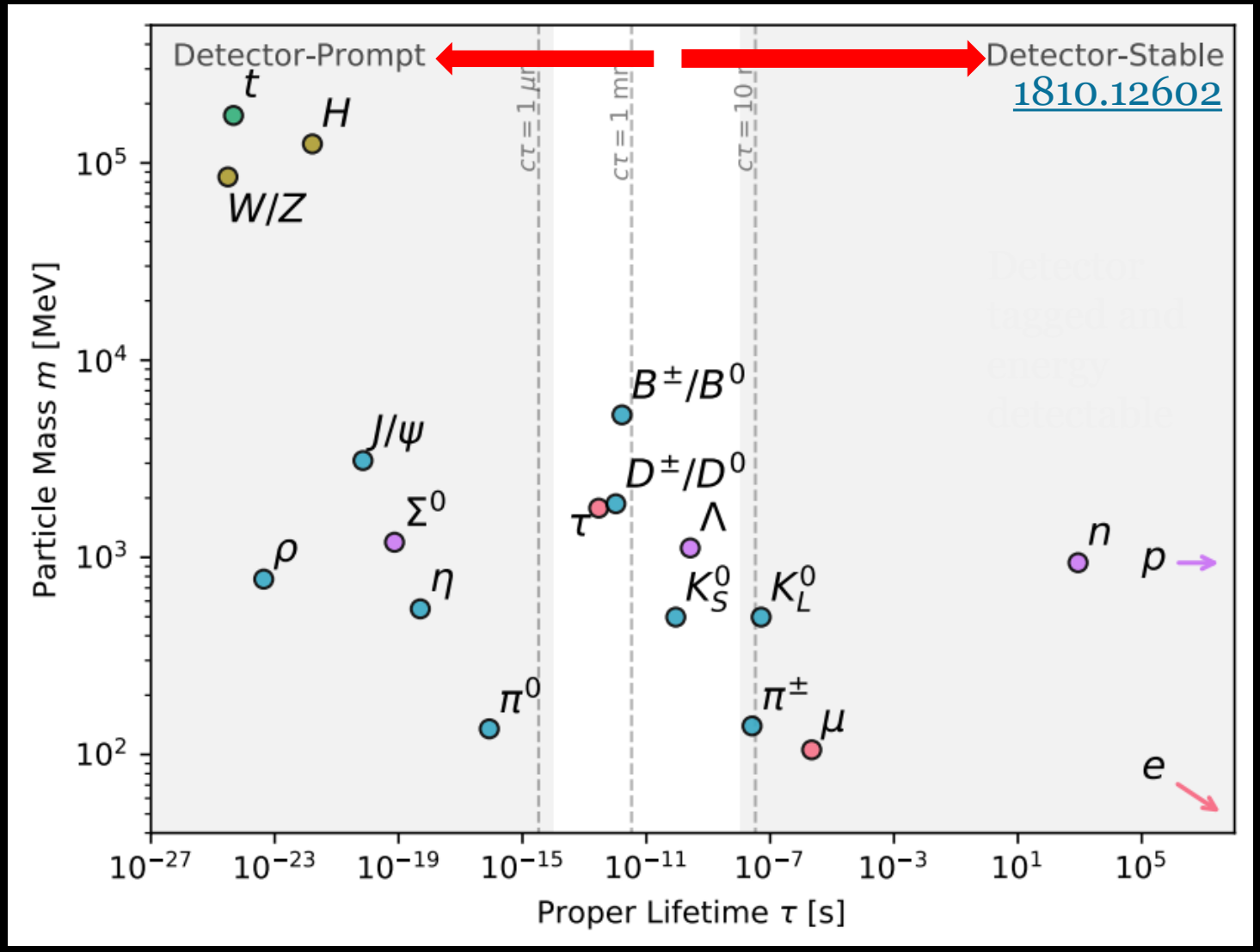
What is LLP & Why searching for them?

Long-lived particles in the standard model:

- approximate symmetries;
- kinematic suppressions;

For BSM particles:

- Prompt particles being actively probed;
- Many scenarios give raise to long-lived signatures:
  - SUSY (GMSB, RPV, Split, etc.)
  - Hidden Sector Dynamics



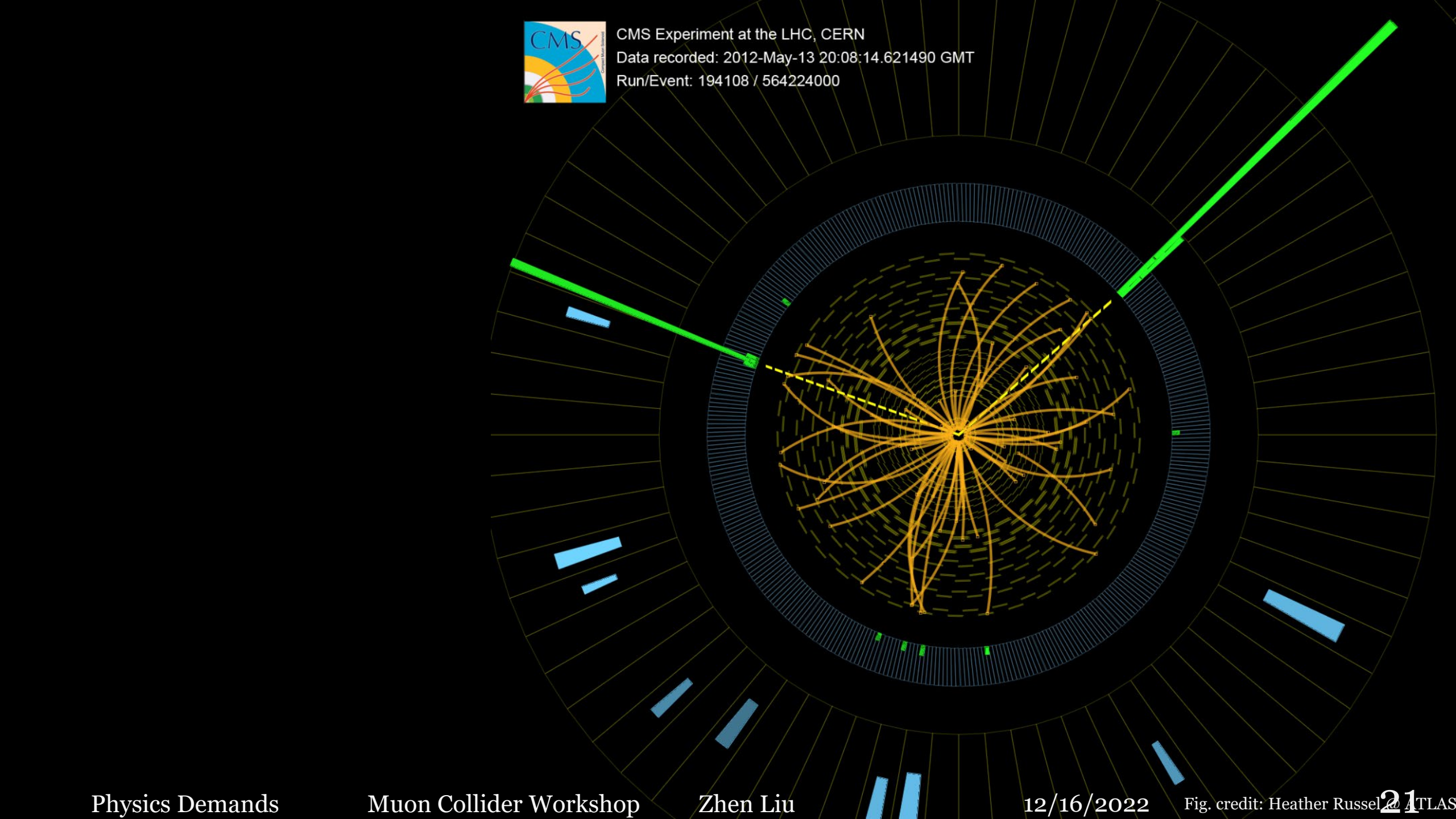


Fig. credit: Heather Russell @ ATLAS

But, a new experimental challenge.

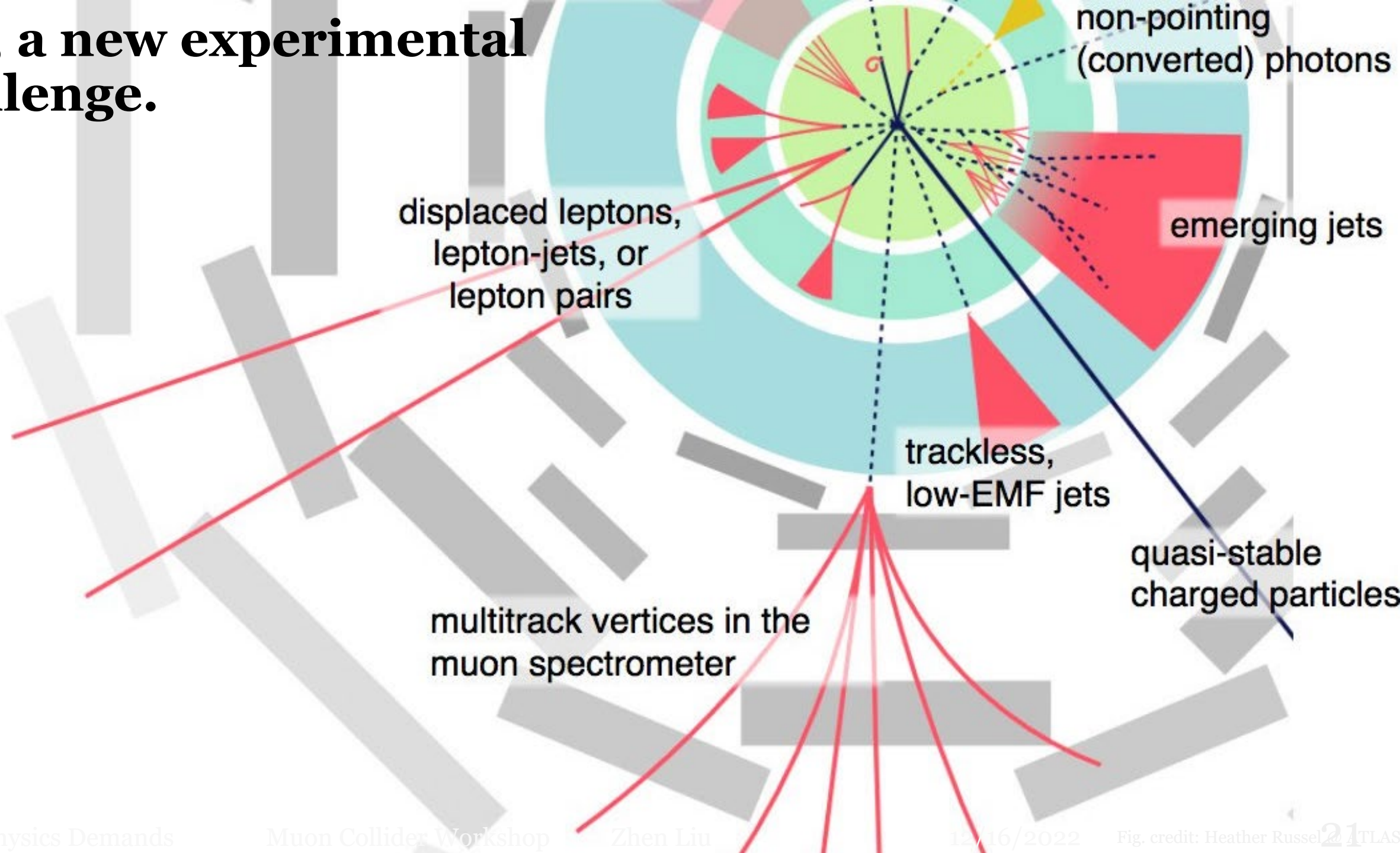


Fig. credit: Heather Russell @ ATLAS

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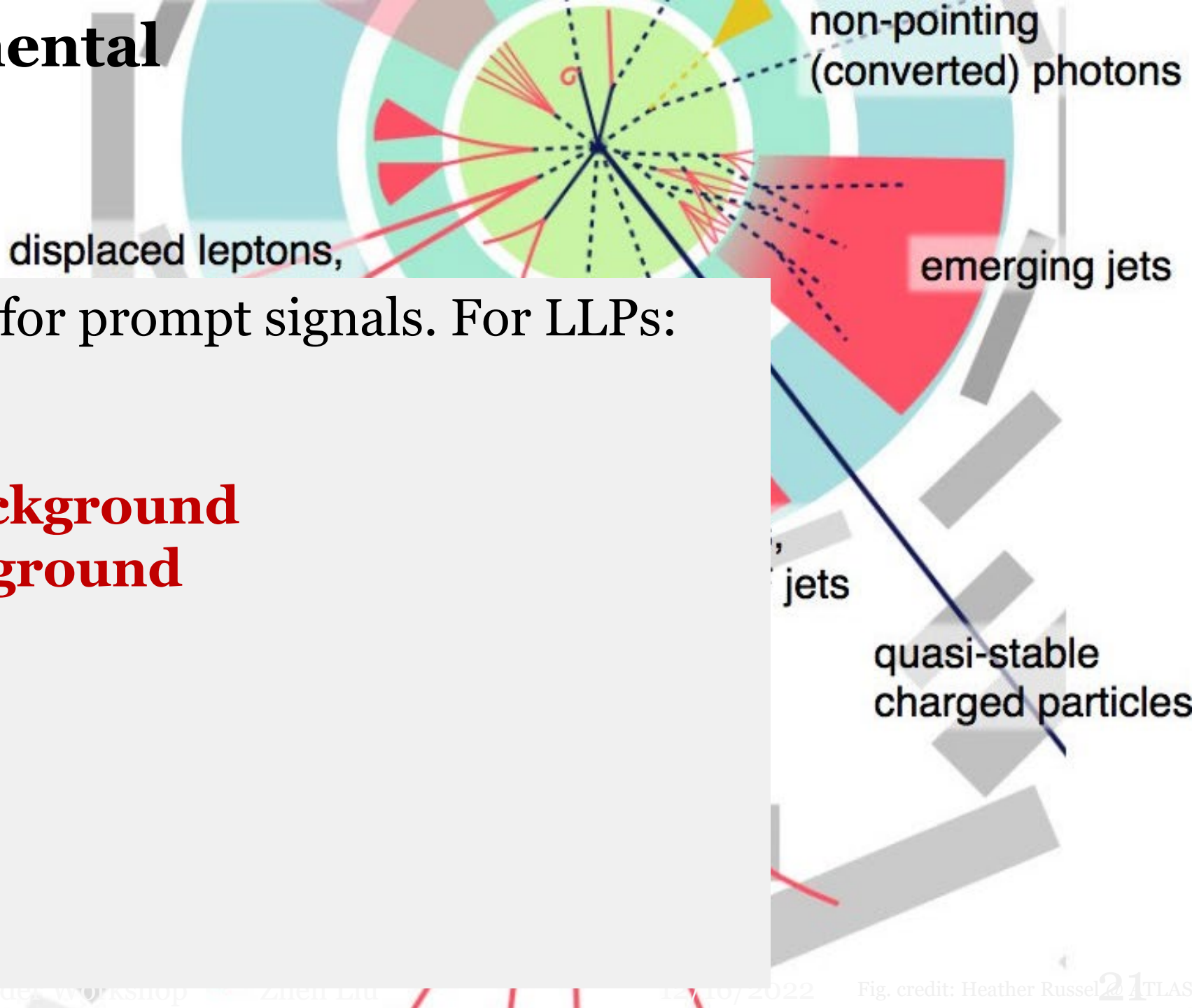


LHC detectors designed for prompt signals. For LLPs:

☹trigger

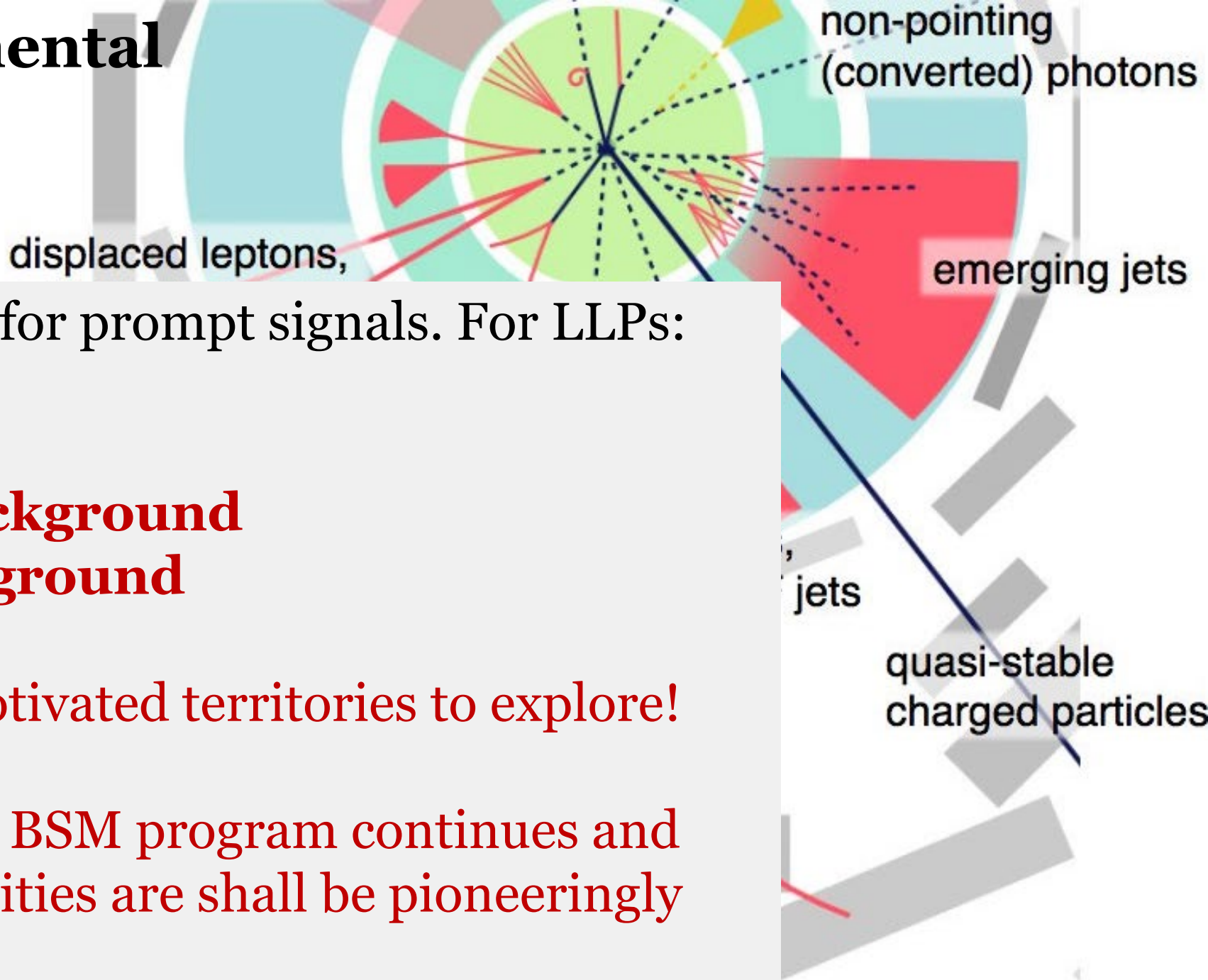
☹reconstruction

☺standard model background

☹non-standard background

Fig. credit: Heather Russell @ ATLAS

But, a new experimental challenge.



LHC detectors designed for prompt signals. For LLPs:

☹trigger

☹reconstruction

☺standard model background

☹non-standard background

Huge uncharted well-motivated territories to explore!

While the LHC standard BSM program continues and improves, new opportunities are shall be pioneeringly explored by theorists!

Fig. credit: Heather Russell

A veritable Renaissance of Long-Lived Particles

MATHUSLA
Codex-B
AL3X
Anubis
} Central/Hard LLPs

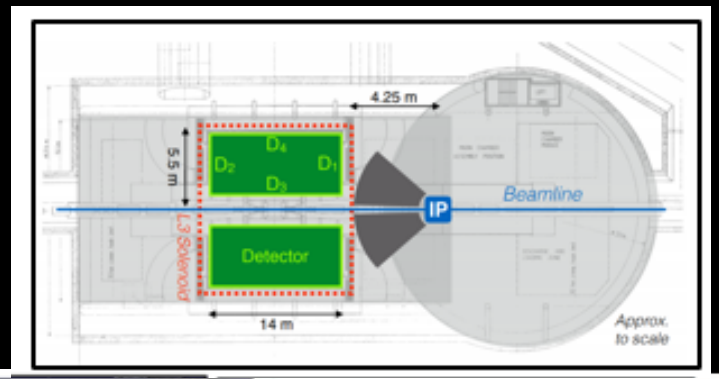
FASER
SHiP
NA62
SeaQuest
} Forward/lighter LLPs

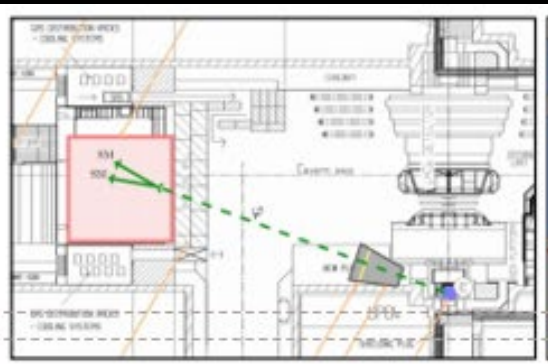
} Beamdump experiments

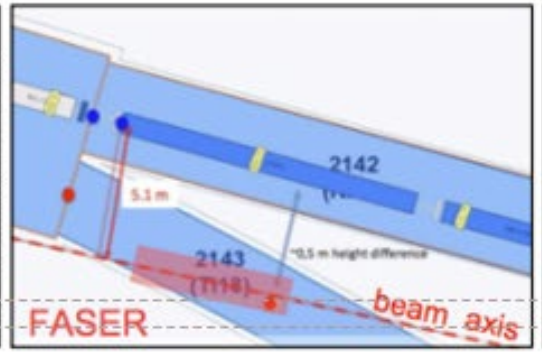
MoEDAL
MilliQan
} monopole
millicharged particles

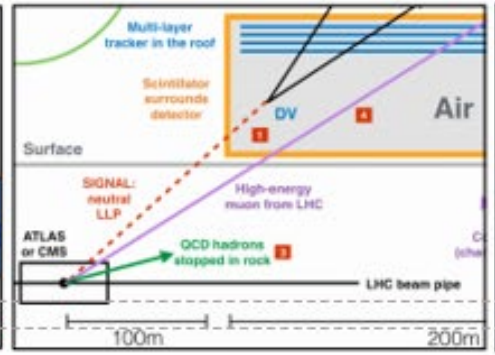
} Search for LLPs

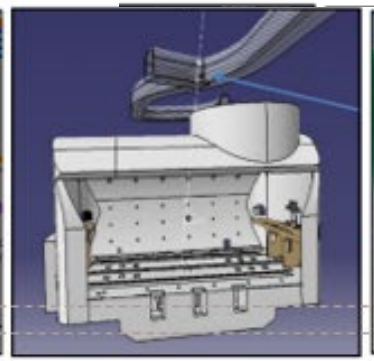
The world is planning on conducting new experiments searching for these hidden long-lived particles.

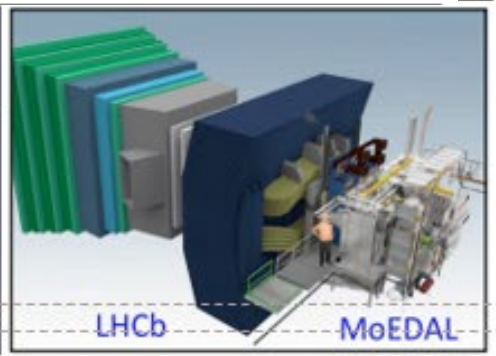




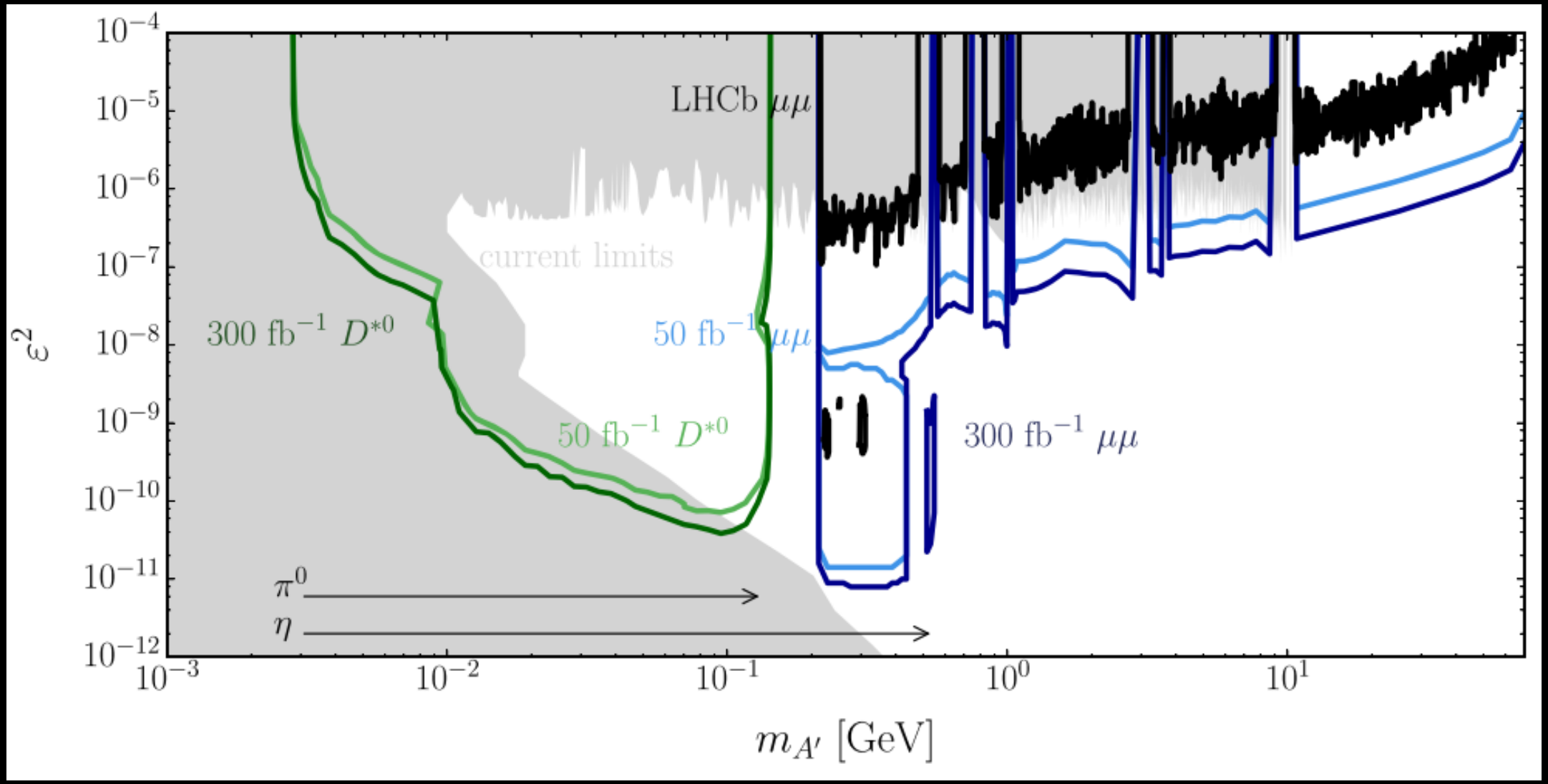






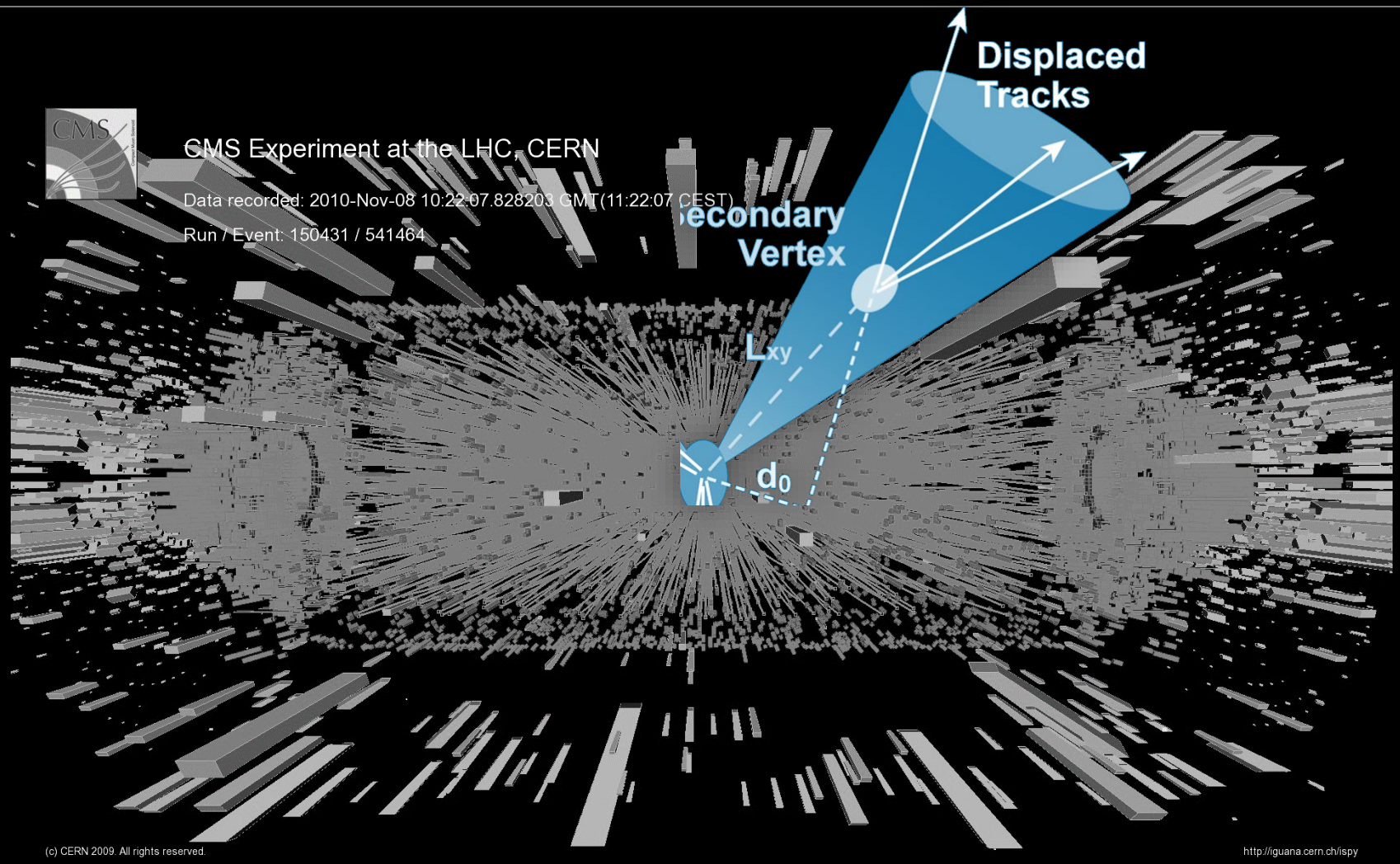


Log-log open parameter space to concur



Long-Lived particles Community Report: [1903.04497]

Long-Lived Particles (LLPs): timing

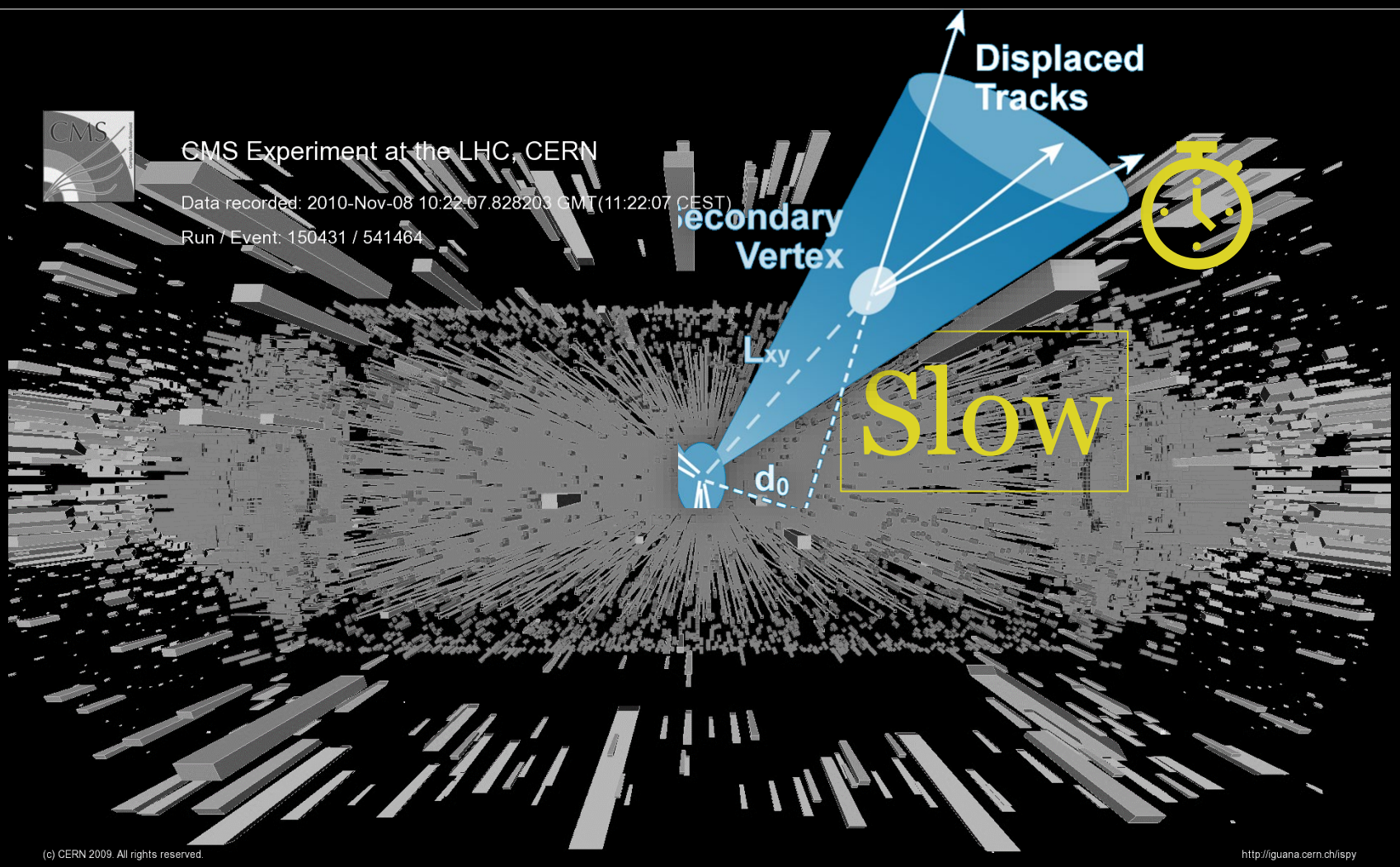


For a LLP community review: [1903.04497]

Long-Lived Particles (LLPs): timing

Delay is a universal feature of Long-Lived Particles*

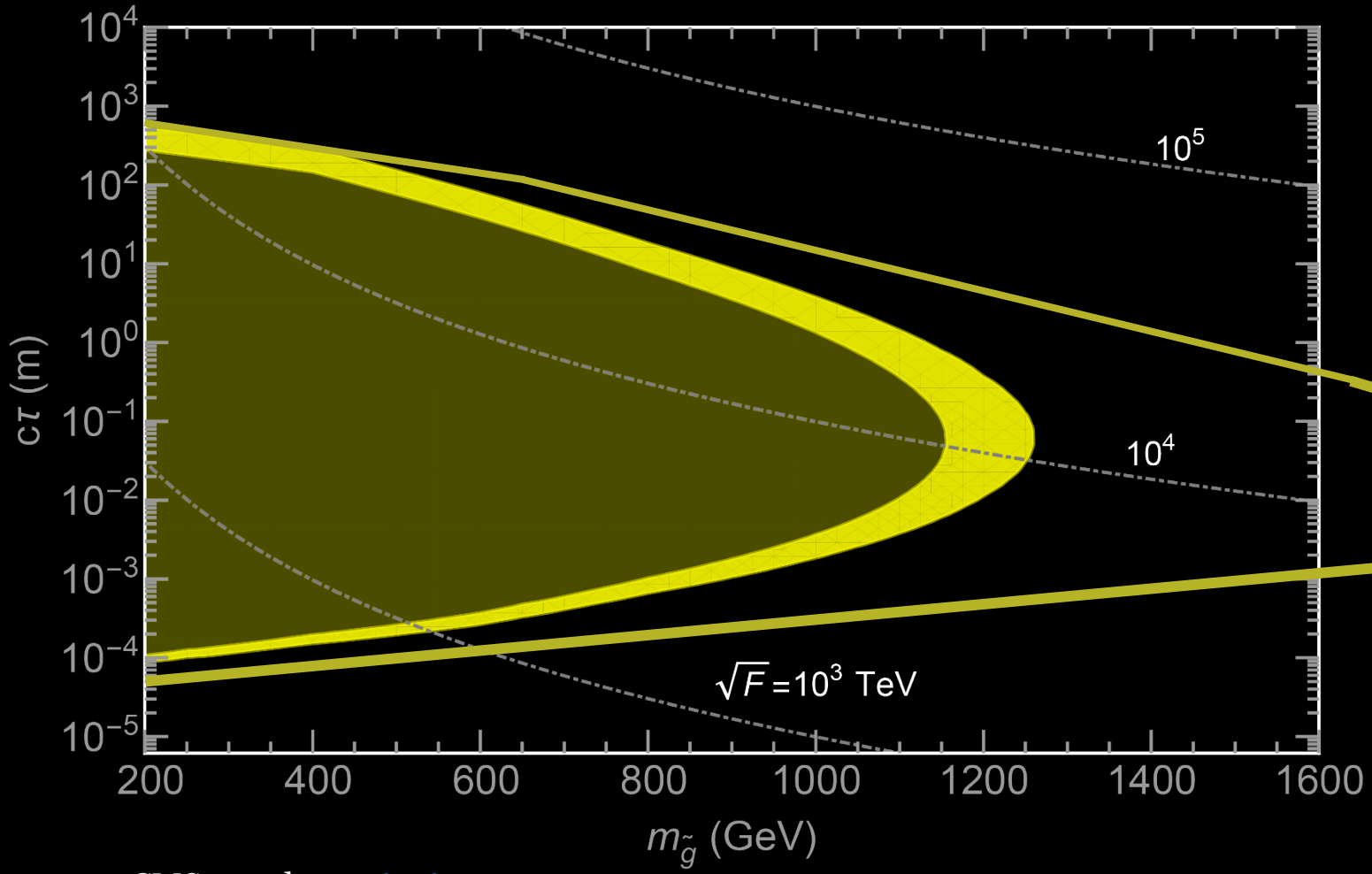
Liu, ZL, Wang, 1805.05957

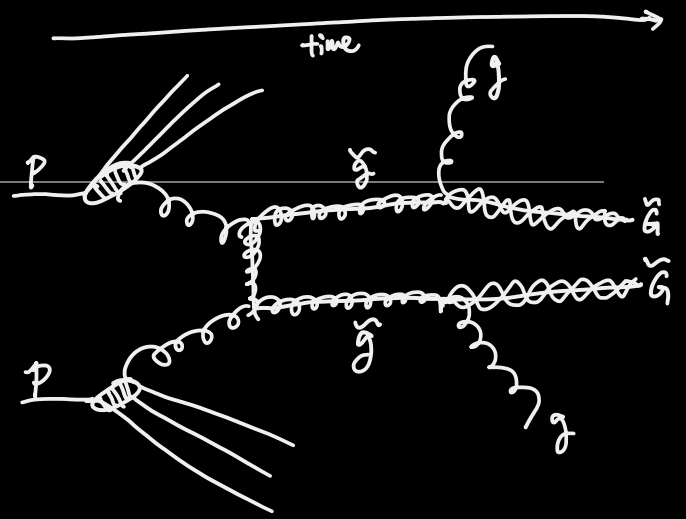


For a LLP community review: 1903.04497

*except for those hyper-boosted $\gamma \geq 7$

E.g., delayed jet



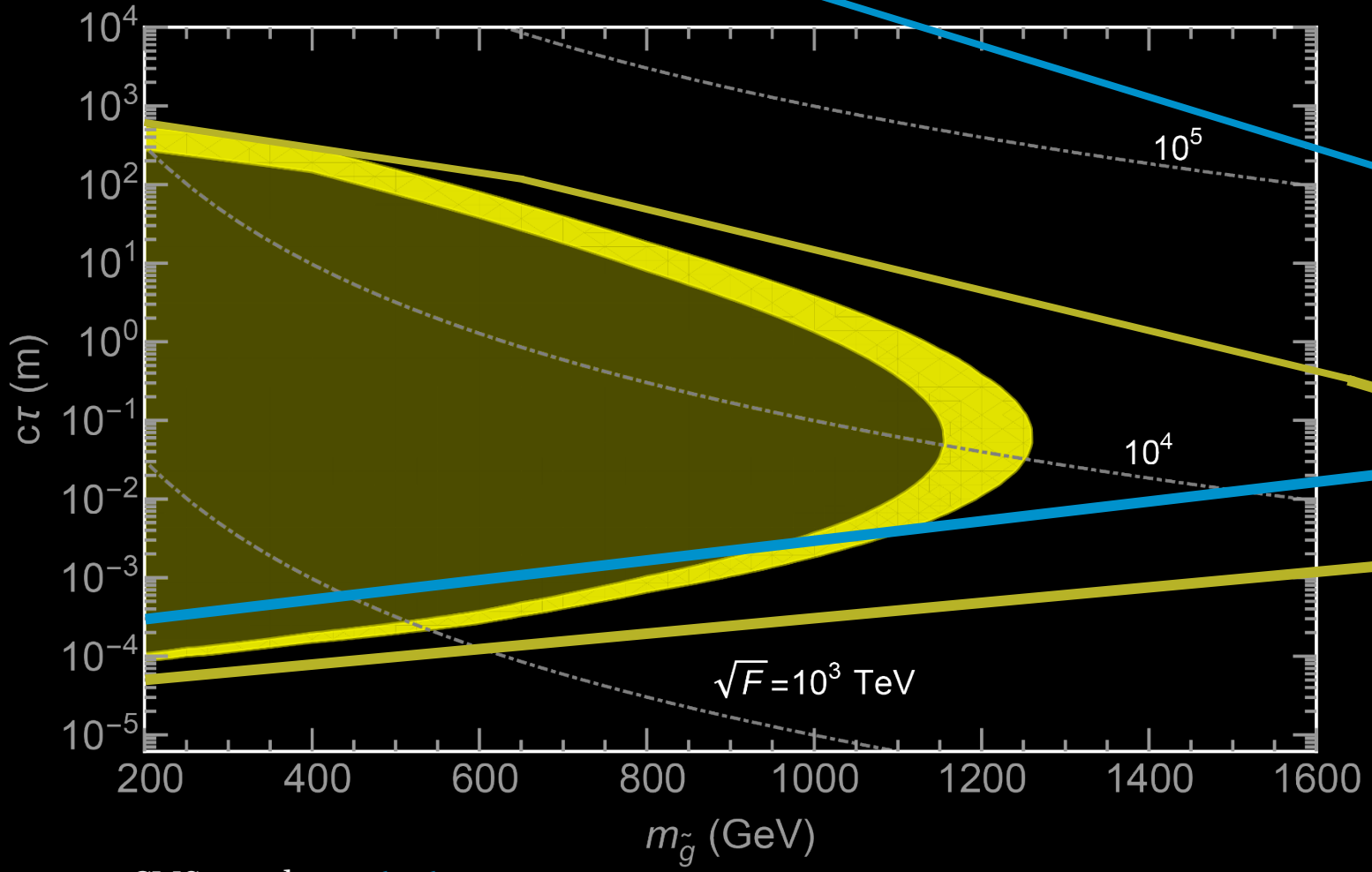


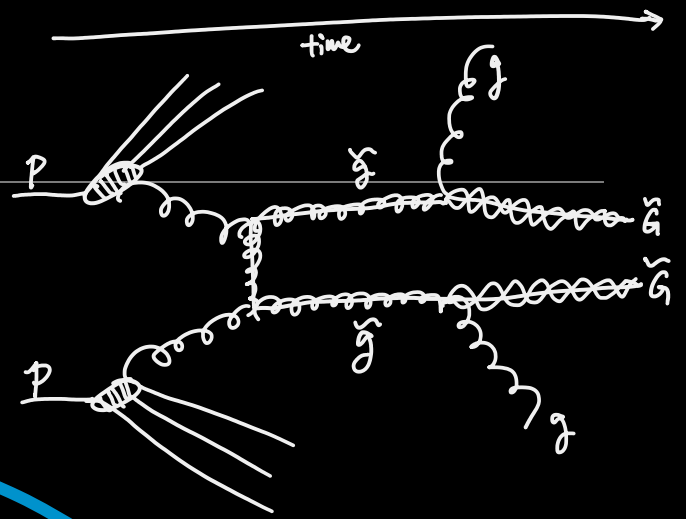
Displaced jet at 13 TeV, 39 fb^{-1}

More to come:
CMS MTD upgrade
ATLAS HGTD upgrade
Ecal, Muon system, HCal, timing information to be used

CMS search, 1906.06441
Liu, ZL, Wang, 1805.05957
8 TeV results, ZL, Tweedie, 1503.05923

E.g., delayed jet





Delayed Jet analysis carried out by CMS, 139 fb^{-1}

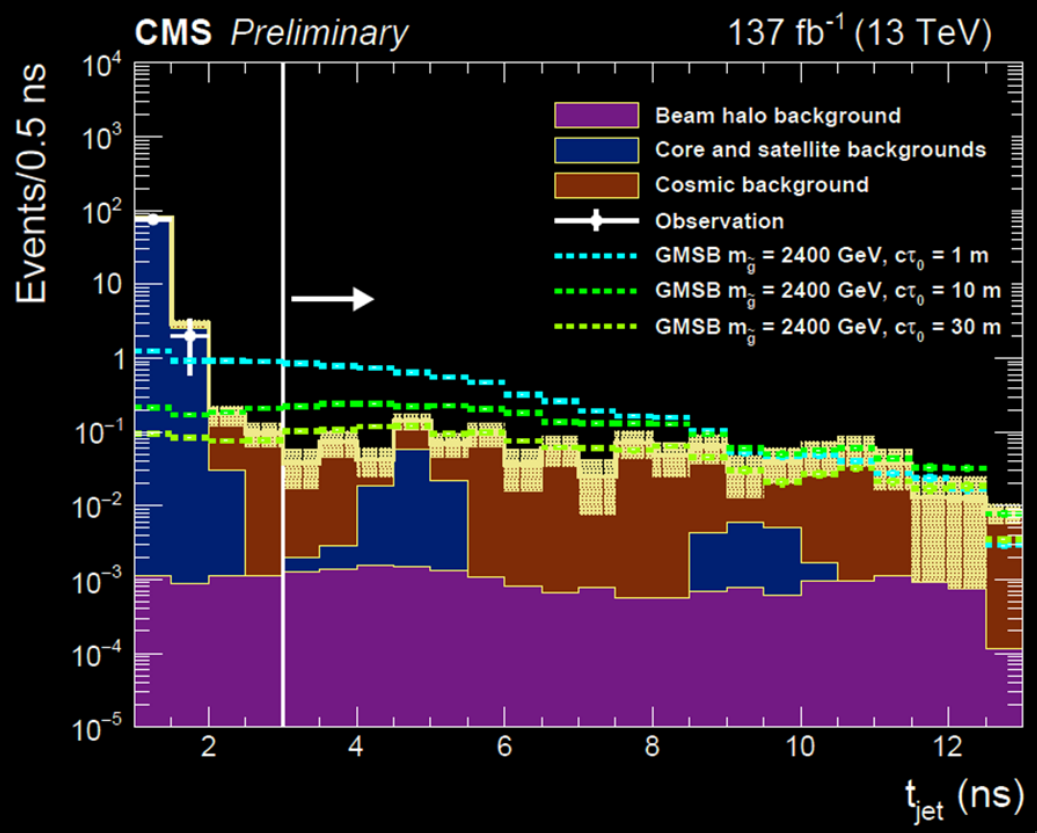
Displaced jet at 13 TeV, 39 fb^{-1}

More to come:
CMS MTD upgrade
ATLAS HGTD upgrade
Ecal, Muon system, HCal, timing information to be used

CMS search, 1906.06441
Liu, ZL, Wang, 1805.05957
8 TeV results, ZL, Tweedie, 1503.05923

What is the time of a jet?

Theoretically and experimentally interesting

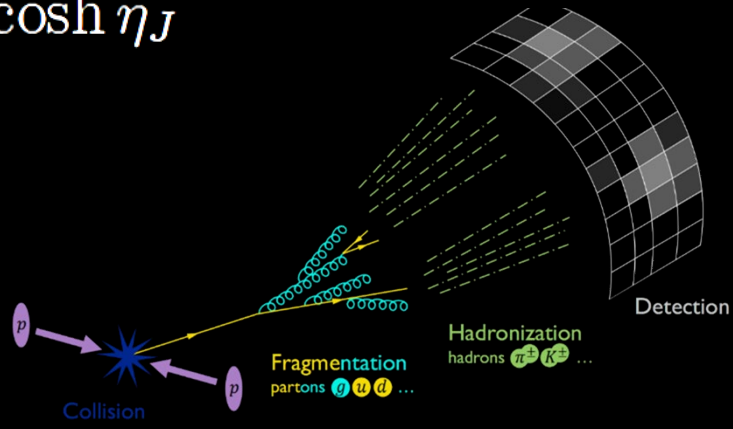


$$t_J^{\{\text{median,hardest,random}\}} = t_{\{i_m,i_h,i_r\}} = \frac{r_T}{c}\cosh\eta_{\{i_m,i_h,i_r\}}$$

$$t_J^{\text{null}} = \frac{r_T}{c}\frac{|\vec{p}_J|}{p_{T,J}} = \frac{r_T}{c}\cosh\eta_J$$

$$t_J^{\text{kinematic}} = \frac{r_T}{c}\frac{E_J}{p_{T,J}}$$

$$t_J^{\text{average}} = \frac{1}{N}\sum_{i=1}^{N} t_i$$



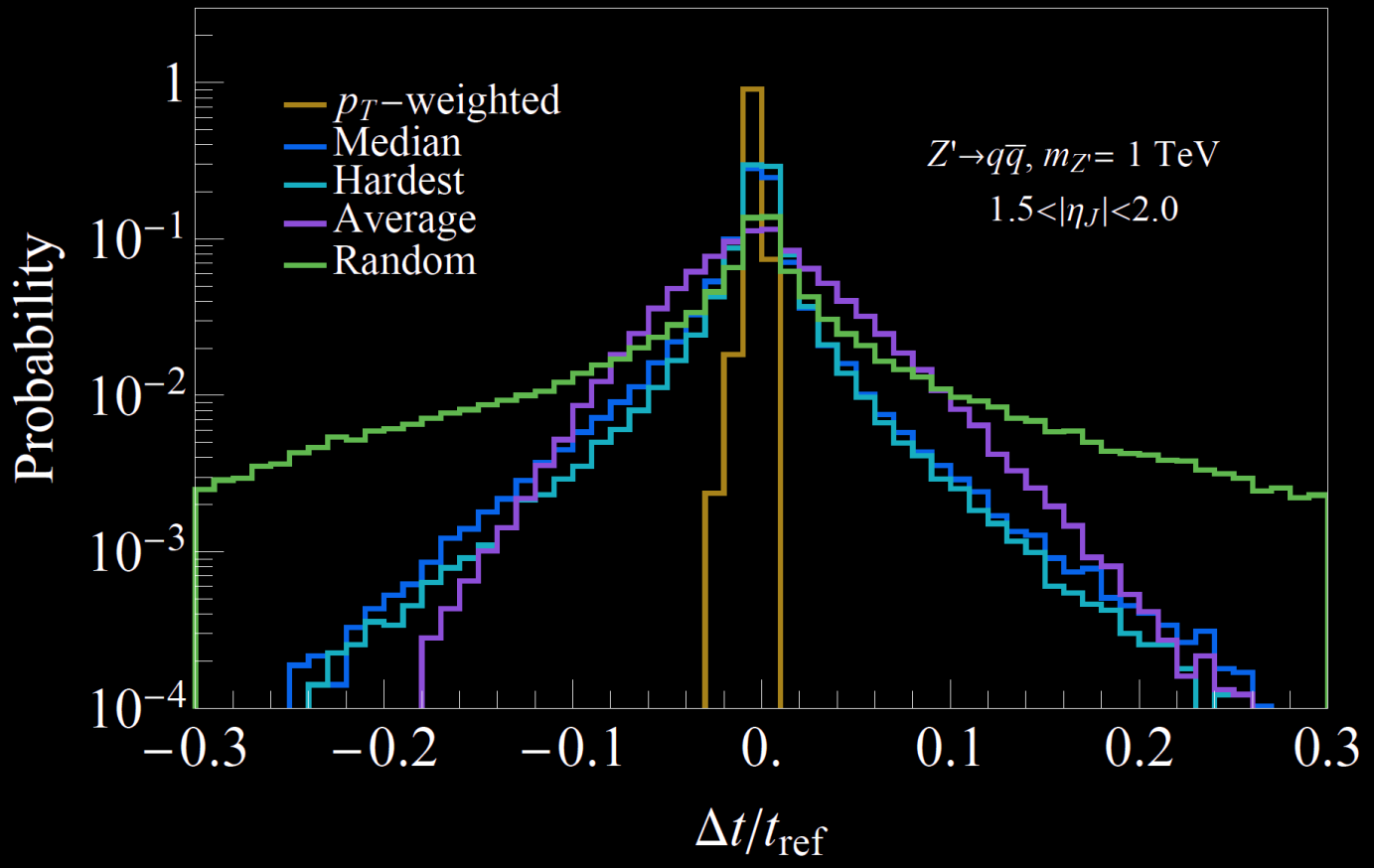
$$t_J^{p_T} = \frac{1}{p_{T,S}}\sum_{i=1}^{N} p_{T,i}t_i, \qquad p_{T,S} = \sum_{i=1}^{N} p_{T,i}$$

$$t_J^{(\alpha,\beta,\gamma)} \propto \sum_{i\in\text{jet}} (p_{T,i})^\alpha (\Delta R_i)^\beta t_i^\gamma$$

The pioneering delayed jet search used median time, clearly having large room to improve.

Chiu, ZL, Low, Wang, 2109.01682

Tackle Time: what is the time of a jet?



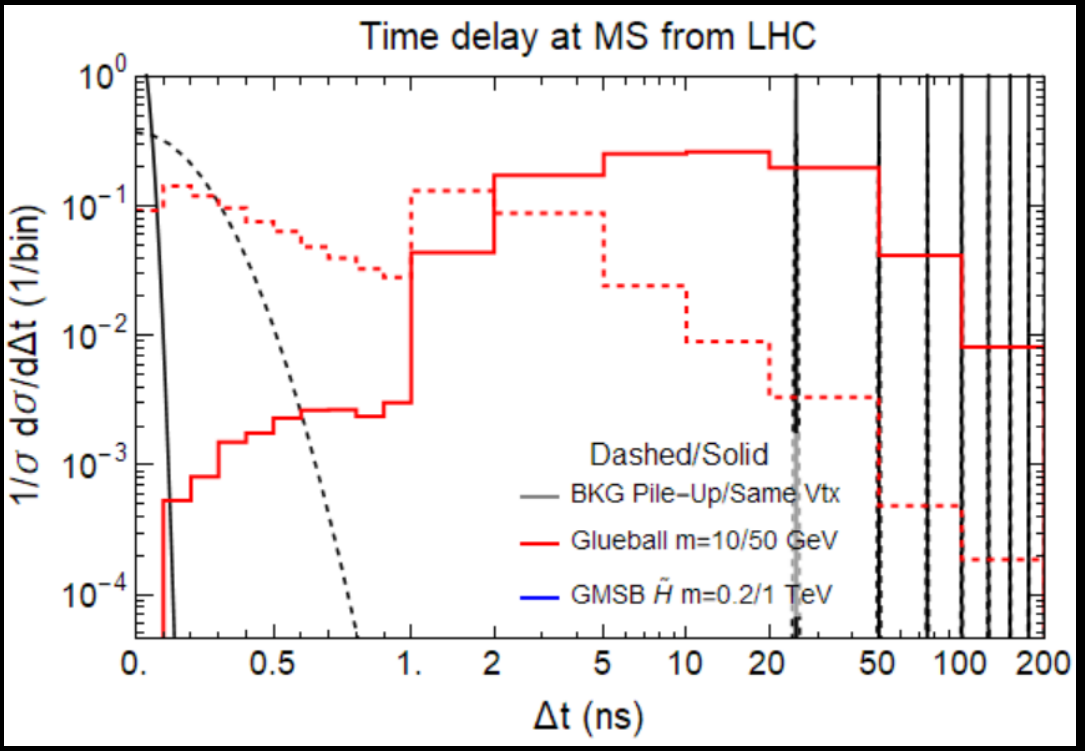
pT-weighted time provides the best convergence, and hence the quasi-optimal experimental definition of the jet time.
It is also IR-safe and calculable quantity.
Other jet time definitions spreads out driven by soft/colinear behaviors, further imprinted by geometrical effects..

$$t_J^{(\alpha,\beta,\gamma)} \propto \sum_{i\in\text{jet}} (p_{T,i})^\alpha (\Delta R_i)^\beta t_i^\gamma$$

Chiu, ZL, Low, Wang, 2109.01682

J. Liu, ZL, LT Wang, [1805.05957]

Late comers will be spotted easily: Higgs decays



J. Liu, ZL, LT Wang, 1805.05957

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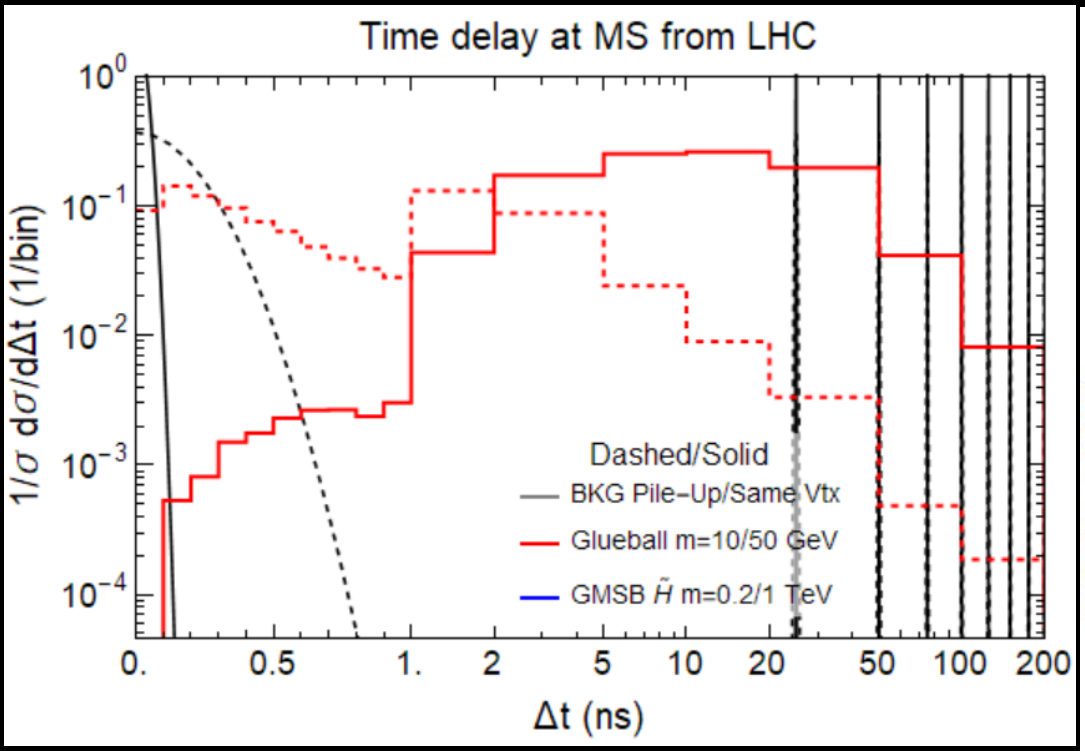
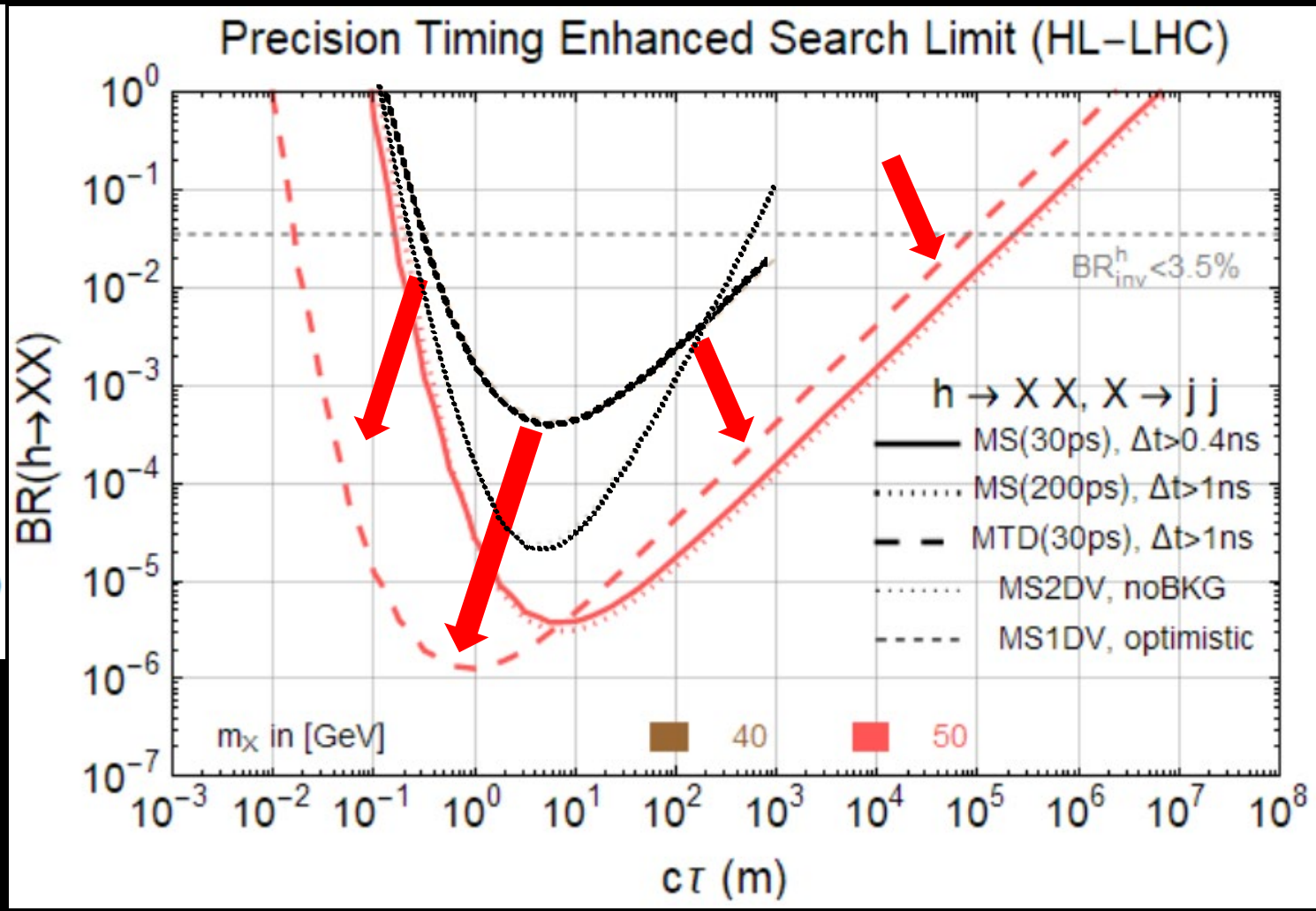
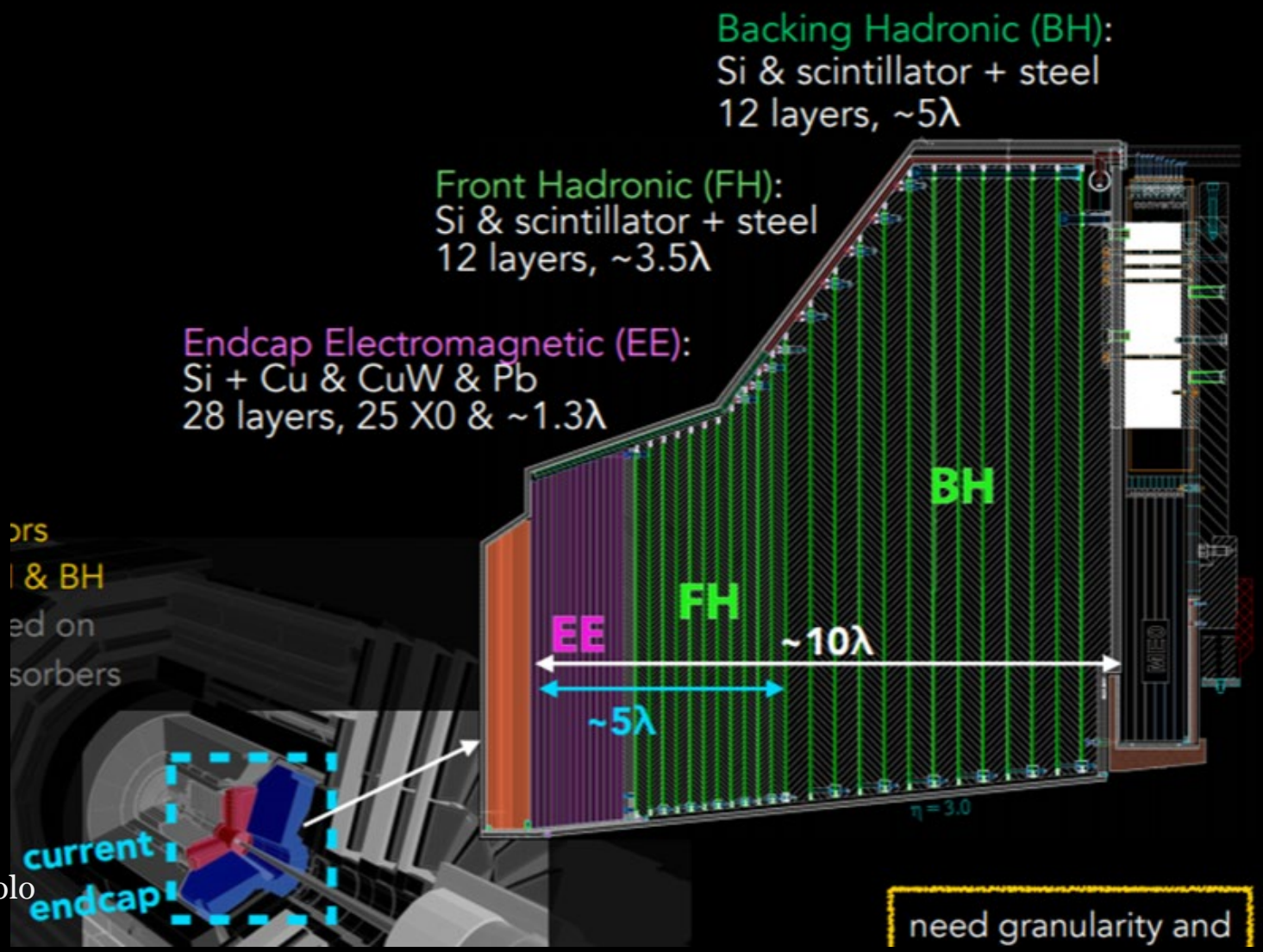




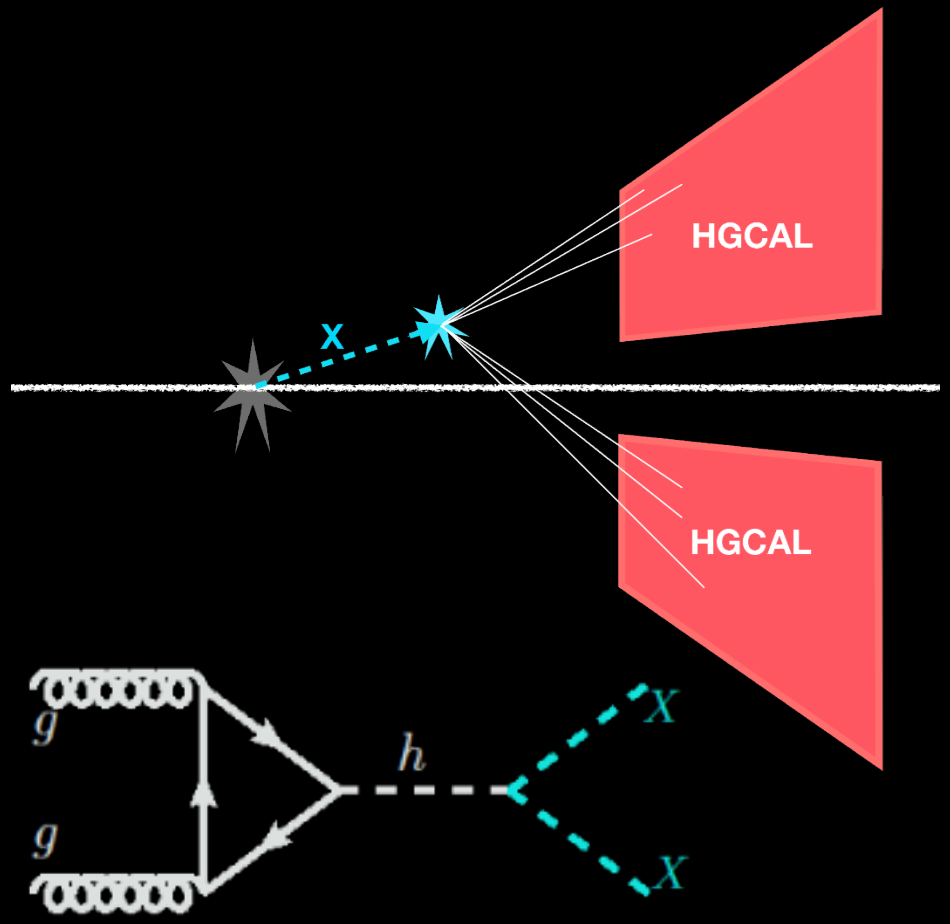
High Granularity

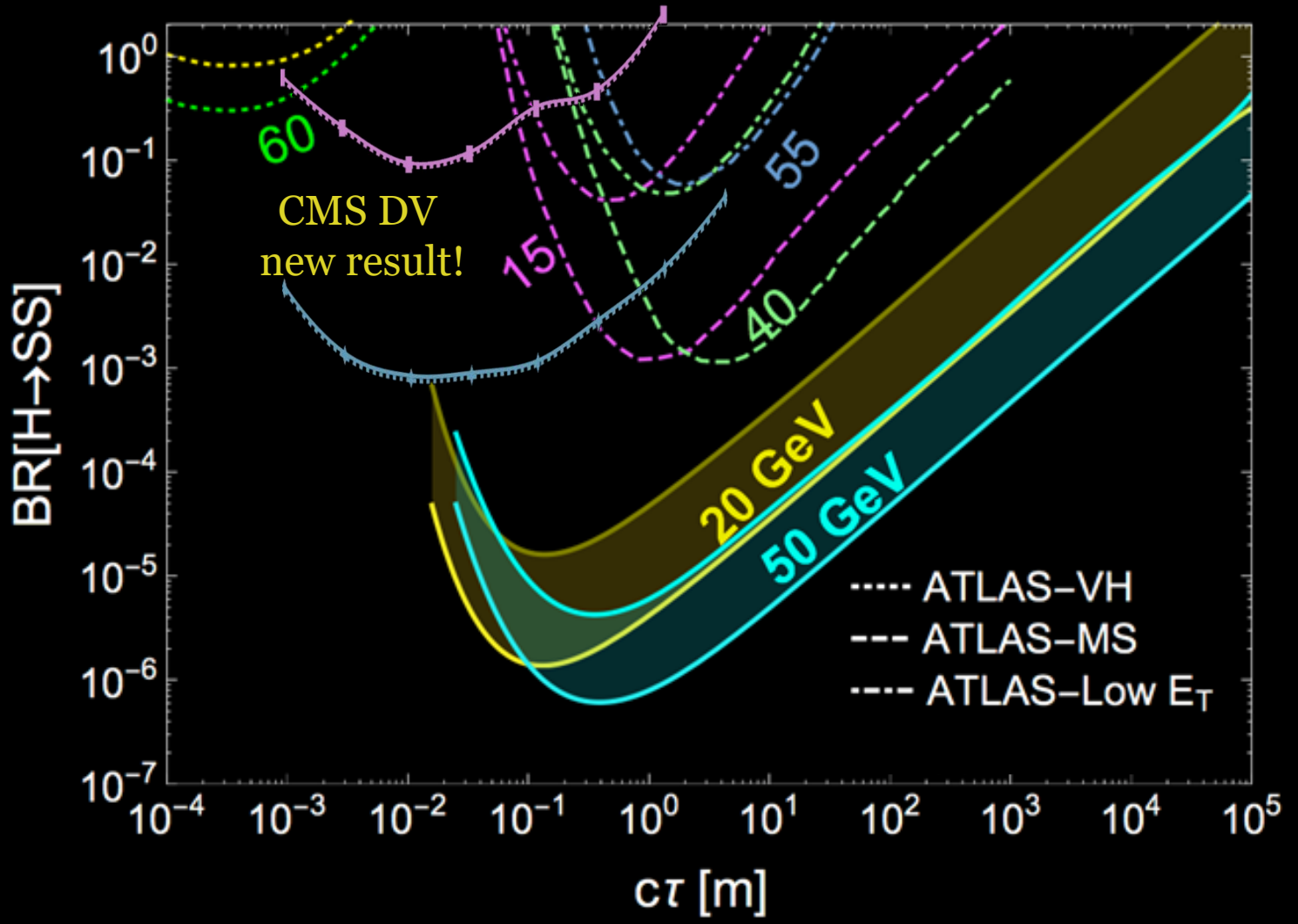
High Granularity Calorimeter provides both high precision in timing and position, as well as energy deposition (one sees shower).



Look for LLPs in HGCAL, Liu, ZL, Wang, Wang, 2005.10836; Displaced Trigger, Gershtein 1705.04321, Gerstein, Kanpen, 1907.00007, Gerstein, Knapen, Redigolo 2012.07864 ; Linthorne,Stolarski, 2103.08620

HGCAL potential





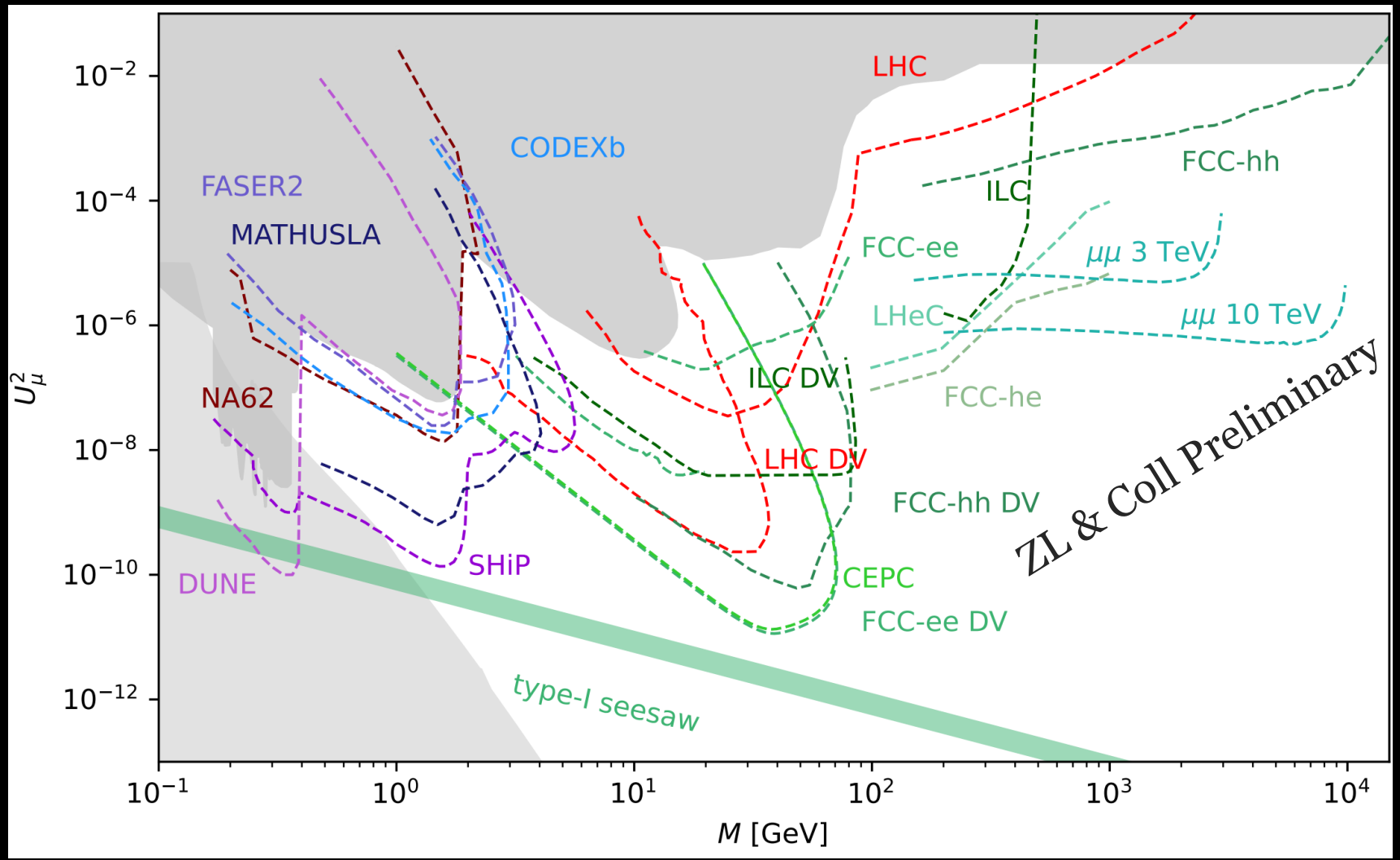
Liu, ZL, Wang, Wang, 2005.10836

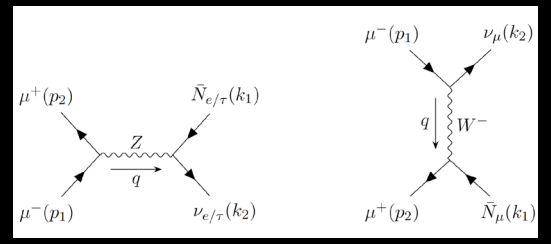
Another EW BSM example: Heavy Neutral Leptons

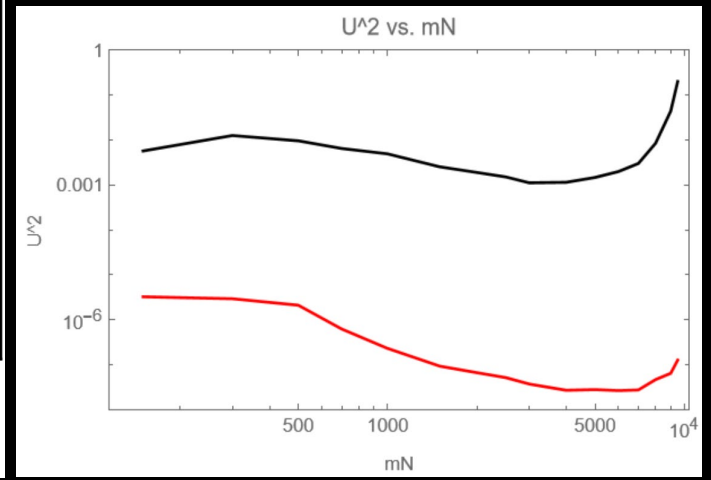
HNL

Speaker: Kunfeng Lyu (University of Minnesota)

P.R. Li, ZL, K.F. Lyu, in progress







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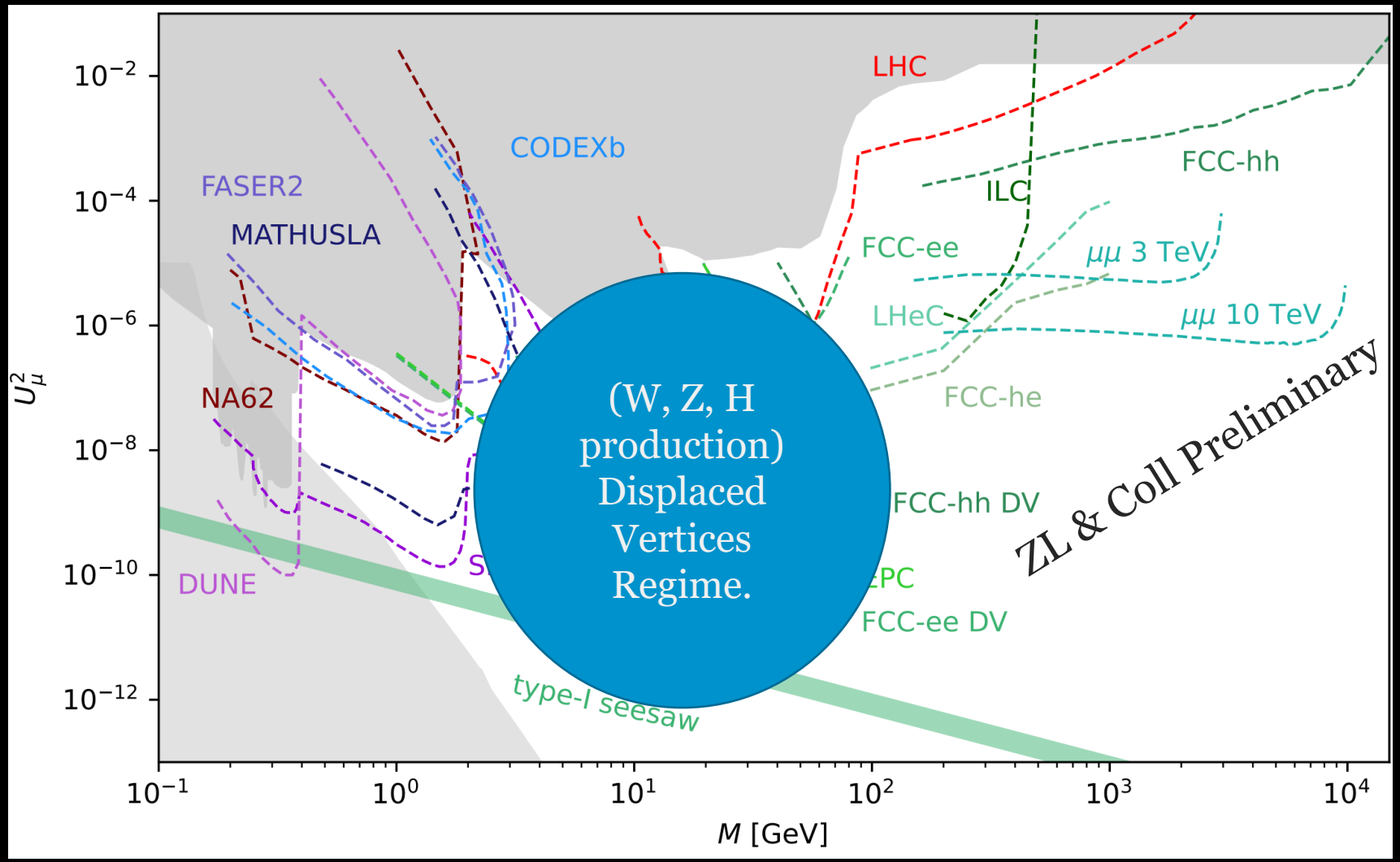

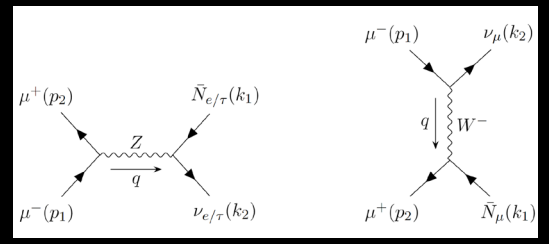

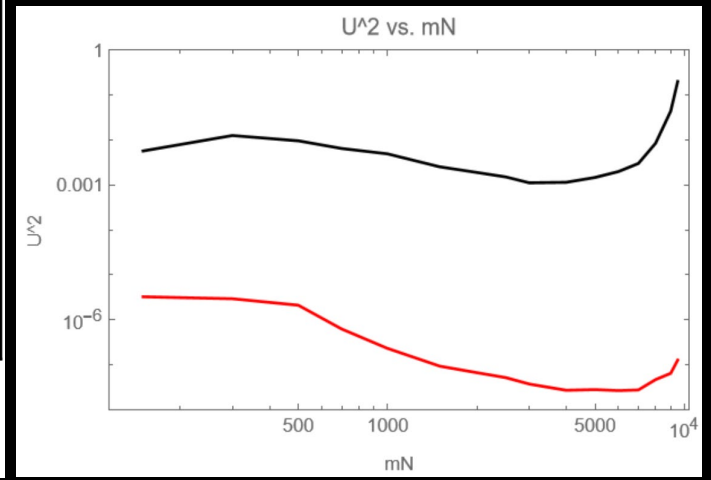

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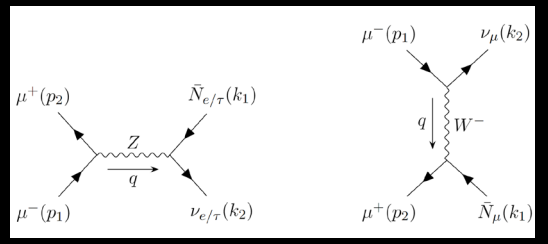
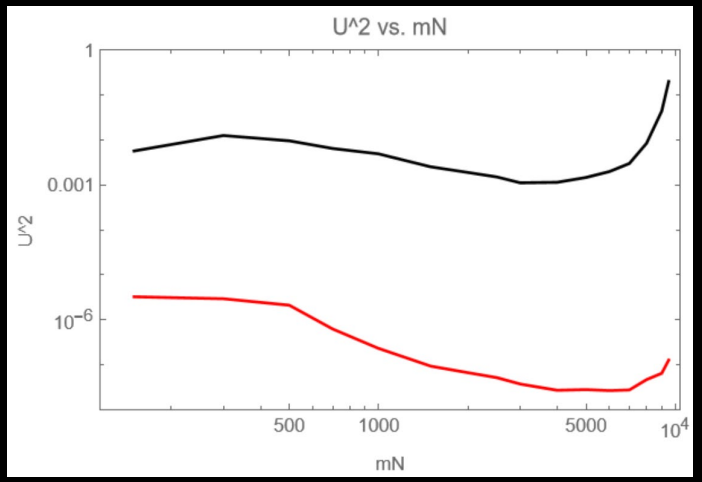
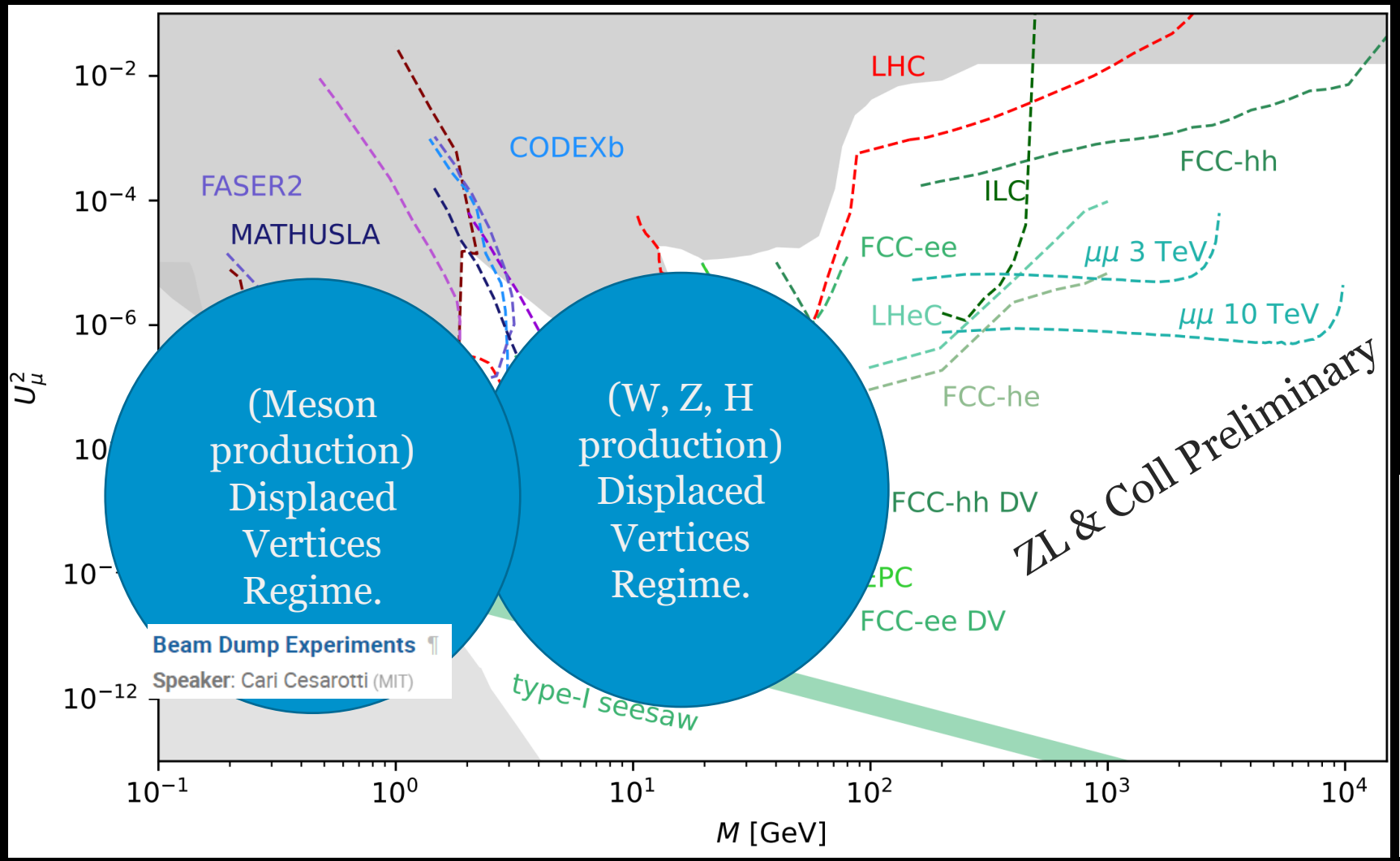
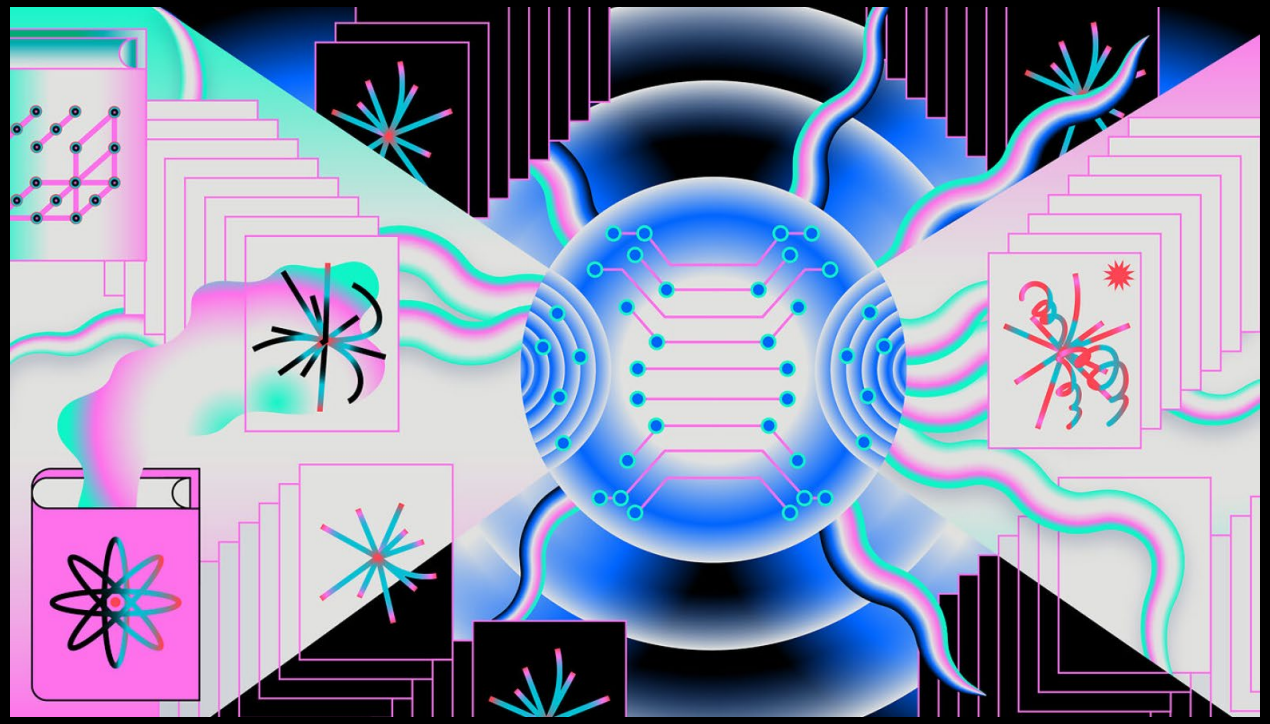


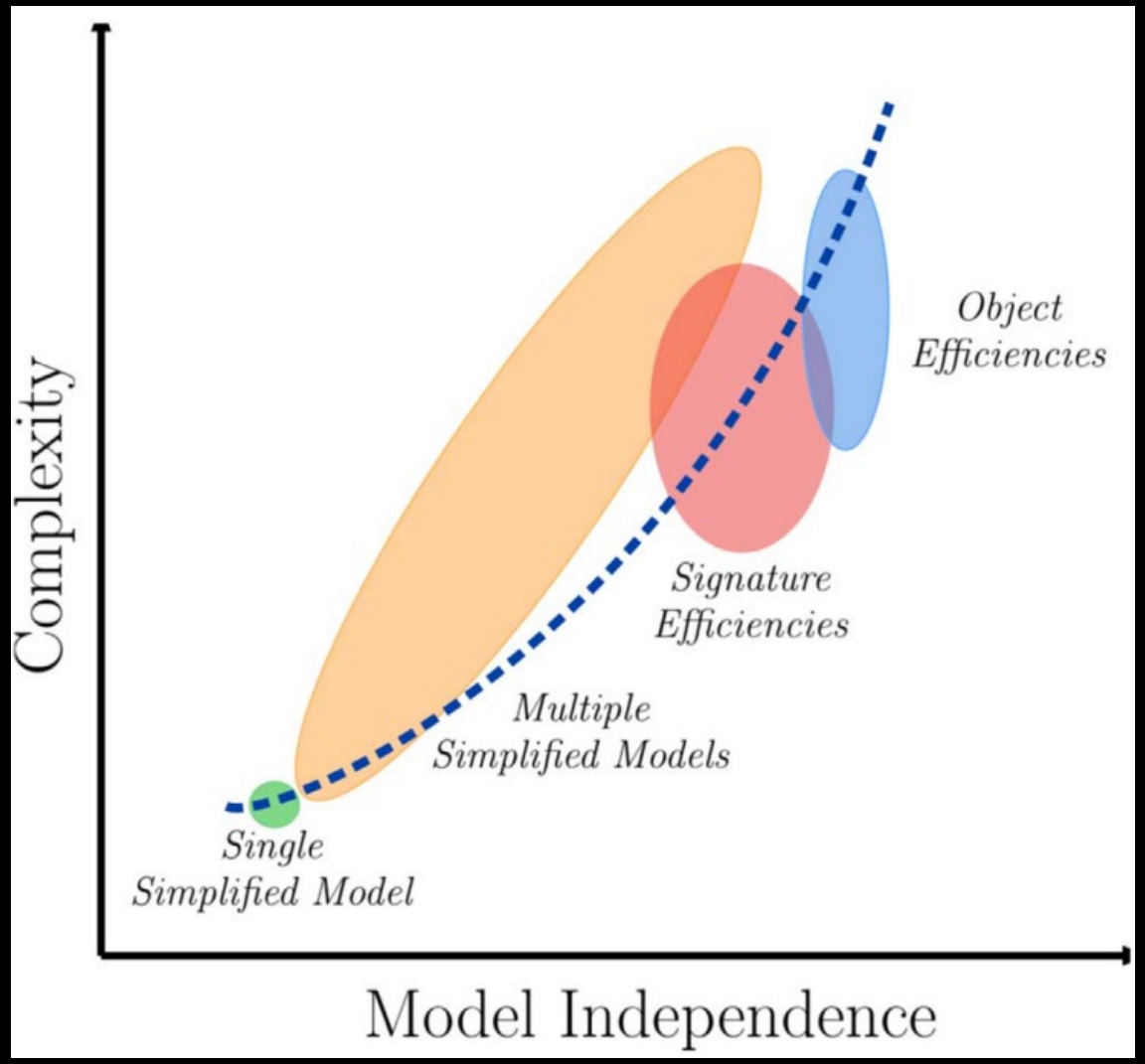




Open & Anomalies

- Open to search for anomalies;
- (Must) open for interpretations;
- Open to be surprised





Zeroth Order

Let's get a high-energy muon collider running!

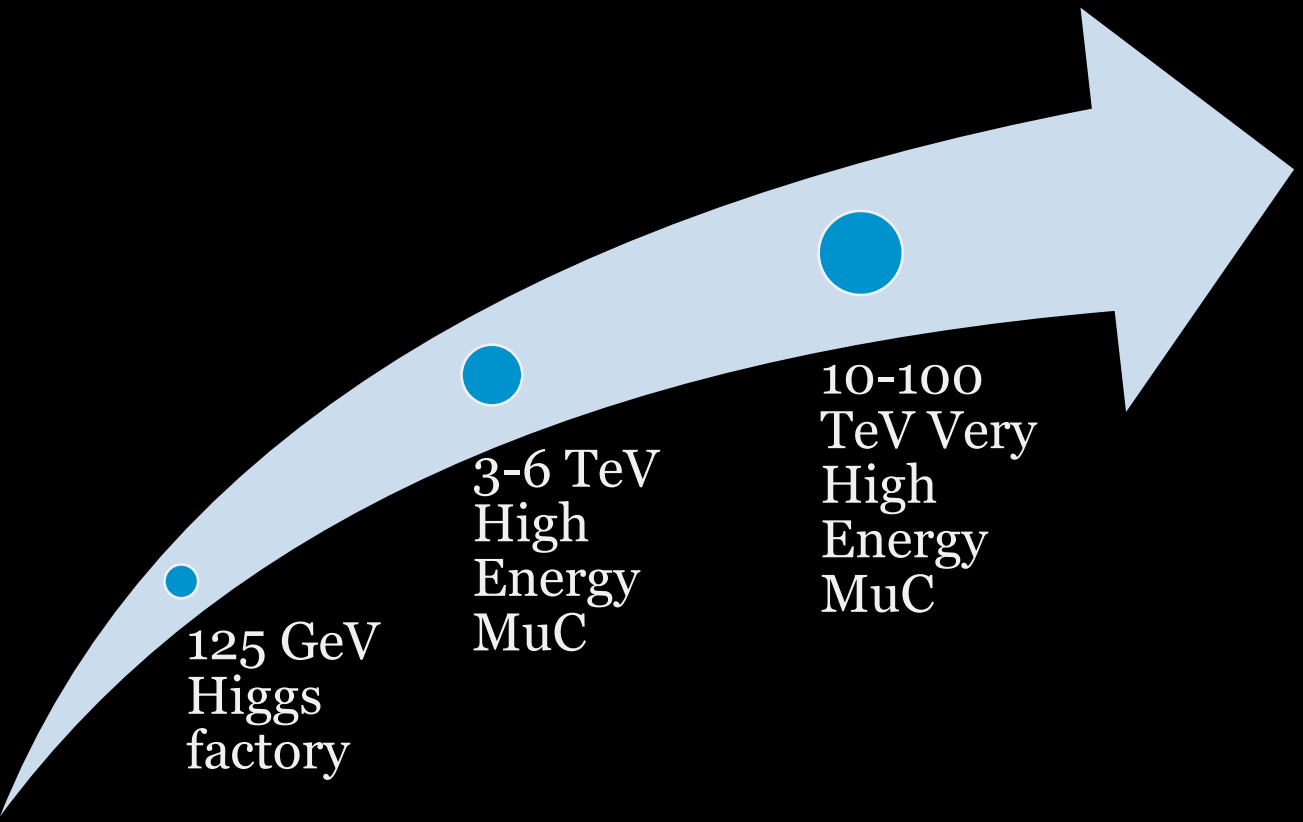
- Energy Resolution (comparable to current)
- Granularity (comparable to current)

(reasonable detector performance would deliver baseline physics goals: dive deeply into the 10~TeV realm.)

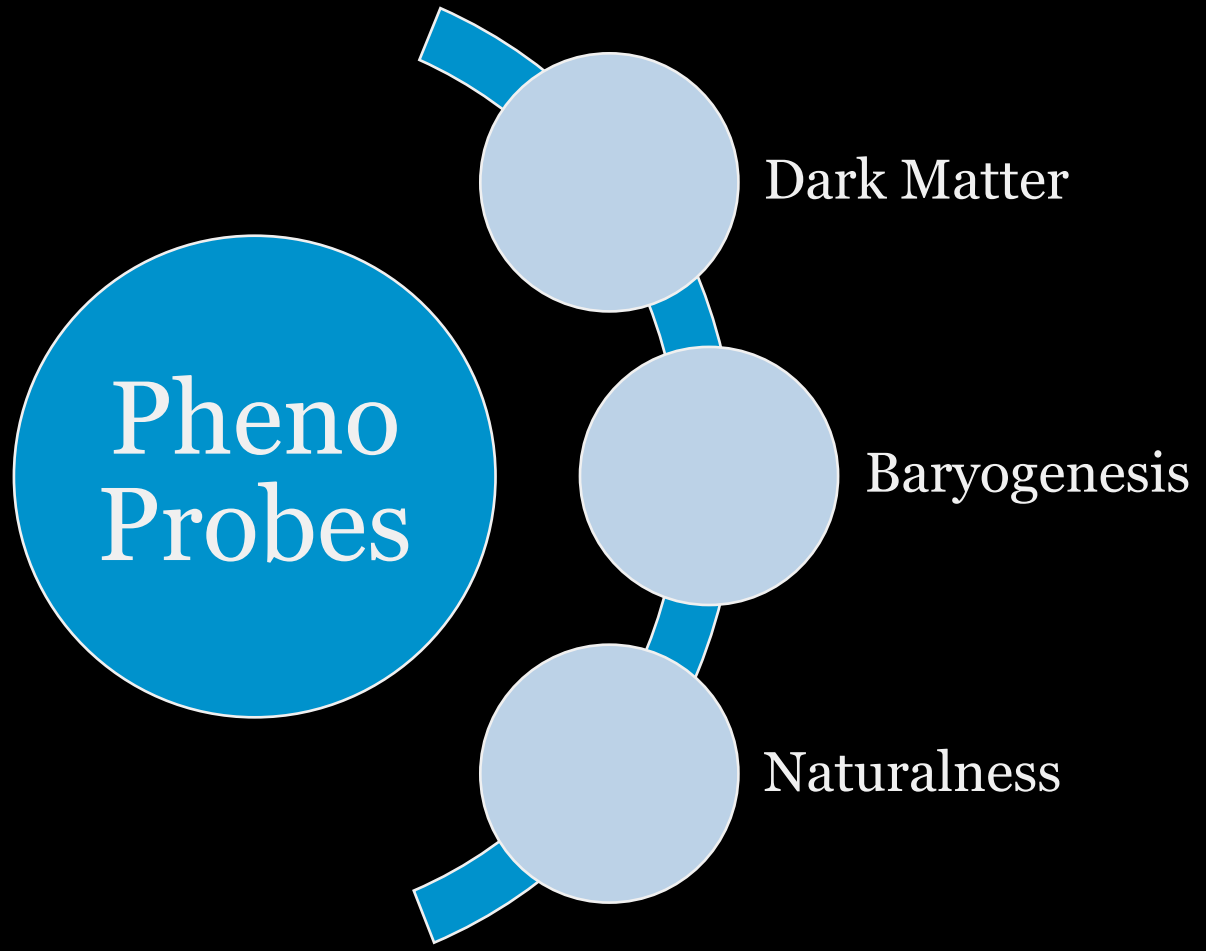
Demands? (randomly ordered)

- 0) great energy resolution for all SM precisions;
- forward muon;
- additional long-lived particles trigger;
- dark showers;
- triggerless data possible? At least a triggerless readout?
- disappearting track (low threshold and low bkg);
- good missing energy measurements?
- anomaly detection (lepton collider environment make it stand out more sharply, let's use the clean data!)
- precision timing
- On beam: high energy & high Lumi (also low energy s-channel with low beam energy spread).

The Dream Machine



Physics Driver



International muon collider collaboration:
https://simba3.web.cern.ch/simba3/SelfSubscription.aspx?groupName=MUONCOLLIDERDETECTOR-PHYSICS
Muon Collider Forum: SNOWMASS-MUON-COLLIDER-FORUM@FNAL.GOV at https://snowmass21.org/energy/start#communications.

Thank you!