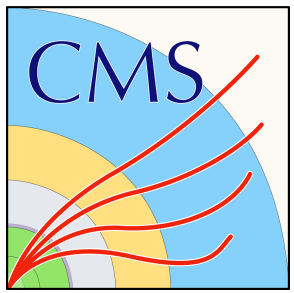
Large radius tracking and displaced vertex searches at the LHC

LHCP 2021 (June 7 – 12, 2021)

Carlos Vázquez Sierra
on behalf of LHCb, ATLAS and CMS collaborations

European Organization for Nuclear Research (CERN)

June 7, 2021



Overview

LRT and displaced vertices (DVs) $\rightarrow$ **long-lived particles (LLPs).**
Displaced and delayed signatures not using DVs $\rightarrow$ **see Rachel's talk.**

ATLAS latest results (summary plot in backup):

- Higgs from ZH^0 and decaying into LLPs **[ATLAS-CONF-2021-005]** $\rightarrow$ **this talk.**
- LLPs into displaced hadronic jets **[PRD (2020) 052013]**

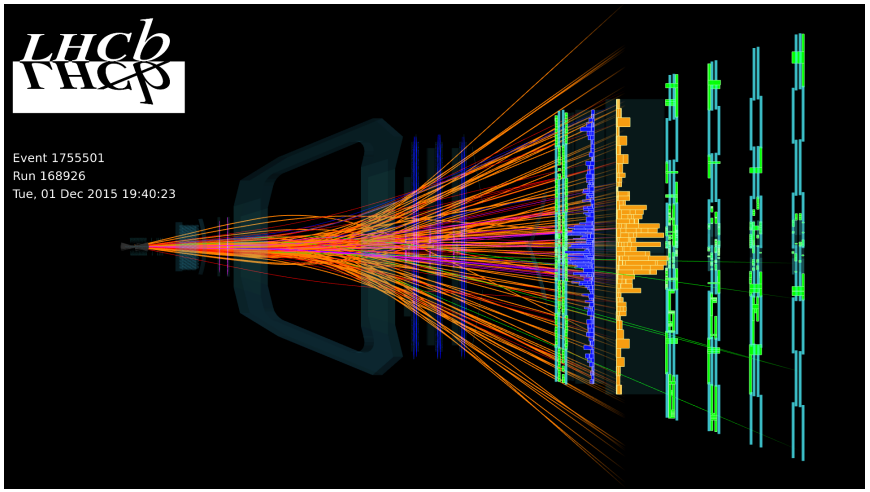
CMS latest results (summary plot in backup):

- Higgs from ZH^0 and decaying into LLPs **[CMS-PAS-EXO-20-033]** $\rightarrow$ **this talk.**
- LLPs decaying into $\mu^+\mu^-$ **[CMS-PAS-EXO-20-014]** $\rightarrow$ **this talk.**
- LLPs into displaced jets **[CMS-EXO-19-021]**
- LLPs into displaced hadronic jets **[CMS-EXO-19-013]**

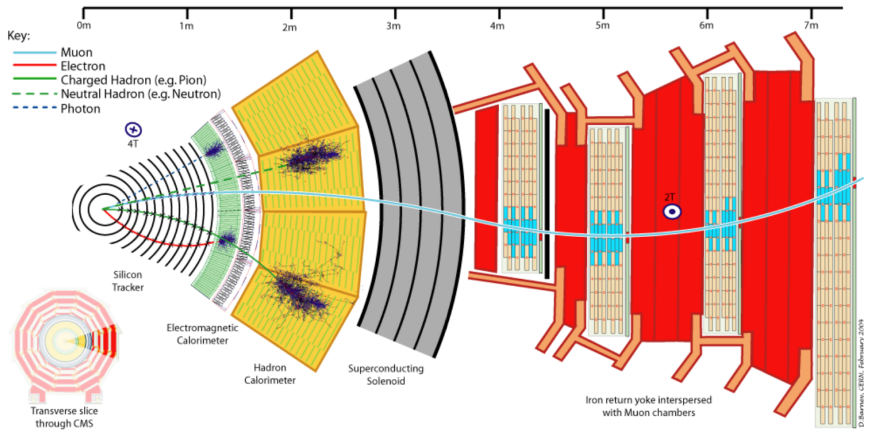
LHCb latest results:

- LLPs decaying into $e^+\mu^-\nu$ **[EPJC (2021) 81 261]** $\rightarrow$ **this talk.**
- HNLs from W boson decays **[EPJC (2021) 81 248]** $\rightarrow$ **see Matthias' talk.**
- Dark photons into $\mu^+\mu^-$ **[PRL (2020) 124 041801] [JHEP (2020) 10 156]** $\rightarrow$ **see Fede's talk.**

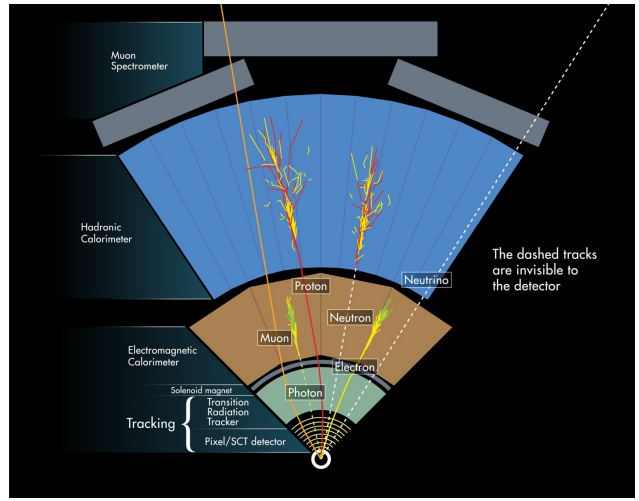
Complementarity is the key



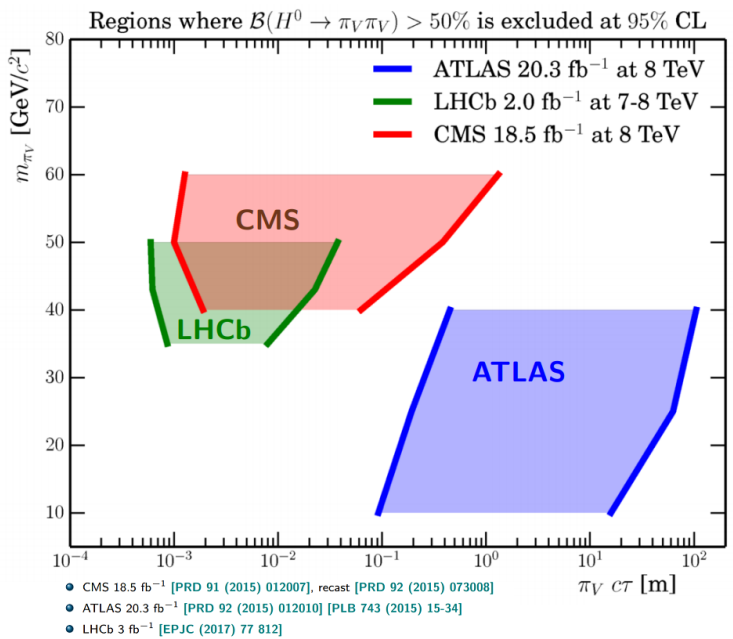
LHCb trigger and reconstruction
[JINST 14 (2019) P04013] [IJMP A30 (2015) 1530022]

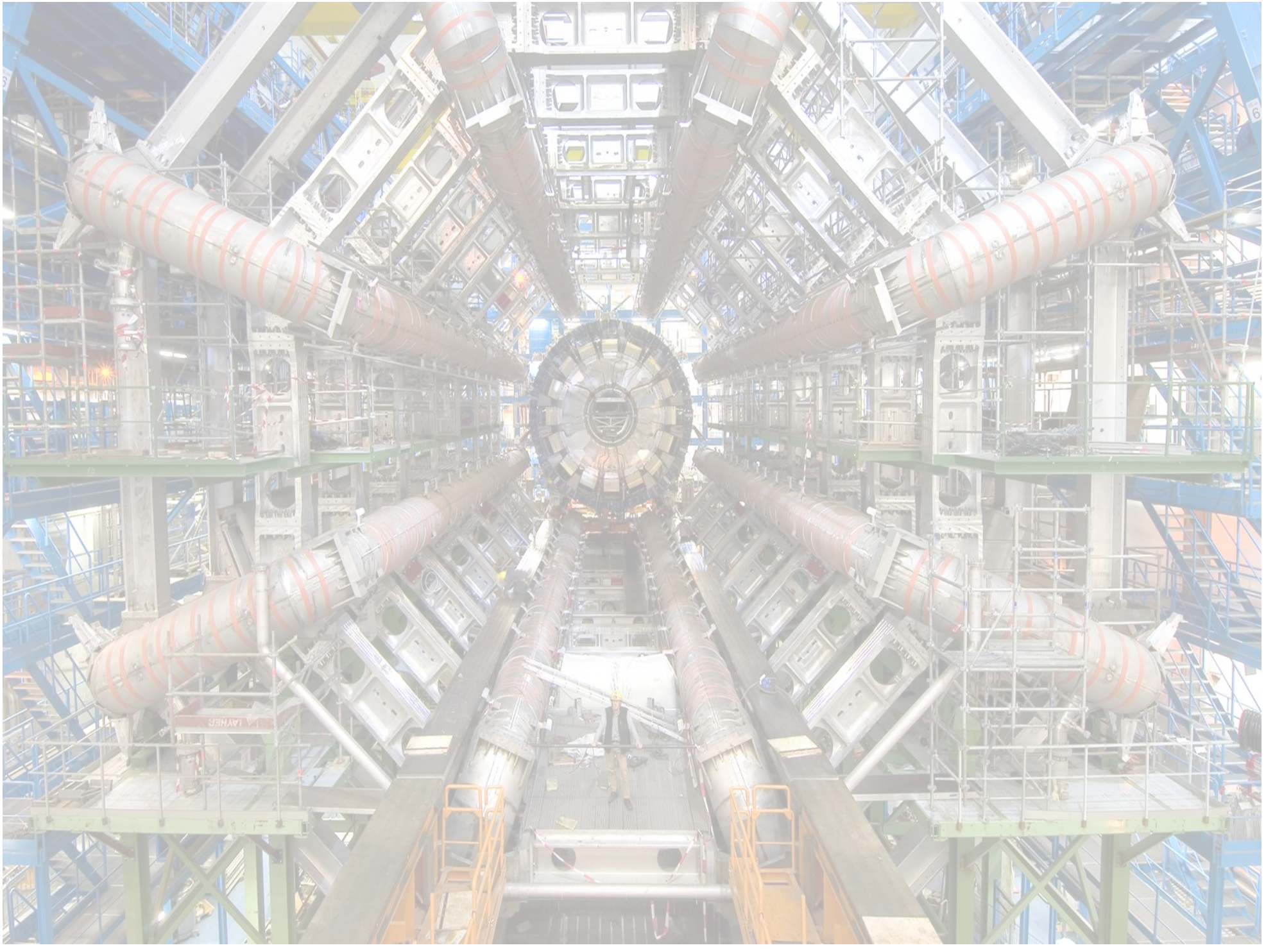


CMS displaced tagging algorithm
[CMS-PAS-EXO-19-011]



ATLAS LRT and vertexing algorithms
[ATL-PHYS-PUB-2017-014] [ATL-PHYS-PUB-2019-013]

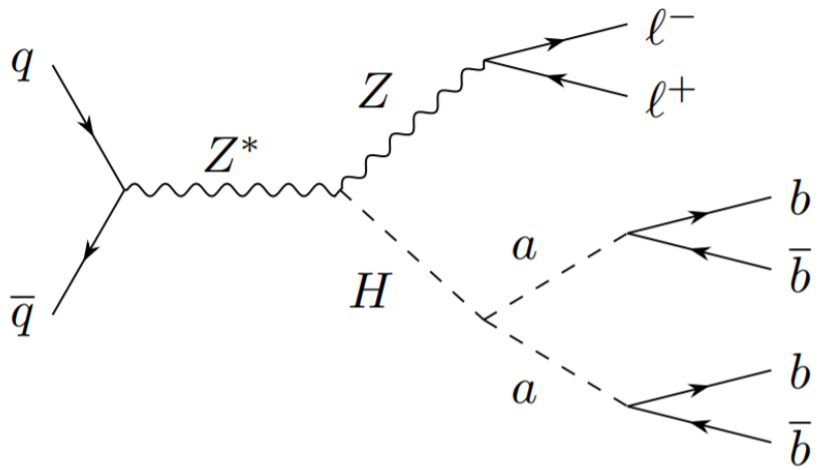




Higgs from ZH^0 and decaying into LLPs [ATLAS-CONF-2021-005]

Introduction:

- Search for an exotic decay of a Higgs boson, produced in association with a Z^0 boson.
- Leptons from decays of the Z^0 boson are used to trigger this signature.
- The Higgs boson decays into two generic scalars a, that decay into $b\bar{b}$ pairs each:



- ATLAS Run 2 (2015 – 2018) dataset (139 fb^{-1} at 13 TeV).
- Trigger on leptons from Z^0 with the lowest unprescaled single-lepton trigger,
- Require at least two DV reconstructed using tracks from inner detectors.
- Mass and $c\tau_a$ of the generic scalar a as free parameters, with $2 < c\tau_a < 200$ mm.

Higgs from ZH^0 and decaying into LLPs [ATLAS-CONF-2021-005]

Reconstruction and selection:

- **Signal samples** simulated for various $m(a)$ and $c\tau_a$ values.
- **Background sample** of Z+jet simulated events.
- LRT algorithm to reconstruct LLPs $\rightarrow$ looser requirements than standard reconstruction.
- Suppress backgrounds using vertex-related and track-related quantities.
- Distinguish between **displaced** and prompt jets using info from tracks and calo deposits.

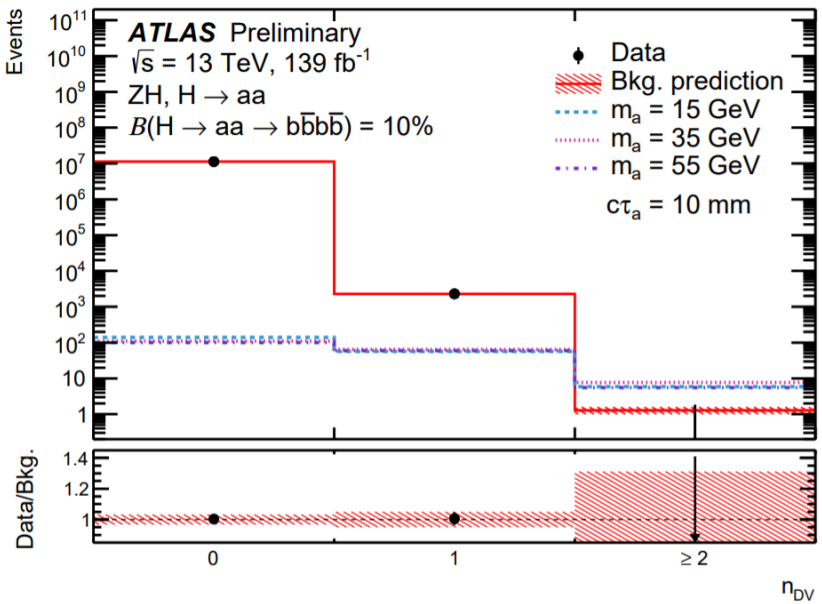
Background estimation:

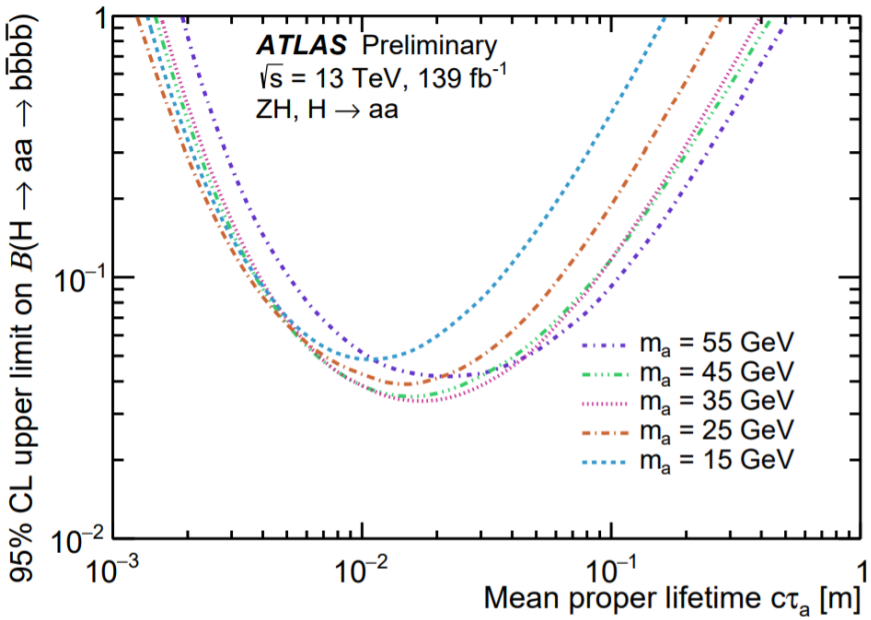
1. Signal region (SR) (DVs $\geq$2) and control region (CR) (DVs $<$ 2) are defined.
2. $\mathcal{P}$ for a jet to be matched to a DV computed in CR.
3. $\mathcal{P}$ for an event to contain n DVs among the 4 jets computed with binomial distributions.
4. Compute $\mathcal{P}$ for **that** event to fall in the SR from complements 0 DV and 1 DV $\mathcal{P}$.
5. Validate the procedure using a γ+jet sample from single and di-photon triggers.
6. Weight the selected data events using these probabilities.

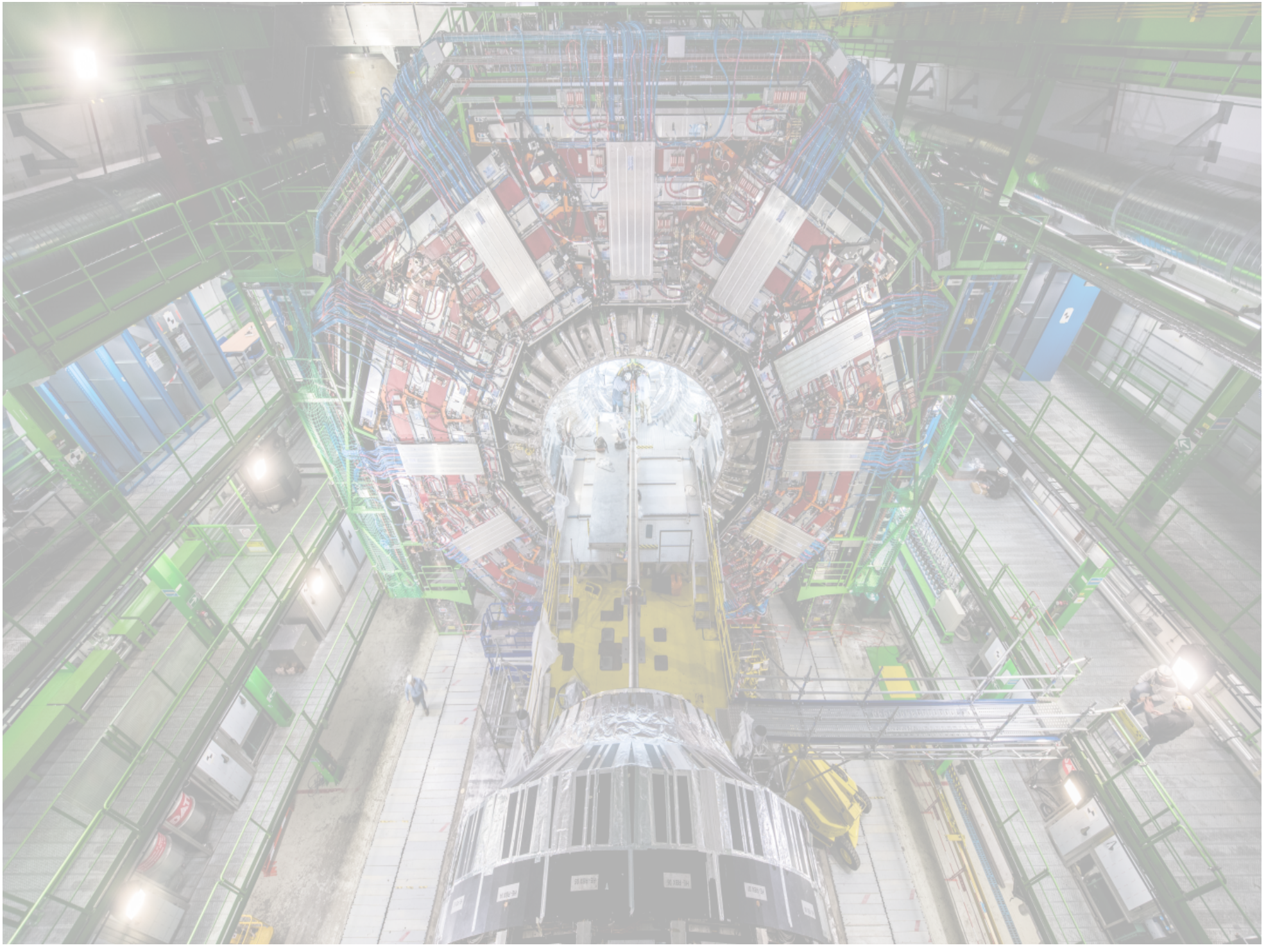
Higgs from ZH^0 and decaying into LLPs [ATLAS-CONF-2021-005]

Results:

- Dominated by statistical uncertainty. Systematics not dependent of $m(a)$ and $c\tau_a$.
- Systematics dominated from non-standard reconstruction method.
- Compare predicted background events with observed data in SR – **no excess observed**.
- Stringent UL at 95% C.L. set on $H^0 \to aa \to b\bar{b}b\bar{b}$ branching fraction.
- Exclusion down to almost 1% in branching fraction for $m(a)$ of 35 GeV and $c\tau_a \sim 1$ cm.



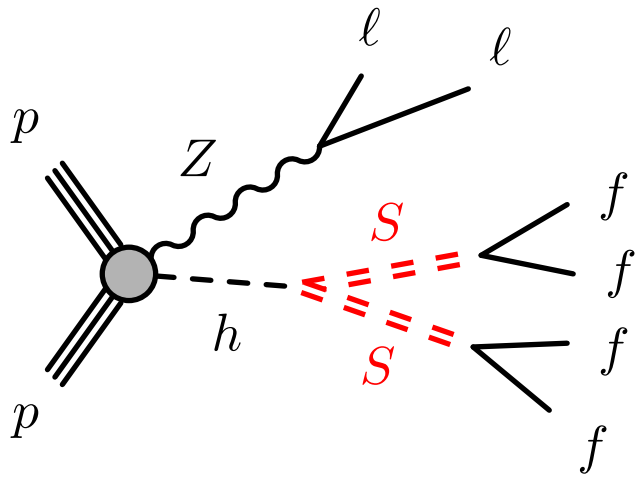




Higgs from ZH^0 and decaying into LLPs [CMS-PAS-EXO-20-033]

Introduction:

- Search for an exotic decay of a Higgs boson, produced in association with a Z^0 boson.
- Decays of the Z^0 boson into pairs of leptons are used to trigger this signature.
- The Higgs boson decays into two generic scalars S, that decay into two fermions each:



- CMS Run 2 (2016 – 2018) dataset (117 fb^{-1} at 13 TeV).
- Leptonic triggers selecting opposite-sign or different-flavour di-leptons (Z^0 decay),
- Simulated signal samples for this signature, where S decays into b or d quarks.

Higgs from ZH^0 and decaying into LLPs [CMS-PAS-EXO-20-033]

Reconstruction and selection:

- Require the presence of opposite-sign **lepton pair** from Z^0 decays in the event.
- Tag **displaced jets** using variables defined from track-related and p_T-related jet quantities.
- Drell-Yan, $t\bar{t}$ and single top quark as **dominant** backgrounds, obtained from simulation.
- Data-driven methods to estimate sub-dominant contributions from other SM backgrounds.

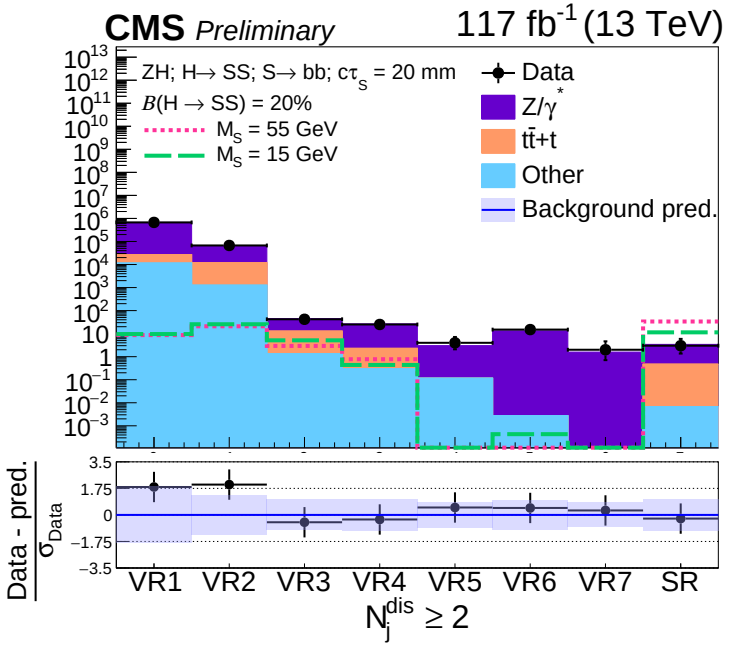
Background estimation procedure:

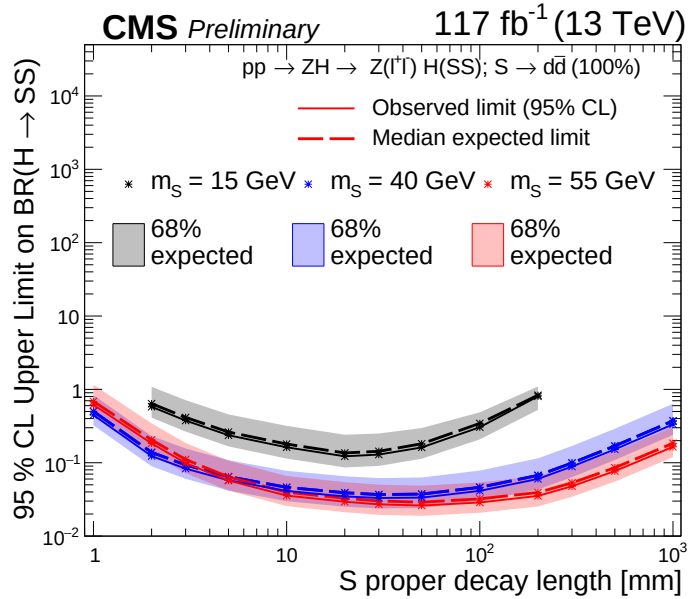
- Define bins on **number of displaced jets** (Nj) in the event ($Nj \geq 2$ for signal).
- Two **control samples** from simulation and a **validation sample** from same-sign data.
- *Transfer factors* in bins of Nj as the ratio of yields between signal and control samples.
- Estimate Nj in signal from a ML fit to control samples using transfer factors.

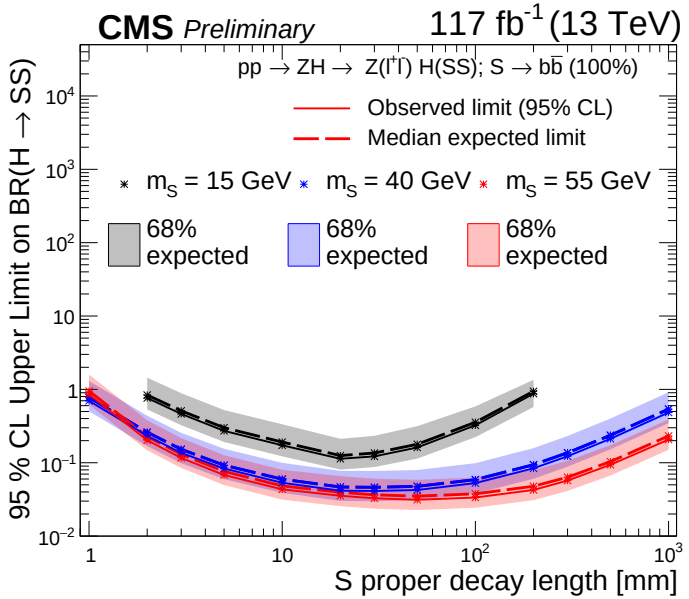
Higgs from ZH^0 and decaying into LLPs [CMS-PAS-EXO-20-033]

Results:

- Systematics dominated by corrections to jet tagging and transfer factors.
- Compare background estimation results with observed data – **no excess is found.**
- UL at 95% C.L. set for $H^0 \rightarrow SS$ branching fraction, for both $S \rightarrow d\bar{d}$ and $S \rightarrow b\bar{b}$.
- Stringent limits for $S \rightarrow b\bar{b}$ with $m(S)$ around 15 GeV and decay lengths of 2–30 mm.



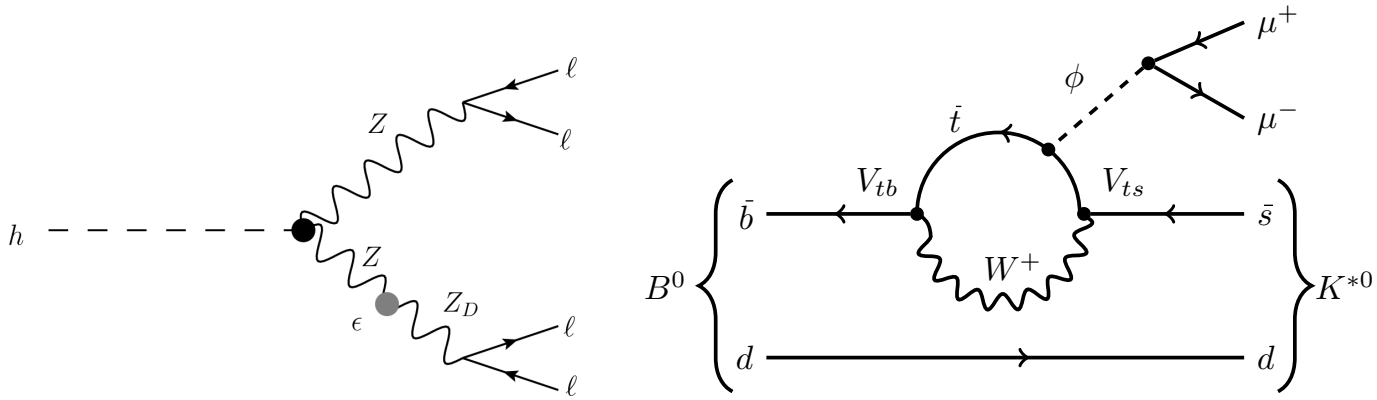




LLPs decaying into $\mu^+\mu^-$ [CMS-PAS-EXO-20-014]

Introduction:

- Search for a narrow $\mu^+\mu^-$ resonance produced either via:
  - a Higgs portal to a dark photon, $H^0 \to Z_D Z_D \to 4\mu$,
  - or a scalar resonance from a B-hadron decay, $B \to X\phi(\to\mu^+\mu^-)$.



- CMS Run 2 (2017 + 2018) dataset (101 fb^{-1} at 13 TeV).
- Look for a narrow peak on top of $\mu^+\mu^-$ continuum:
  - Explore $0.2 < m(\mu^+\mu^-) < 50$ GeV and a transverse displacement (l_{xy}) up to 11 cm.
  - Dimuon *scouting* triggers for $m(\mu^+\mu^-) < 45$ GeV $\to$ low p_T threshold, prescaled.
  - Standard triggers for higher mases $\to$ higher p_T thresholds.

LLPs decaying into $\mu^+\mu^-$ [CMS-PAS-EXO-20-014]

Reconstruction and selection:

- Signal samples simulated for $H^0 \to Z_D Z_D \to 4\mu$ and $B \to X\phi(\to \mu^+\mu^-)$ models.
- Data required to have at least one $\mu^+\mu^-$ with an associated displaced vertex (DV).
- Good vertex spatial resolution and a good quality fitted tracks are required.
- Backgrounds removed using angular-based and track-based quantities of both muons.

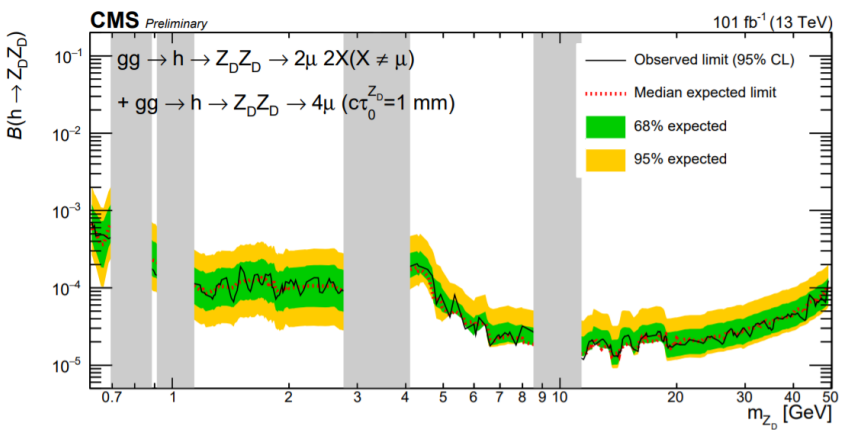
Mass parametrisation:

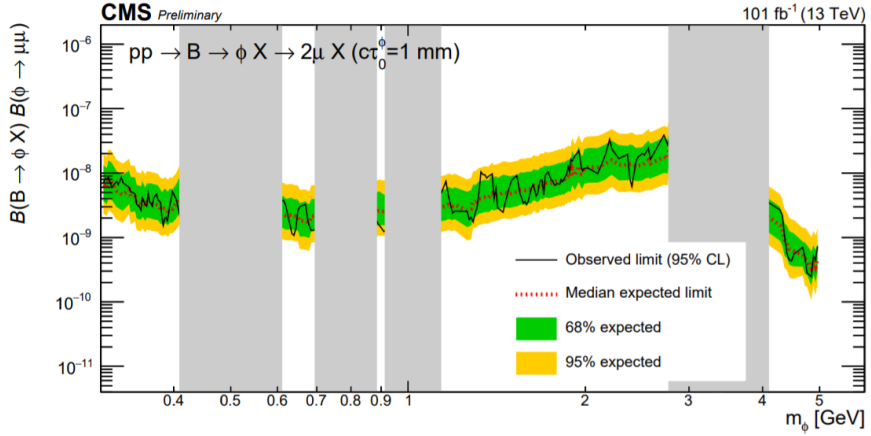
- Signal categorised in bins of isolation (3), displacement (4) and di-muon p_T (2).
- Mass window requirements $\to$ veto all SM $\mu^+\mu^-$ and h^+h^- known resonances.
- Signal modelled with a Gaussian function + double Crystal Ball.
- SM background modelled with Bernstein polynomials + exponential functions.

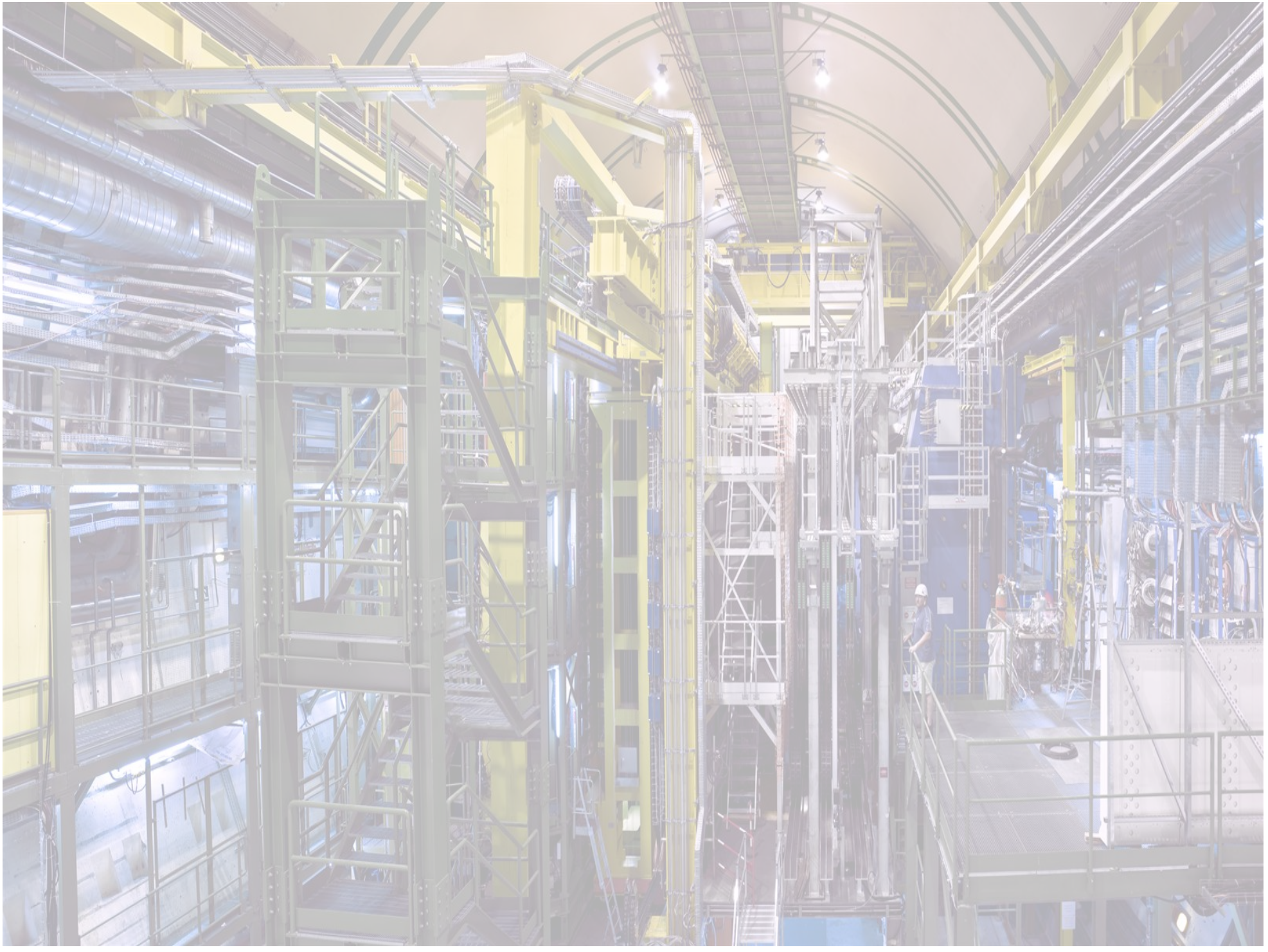
LLPs decaying into $\mu^+\mu^-$ [CMS-PAS-EXO-20-014]

Results:

- Systematics dominated by trigger efficiencies, dependence with mass and lifetimes.
- Simultaneous maximum likelihoood (ML) fit to di-muon mass in all bins.
- Upper limits at 95% C.L. set to $B \to X\phi(\to\mu^+\mu^-)$ and $H^0 \to Z_D Z_D$ branching fractions.
- No excess observed $\to$ **most stringent limits to date on these BSM models.**



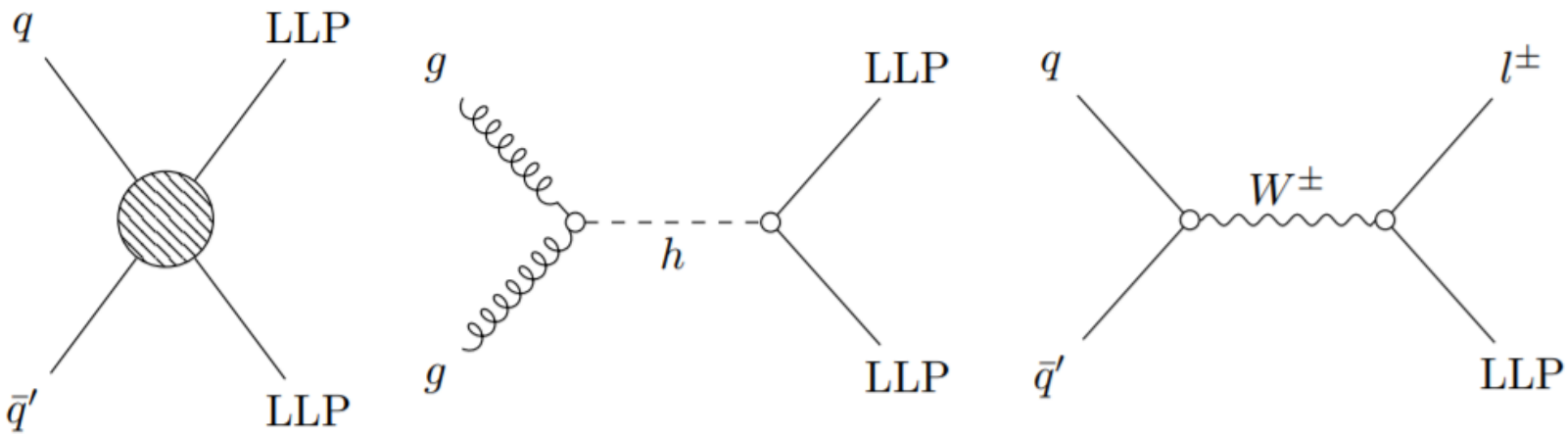




LLPs decaying into $e^+\mu^-\nu$ [EPJC (2021) 81 261]

Introduction:

- Search for a long-lived particle decaying into $e^+\mu^-\nu$, and produced:
  - via direct pair production (DPP) from pp collisions,
  - from an exotic Higgs decay (HIG), produced in pairs,
  - or from a charged current process (CC).



- LHCb Run 2 (2016 – 2018) dataset (5.38 fb^{-1} at 13 TeV).
- Explore masses between and 7 and 50 GeV and lifetimes between 2 and 50 ps.
- Leptonic triggers with low p_T requirements $\rightarrow$ allow to access small LLP masses.

LLPs decaying into $e^+\mu^-\nu$ [EPJC (2021) 81 261]

Simulation:

- Signal (DPP and HIG) using MSSM RPV model – LLP as $\tilde{\chi}_0^1$ light neutralino,
- Signal (CC) using LRSM model – LLP as a HNL from on-shell W boson decay,
- Several **signal samples** per model for different LLP mass and lifetimes.
- **Background sample** simulated for QCD $b\bar{b}$ events.

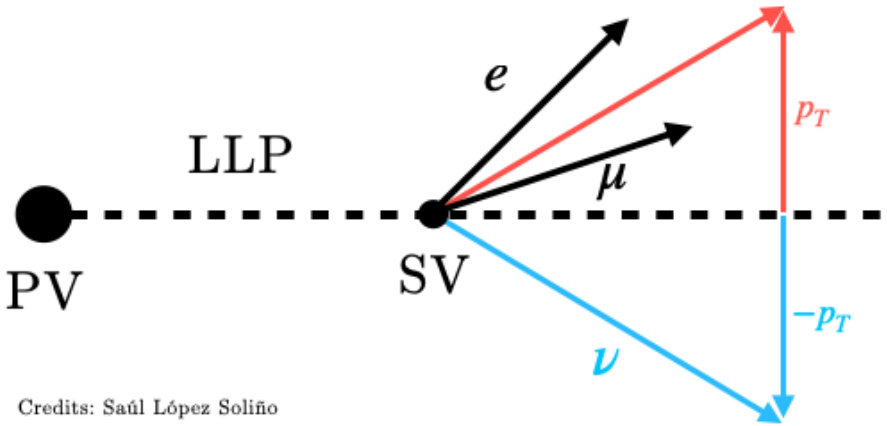
Selection:

- Require good quality DVs with minimum displacement and kinematic requirements.
- BDT with uniform boosting (response independent in mass) to purify signal sample.
- Two QCD categories: $e\mu$ from same jet ($\Delta R < 1$) or from different jets ($\Delta R \geq 1$).
- Leptons isolated to suppress QCD background – isolation optimised with same-sign data.
- After full selection $\rightarrow$ 60k $b\bar{b} \rightarrow e\mu X$ events (consistent with observed yield).

LLPs decaying into $e^+\mu^-\nu$ [EPJC (2021) 81 261]

Corrected mass approach:

- LHCb is a non-hermetic spectrometer $\rightarrow$ we **can not do invisibles.**
- However, we can compute a proxy to X+invisible invariant mass $\rightarrow$ **corrected mass**.
- **Required** to have only one **massless** invisible in the final state (ν).
- **Required** to know the **direction of flight** of the parent particle.



1. Assume LLP origin vertex approximately be the same as the *pp* collision.
2. Obtain a (pseudo) decay vertex using the di-lepton systems.
3. Project the di-lepton system momenta to the LLP direction of flight.

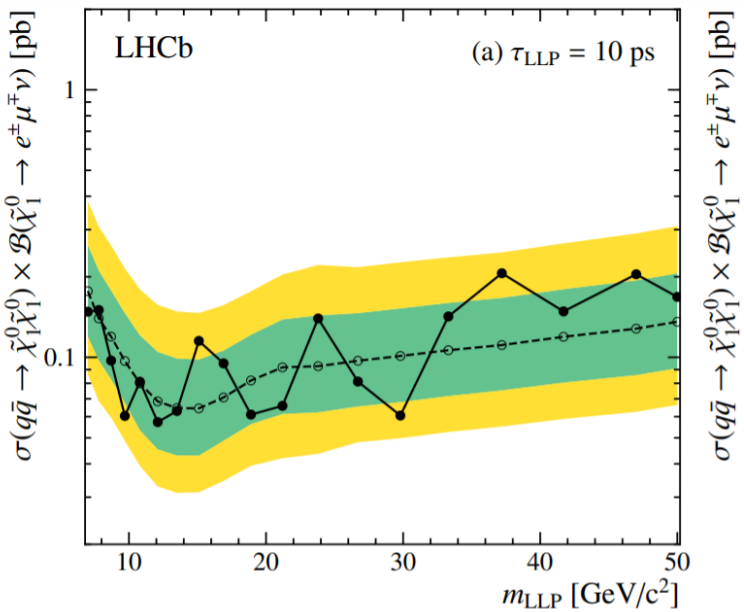
$$m_{\text{corr}} = \sqrt{m(e\mu)^2 + p(e\mu)^2 \sin^2\theta} + p(e\mu)\sin\theta$$

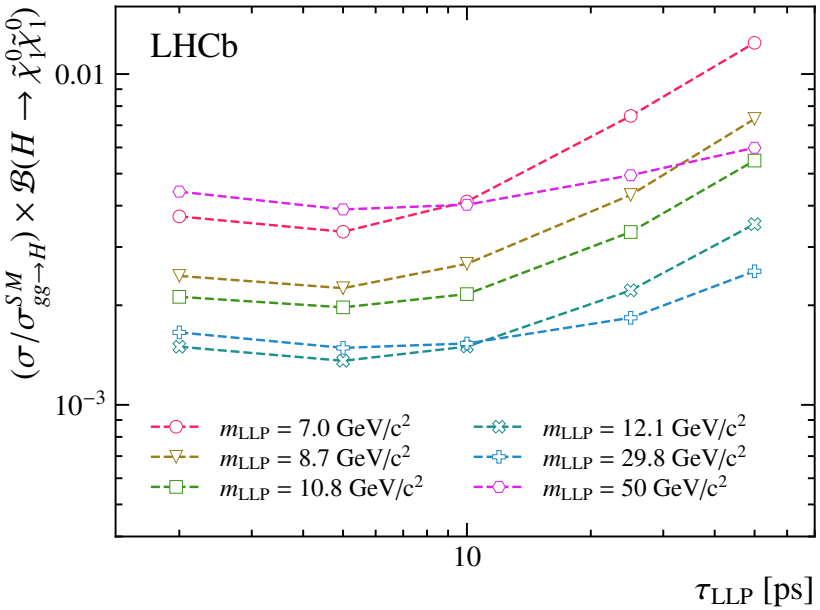
Corrected mass as a good proxy to real mass $\rightarrow$ discriminating variable.

LLPs decaying into $e^+\mu^-\nu$ [EPJC (2021) 81 261]

Results:

- Simultaneous ML fit to m_{corr} and LLP flight distance in two BDT bins.
- Backgrounds: Gaussian + Crystal Ball ($\Delta R < 1$) and Johnson SU ($\Delta R \geq 1$).
- Signal: modified Gaussian (left tail exponential, right tail power law) + Gaussian.
- Systematics dominated by choice of signal models.
- UL at 95% C.L. on σB per model – **no excess found**.
- Best UL for DPP with lifetimes below 10 ps and masses above 10 GeV → order of 0.1 pb.





Conclusions

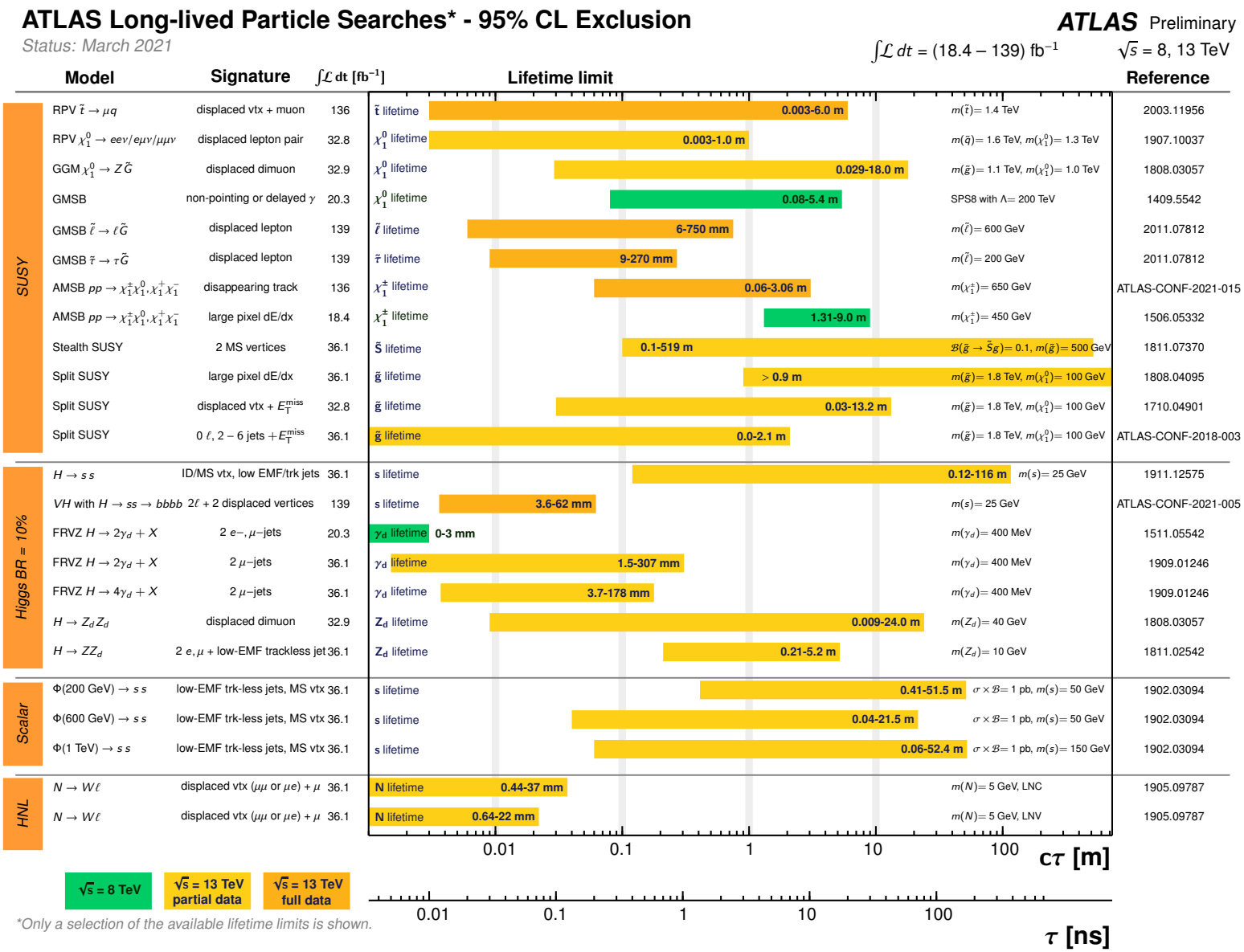
- New analyses from ATLAS (1), CMS (2) and LHCb (1) have been presented.
- Great results and encouraging prospects...
- ...but there is still a **large part of the parameter space to be explored!**
- Exploiting complementarity between the three experiments becomes **mandatory.**
- Vibrant LLP open community → **LLP9 workshop with more than 300 participants!**
- Review on LHCb capabilities on *Stealth* physics → **[arXiv:2015.12668]** (26/May!)
- **Bright future ahead and many new results to come → stay tuned!**

Thanks for your attention!

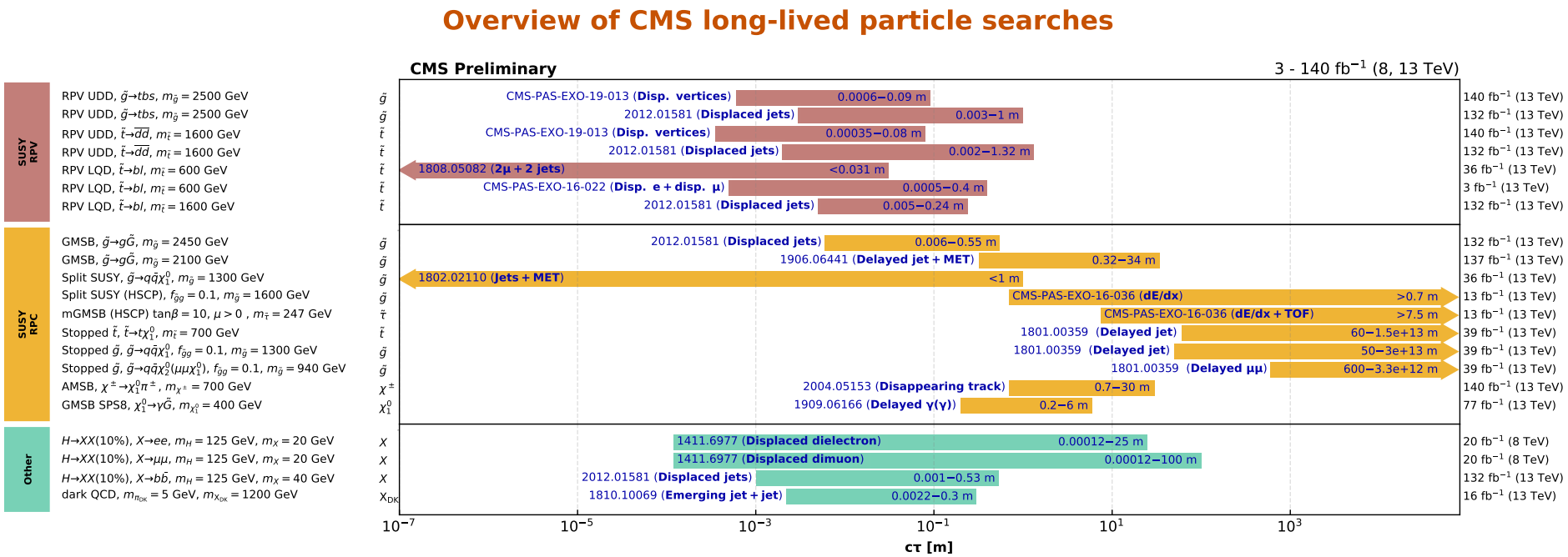
LIVE LONG
AND PROSPER
Credit: David Curtin

Backup

ATLAS summary plot



CMS summary plot



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

Selecting and reconstrucing displaced objects

ATLAS LRT and vertexing algorithms: [ATL-PHYS-PUB-2017-014]

- Complement standard reco algorithm (optimised for finding tracks pointing back to IP).
- Designed to reconstruct tracks originating in the inner detector far from the IP.
- Optimised for Run 3 $\rightarrow$ to be included in the standard reco! [ATL-PHYS-PUB-2021-012]
- Secondary vertexing algo (tracks from inner detectors) is key [ATL-PHYS-PUB-2019-013]

CMS displaced tagging algorithm: [CMS-PAS-EXO-19-011]

- Deep Neural Network (DNN) inspired by the **DeepJet** approach.
- Trained using MC based on GMSB and RPV models, with $c\tau_0$ as an external parameter.
- Optimal performance over a large jet p range.

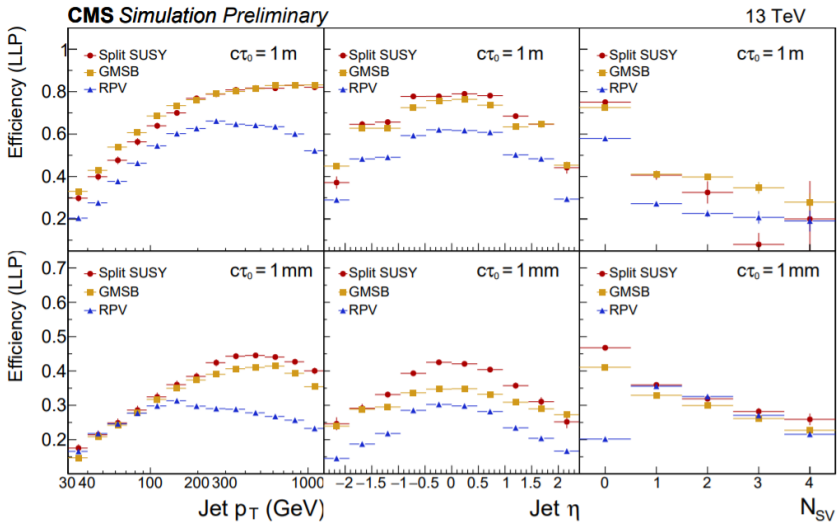
LHCb trigger and reconstruction: [JINST 14 (2019) P04013] [IJMP A30 (2015) 1530022]

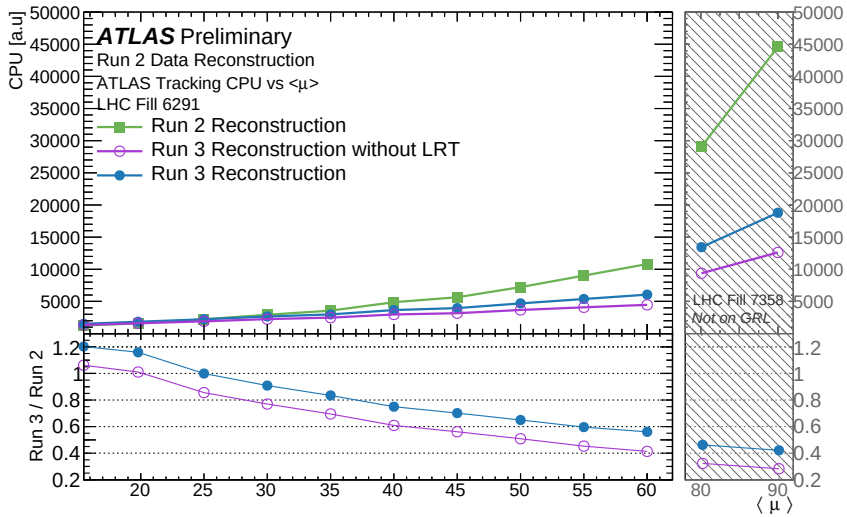
- LHCb as a natural low-mass LLP hunter $\rightarrow$ designed to study heavy flavour meson decays.
- Soft triggers and excellent vertex resolution (resolve B_s^0 meson oscillations).
- Excellent tracking capabilities and (low) mass resolutions $\rightarrow$ especially for *long tracks*.

Selecting and reconstrucing displaced objects

	Standard	Large radius
Maximum d_0 (mm)	10	300
Maximum z_0 (mm)	250	1500
Maximum $\|\eta\|$	2.7	5
Maximum shared silicon modules	1	2
Minimum unshared silicon hits	6	5
Minimum silicon hits	7	7
Seed extension	Combinatorial	Sequential

L0 trigger	E_T/p_T threshold			SPD threshold
	2015	2016	2017	
Hadron	> 3.6 GeV	> 3.7 GeV	> 3.46 GeV	< 450
Photon	> 2.7 GeV	> 2.78 GeV	> 2.47 GeV	< 450
Electron	> 2.7 GeV	> 2.4 GeV	> 2.11 GeV	< 450
Muon	> 2.8 GeV	> 1.8 GeV	> 1.35 GeV	< 450
Muon high p_T	> 6.0 GeV	> 6.0 GeV	> 6.0 GeV	none
Dimuon	> 1.69 GeV^2	> 2.25 GeV^2	> 1.69 GeV^2	< 900





Higgs from ZH^0 and decaying into LLPs [ATLAS-CONF-2021-005]

Simulation and backgrounds:

- Signal samples simulated for $15 < m(a) < 55$ GeV and $c\tau_a$ of 10, 100 and 1000 mm.
- Samples reweighted in $c\tau_a$ to cover intermediate points in the full lifetime range.
- Simulated sample of Z+jet as background component.
- DV with $\geq$2 tracks $\rightarrow$ suppress material interactions and SM LLPs decays.
- Combinatorial and QCD backgrounds components removed using vertex-related quantities.

Reconstruction:

- LRT algorithm to reconstruct LLPs $\rightarrow$ looser requirements than standard reconstruction.
- Exploit response from DL1 algorithm for jet b-tagging.
- DVs are reconstructed using tracks from standard and LRT reconstruction algorithms.
- Vertices are pruned of tracks loosely associated to the vertex, and then recomputed.

Higgs from ZH^0 and decaying into LLPs [ATLAS-CONF-2021-005]

Selection:

- Material veto and vertex preselection is finally applied to reject low-quality fake DVs.
- Distinguish between **displaced jets** and prompt jets:
  - *Normalised* sum of the p_T of all jet tracks associated to a DV $\rightarrow$ **very small values.**
  - Charged hadron fraction (CHF) using info from calo deposits $\rightarrow$ **very small values.**
- Signal region (SR) and control region (CR) are defined from selected events:
  - SR events are required to have at least two DVs in the event.
  - CR events are required to have less than two DVs in the event.

Background estimation:

1. $\mathcal{P}$ for a jet to be matched to a DV computed in CR.
2. $\mathcal{P}$ for an event to contain n DVs among the 4 jets computed with binomial distributions.
3. Compute $\mathcal{P}$ for **that** event to fall in the SR from complements 0 DV and 1 DV $\mathcal{P}$.
4. Validate the procedure using a γ+jet sample from single and di-photon triggers.
5. Weight the selected data events using these probabilities.

LLPs decaying into $\mu^+\mu^-$ [CMS-PAS-EXO-20-014]

Simulation:

- Signal simulated to cover the mass and displacement ranges of interest.
- $H^0 \to Z_D Z_D \to 4\mu$, where either one or both dark photons decay into $\mu^+\mu^-$ pairs,
- $B \to X\phi(\to \mu^+\mu^-)$, where all types of B-hadrons are allowed to decay into a ϕ scalar,
- Only masses with $\phi < 5$ GeV can be probed due to phase-space constraints.

Selection:

- Data required to have at least one $\mu^+\mu^-$ with an associated displaced vertex (DV).
- Good vertex spatial resolution and a good quality fitted tracks are required.
- Two options considered: one pair and two pairs of muons $\to$ looser requirements for 4μ.
- Use track-based quantities (related to transverse IP) to select candidate DVs.
- Suppress cosmics, and μ from pileup and back-to-back QCD di-jets by requiring:
  - Collinearity between $\mu^+\mu^+$ and DV direction to primary vertex,
  - Small opening angle between both μ in the dimuon system.
- Number of hits in pixel tracker and DV relative position $\to$ deal with material interactions.
- SM background parametrized from data using 5σ sidebands around signal mass hypotheses.
- **Selection efficiency on signal** between 55% and 75% (depending on model details).

LLPs decaying into $\mu^+\mu^-$ [CMS-PAS-EXO-20-014]

Mass parametrisation:

- Signal categorised in bins of isolation (3), displacement (4) and di-muon p_T (2).
- Mass window requirements $\rightarrow$ veto all SM $\mu^+\mu^-$ and h^+h^- known resonances.
- Signal modelled with a Gaussian function + double Crystal Ball.
- SM background modelled with Bernstein polynomials + exponential functions.

Higgs from ZH^0 and decaying into LLPs [CMS-PAS-EXO-20-033]

Selection:

- Require the presence of opposite-sign **lepton pair** in the event:
  - Require the **lepton pair** to satify $70 < m(l^+l^-) < 100$ GeV and $p_T > 100$ GeV.
  - Require zero additional leptons with p_T greater than 15 GeV and at least one jet.
- **Three variables** are defined to **tag displaced jets**:
  - Median $\log_{10}$ of all track impact point significances $\rightarrow$ **large values.**
  - Angle between jet axis and direction between PV and jet vertex $\rightarrow$ **large angles.**
  - *Normalised* sum of the p_T of all jet tracks associated to a DV $\rightarrow$ **values near zero.**

Background estimation procedure:

- Drell-Yan, $t\bar{t}$ and single top quark as **dominant** backgrounds, obtained from simulation.
- Data-driven methods to estimate sub-dominant contributions from other SM backgrounds.
- Define bins on **number of displaced jets** (Nj) in the event ($Nj \geq 2$ for signal).
- Two **control samples** and a **validation sample** are defined:
  - Z^0 control sample: di-leptons with $10 < p_T < 100$ GeV,
  - $t\bar{t}$ and single top control samples: di-leptons of different flavours with p_T >1 GeV.
  - Multi-jet validation sample: inverted Nj requirements ($Nj < 2$).
- *Transfer factors* in bins of Nj as the ratio of yields between signal and control samples.
- Estimate Nj in signal from a ML fit to control samples using transfer factors.

LLPs decaying into $e^+\mu^-\nu$ [EPJC (2021) 81 261]

Simulation:

- Signal (DPP and HIG) using MSSM RPV model – LLP as $\tilde{\chi}_0^1$ light neutralino,
- Signal (CC) using LRSM model – LLP as a HNL from on-shell W boson decay,
- 35 signal samples per model – LLP m and τ from 7 to 50 GeV and from 2 to 50 ps.
- QCD $b\bar{b}$ sample – at least one μ with $p_T > 10$ GeV in acceptance, passing μ triggers.

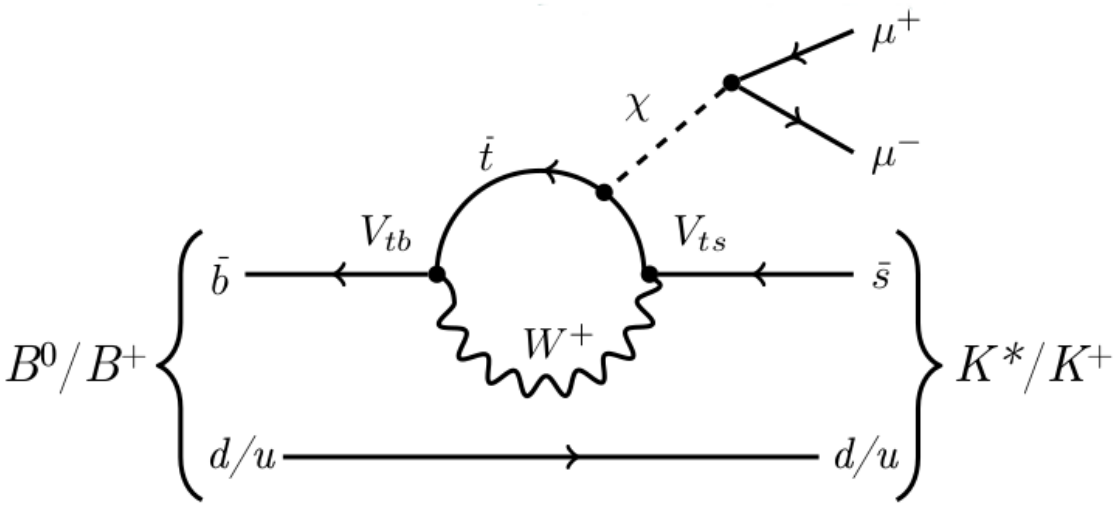
LLPs decaying into $e^+\mu^-\nu$ [EPJC (2021) 81 261]

Selection and backgrounds:

- Good quality DV using $e\mu$ tracks within VELO region.
- Require vertex displacement from any PV and minimum flight distance cut.
- Threshold p_T requirements and correction from electron bremsstrahlung.
- QCD background suppression thanks to cone isolation of both leptons.
- Cone isolation is optimised by using same-sign di-lepton data.
- Good particle identification from muon stations and calorimeters.
- BDT with uniform boosting (response independent in mass) to purify signal sample:
  - Simulated signal samples and same-sign di-lepton data as inputs.
  - Di-lepton vertex and lepton track-related as discriminating variables.
  - Isolations and energy deposits in calorimeters also considered.
- Two background components distinguished in QCD $b\bar{b}$ simulation:
  - Leptons belonging to the same heavy-flavour jets (ΔR separation below 1),
  - and leptons belonging to two different HF jets (ΔR separation above 1).
- After full selection $\rightarrow$ 60k $b\bar{b}\rightarrow e\mu X$ events (consistent with observed yield).

Hidden-sector bosons in $B \to K^{(*)}\chi(\mu^+\mu^-)$

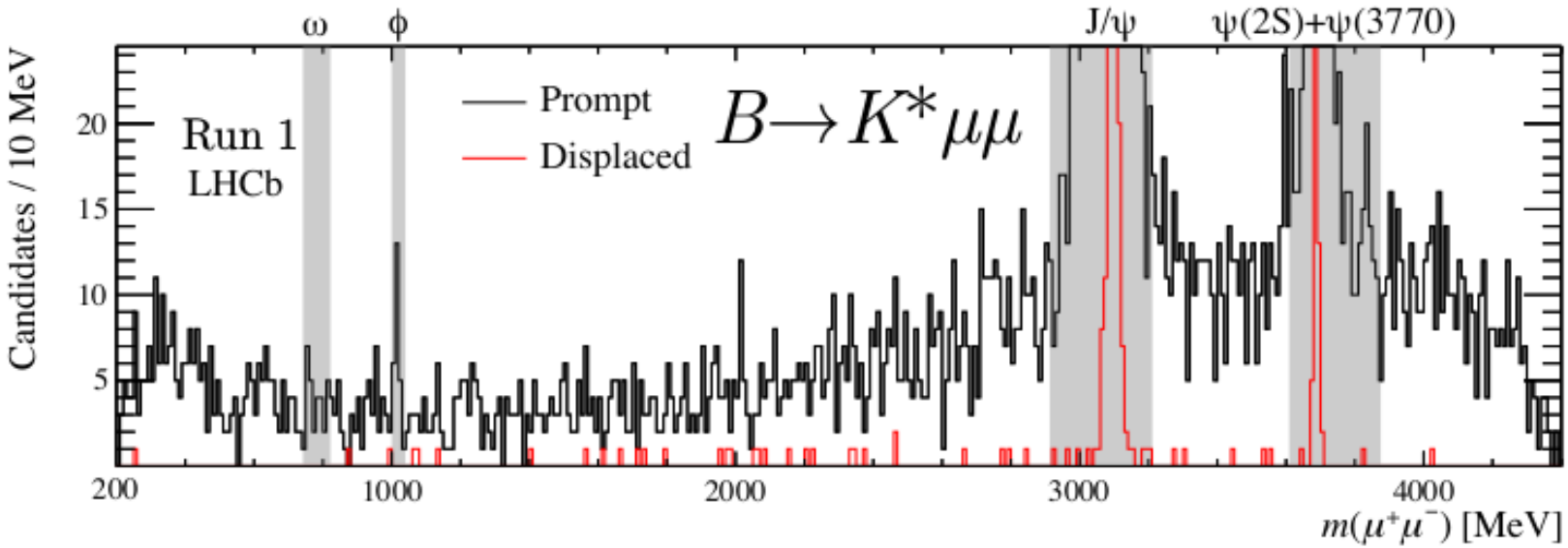
- $\mathrm{B}^0 \to K^{*0}\chi$ **[PRL 115 (2015) 161802]** / $\mathrm{B}^+ \to K^+\chi$ **[PRD 95 (2017) 071101 (R)]**
- Search for hidden-sector bosons $\chi \to \mu^+\mu^-$ in $b \to s$ penguin decays:
  - Axial-vector portal (χ as axion) **[LNP 741 (2008) 3]**
  - **Scalar** (Higgs) portal (χ as inflaton) **[JHEP 05 (2010) 10]**



- First dedicated search ($K^{*0}\chi$) over such a large mass range:
  - **Pro:** $K^{*0} \to K^+\pi^-$ vertex leads to better $\tau(\chi)$ resolution and less background.
  - **Con:** $\mathrm{B}^0 \to K^{*0}\chi$ has smaller branching fraction than the $\mathrm{B}^+ \to K^+\chi$ mode.
- Allow for prompt and **detached** di-muon candidates – up to 1000 ps ($\sim$ 30 cm).

Hidden-sector bosons in $B \to K^{(*)}\chi(\mu^+\mu^-)$

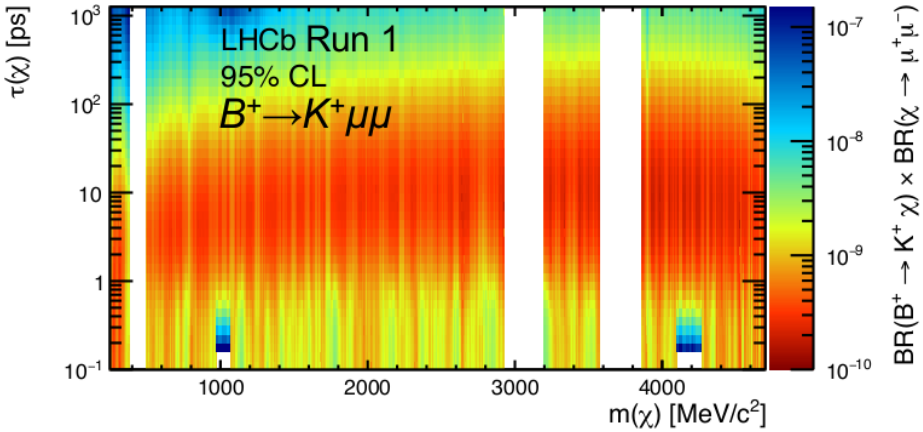
- Full LHCb Run I dataset (3 fb^{-1}) used for both searches.
- Look for a narrow di-muon peak (mass resolution between 2 and 9 MeV/c^2).
- Exclude narrow QCD resonances - mass distribution: **[PRL 115 (2015) 161802]**

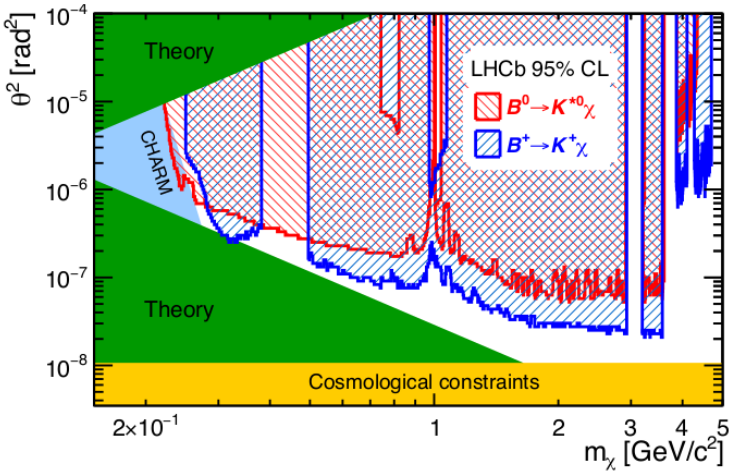


- MVA selection almost independent of χ mass and decay time (uBoost).

Hidden-sector bosons in $B \to K^{(*)}\chi(\mu^+\mu^-)$

- BR normalised to $\mathcal{B}(B^+ \to K^+ J/\psi)$ ($\sim 10^{-4}$) or $\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)$ ($\sim 10^{-7}$).
- Constraints on $\tau(\chi)$ between 0.1 and 1000 ps (left), **[PRD 95 (2017) 071101 (R)]**
- Constraints on mixing angle θ^2 between the Higgs and χ in the inflaton model (right):





- **No evidence for signal observed.**
- **Large fraction of allowed inflaton parameter space ruled out.**