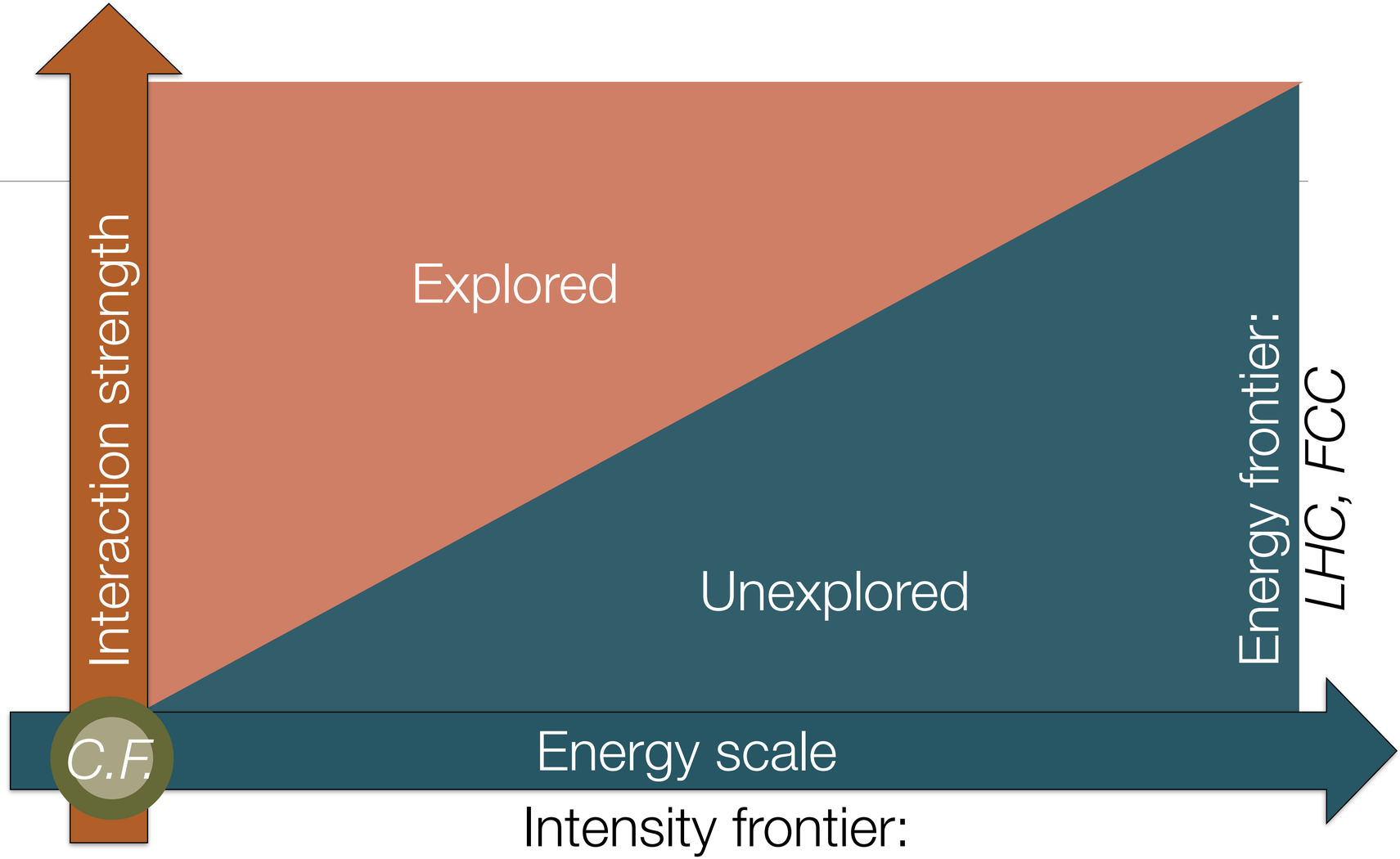
Long-lived particles searches at LHCb

Federico Leo Redi
on behalf of the LHCb collaboration

SUSY 2021
23-28 August 2021

Introduction / 1

- Is the universe “natural”?
- Is the SM an effective field theory up to the Plank?
- So far nothing new from direct searches but
- There are some **anomalies in flavour physics** which (if true) seem to point out that NP does exist
- We should therefore not forget that **we have a 2D** problem (Mass VS Coupling)
- Low coupling → Long Lived

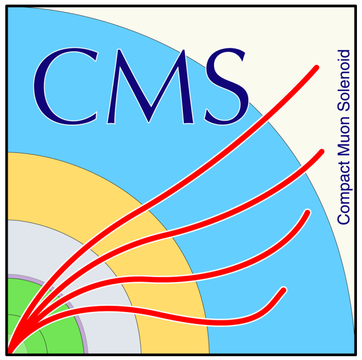


Intensity frontier:
Flavour physics, lepton flavour violation, electric dipole moment, ***dark sector***

Landscape today / 1

- The Intensity frontier is a **broad** and **diverse**, yet **connected**, set of science opportunities: heavy quarks, charged leptons, hidden sectors, neutrinos, nucleons and atoms, proton decay, etc...
- In this talk, I will concentrate on **displaced signatures at LHCb** and related physics searches.
- **Landscape**: LHC results in brief:
  - Direct searches for **NP** by **ATLAS** and **CMS** have not happened so far
    - Parameter space for popular **BSM** models is **decreasing rapidly**, but only < 5% of the complete HL-LHC data set has been delivered so far
    - NP discovery **still may happen**!
  - **LHCb** reported intriguing hints (cautiously optimistic) for the violation of lepton flavour universality
    - In $b \to c\mu\nu$ / $b \to c\tau\nu$, and in $b \to se^+e^-$ / $b \to s\mu^+\mu^-$ decays and in angular variables (P'_5)
    - Possible evidence of **BSM** physics **if substantiated** with further studies (e.g. **BELLE II**)

Summary of results



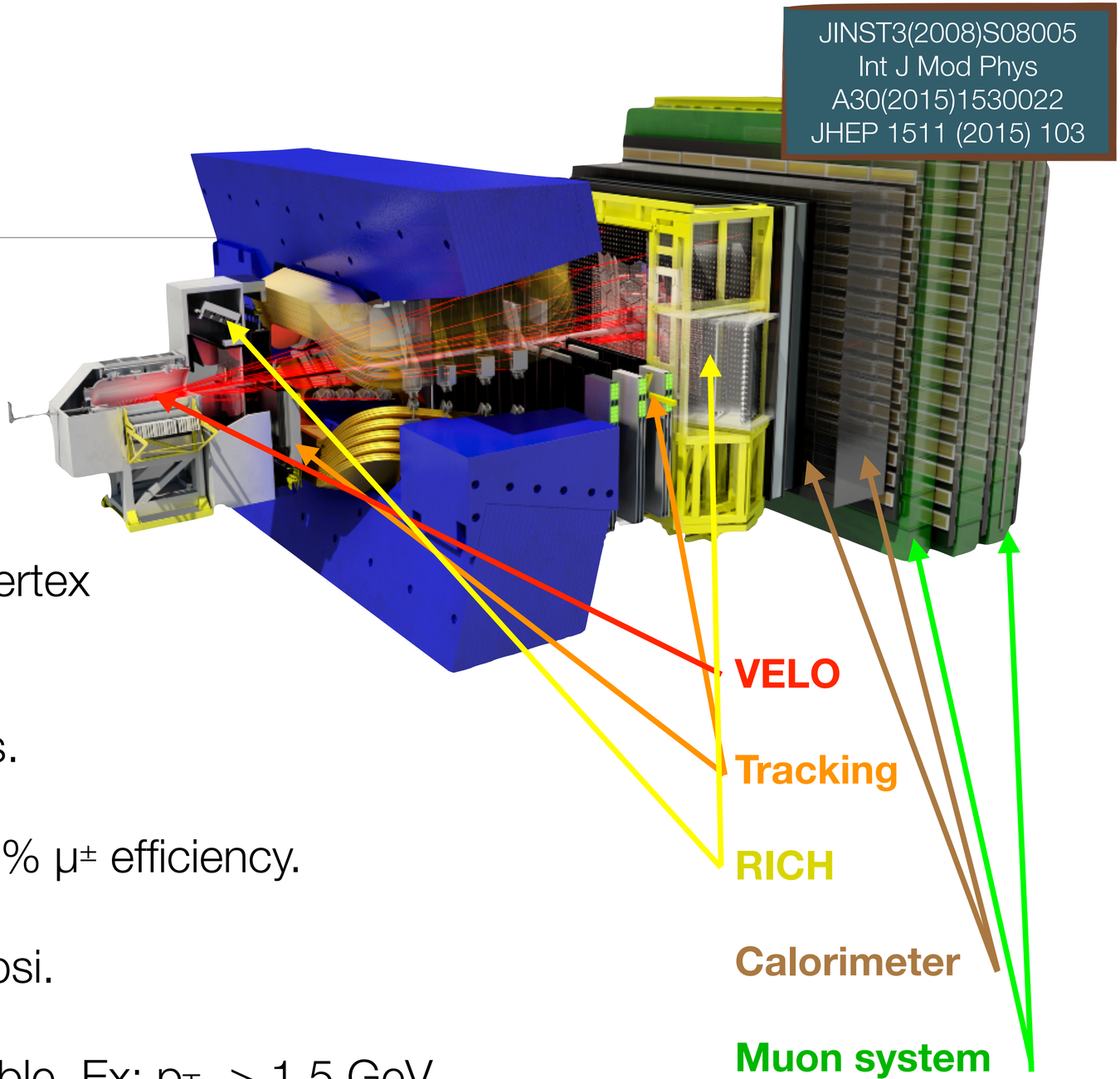
Luo's talk

Giagu's talk

- **Searching for long lived particles at the LHC in the forward region:**
  - **At LHCb**
    - **Displaced leptons**
      - **Dark Photons:**
        Phys. Rev. Lett. 120, 061801 (2018)
        Phys. Rev. Lett. 124, 041801 (2020)
      - **Low-mass dimuon resonances**
        JHEP 10 (2020) 156
      - LLPs in eμν
        Eur. Phys. J. C 81, 261 (2021)
      - HNLs
        Phys. Rev. Lett. 112, 131802 (2014)
      - Light bosons in b to s
        Phys. Rev. Lett. 115, 161802 (2015)
        Phys. Rev. D 95, 071101 (2017)
    - **Displaced jets**
      - HNLs
        Eur. Phys. J. C 81, 261 (2021)
      - **LLPs to jet jet**
        Eur. Phys. J. C (2017) 77:224
      - **LLPs to μ jets**
        Eur. Phys. J. C77 (2017) 812

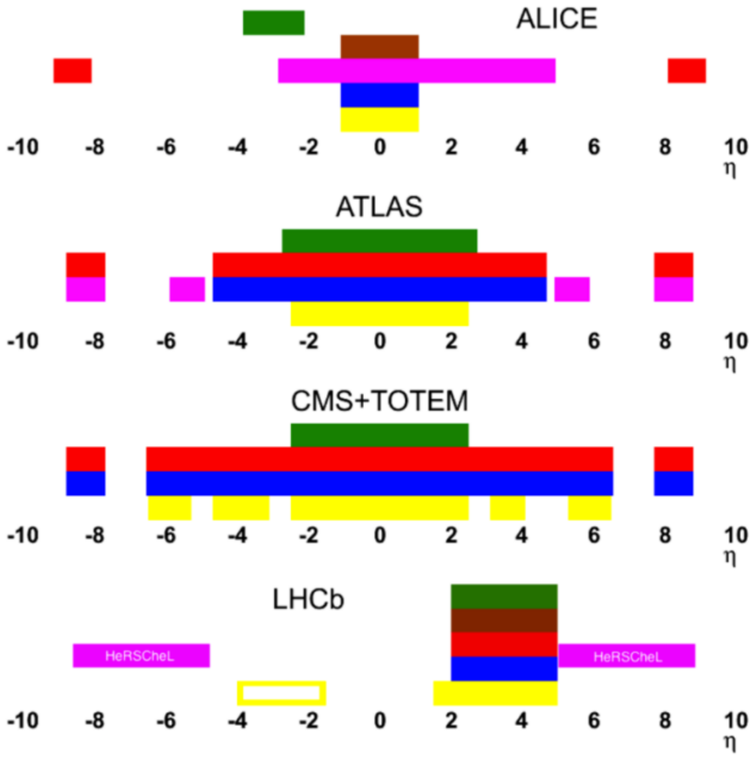
LHCb detector / 1

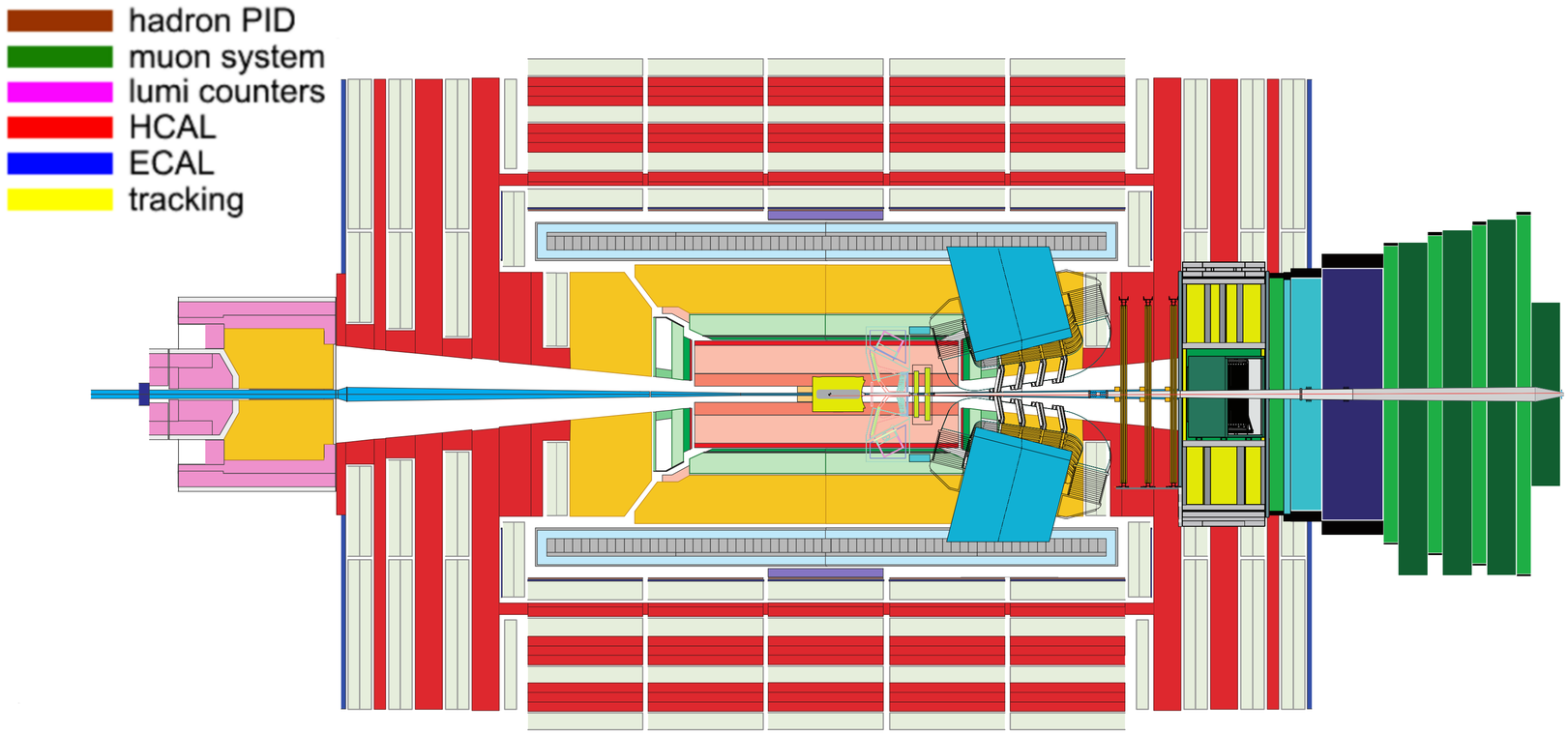
- **LHCb** is a dedicated flavour experiment in the **forward region** at the LHC ($1.9 < \eta < 4.9$) (~1°-15°)
- **Precise vertex reconstruction** < 10 μm vertex resolution in transverse plane.
- Lifetime resolution of ~ 0.2 ps for $\tau = 100$ ps.
- **Muons** clearly identified and triggered: ~ 90% $\mu^{\pm}$ efficiency.
- Great **mass resolution**: e.g. 14 MeV for J/psi.
- **Low p_T trigger** means low masses accessible. Ex: $p_{T\mu} > 1.5$ GeV.



JINST3(2008)S08005
Int J Mod Phys
A30(2015)1530022
JHEP 1511 (2015) 103

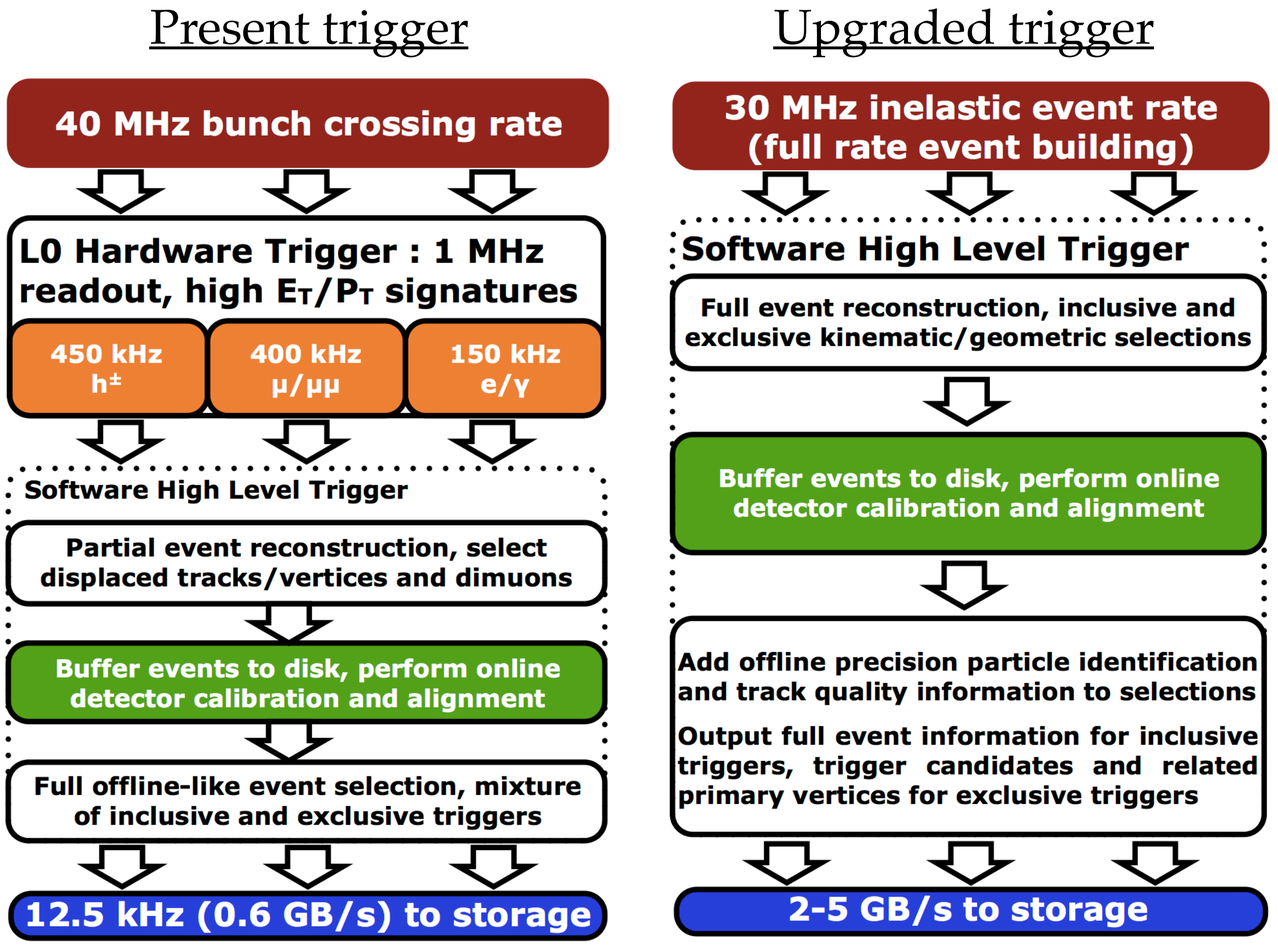
LHCb detector / 1 bis





LHCb detector / 2

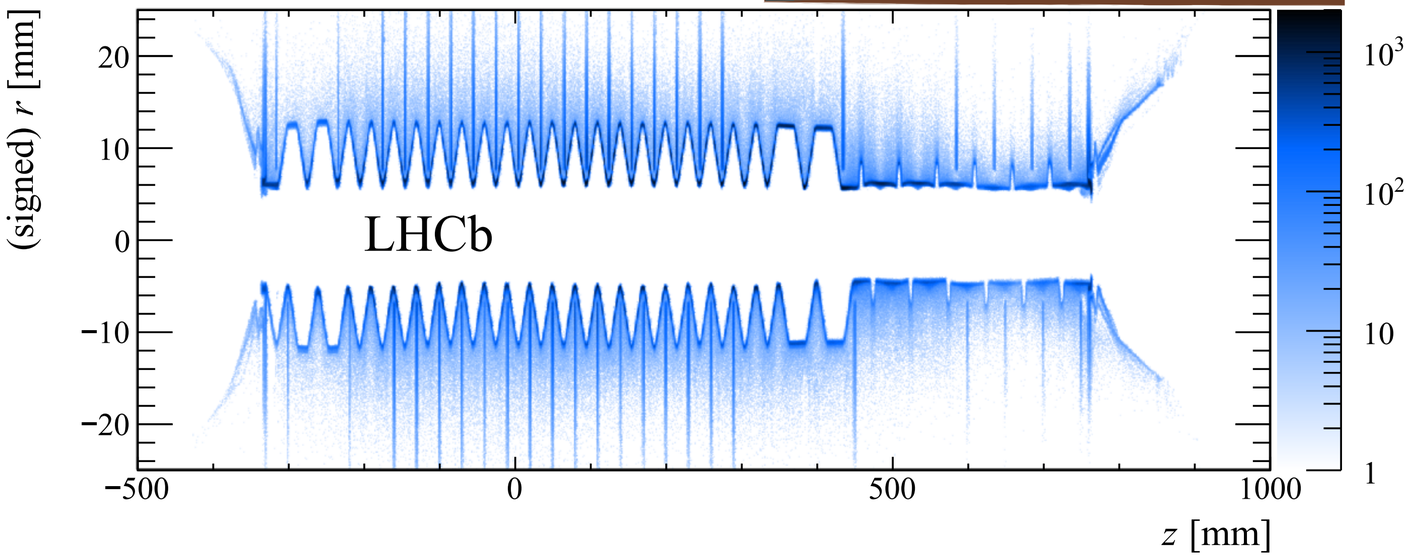
- Lower luminosity (and low pile-up)
  - **~1/8** of ATLAS/CMS in **Run 1**
  - **~1/20** of ATLAS/CMS in **Run 2**
- Hardware **L0 trigger** to be removed
- **Full real-time** reconstruction for all particles available to select events (since 2015)
  - **Real-time reconstruction** for all charged particles with $p_T > 0.4$ GeV
  - We go from 1 TB/s (post zero suppression to 0.7 GB/s (mix of full + partial events)
- LHCb will move to a **readout system without a hardware stage** for LHC Run 3 and process 5 TB/s in real time on the CPU farm

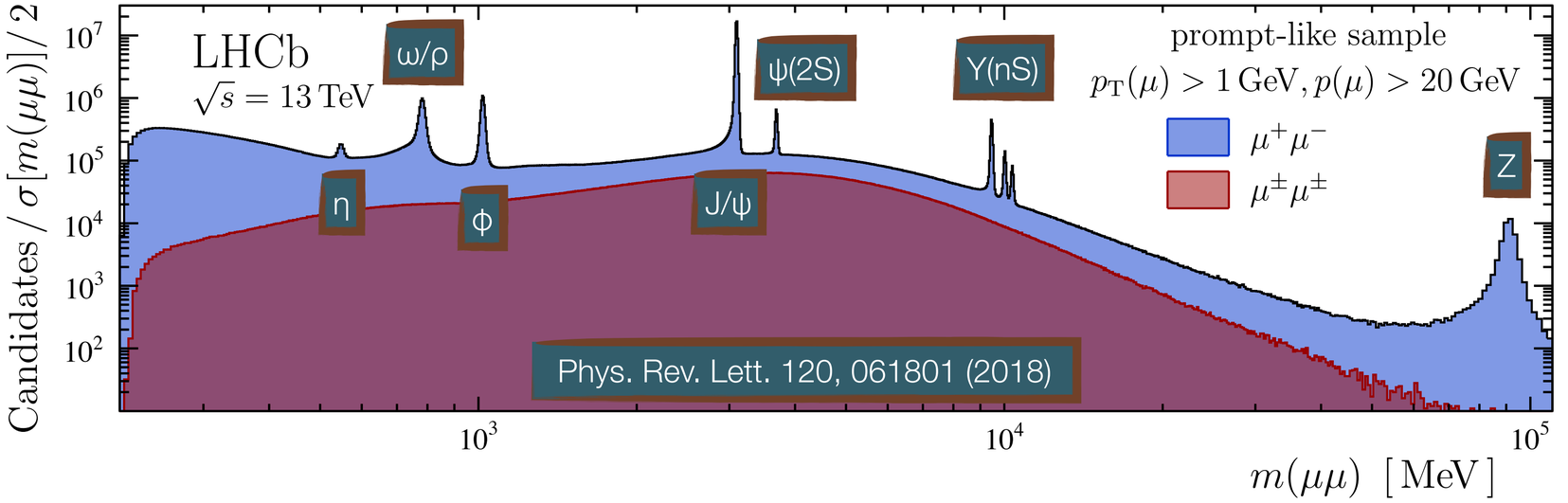


LHCb detector / 3

- Precise knowledge of the location of the material in the LHCb VELO is essential to reduce the background in searches for long-lived exotic particles
- LHCb data calibration process can align active sensor elements, an **alternative approach** is required to fully map the VELO material
- **Real-time calibration** in Run 2 (Turbo Stream)
- Hardware trigger is still there, and only ~10% efficient at low pT

JINST 13 (2018) no.06, P06008



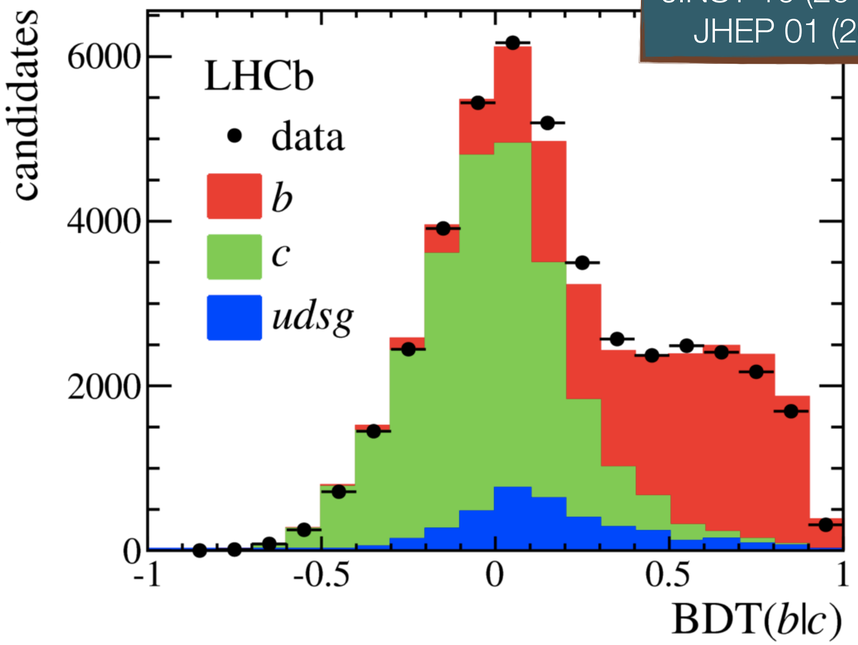


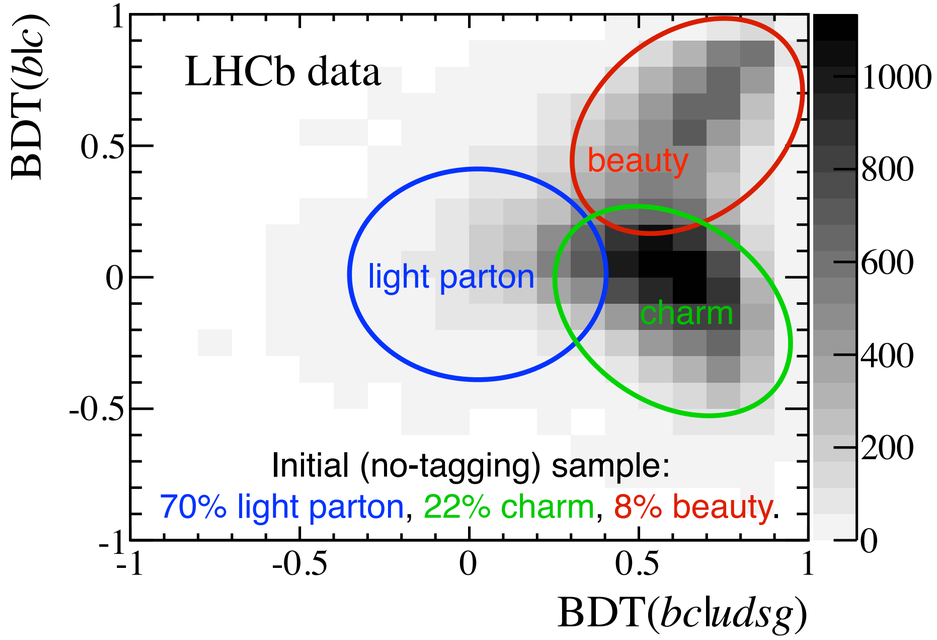
Jet physics at LHCb / 1

- Efficiency above 90% for jets with p_T above 20 GeV
- Jets reconstructed both online and offline!
- **b and c jet tagging**
- Require jets with a secondary vertex reconstructed close enough
- **Light jet** mistag rate < 1%, $\varepsilon_b \sim 65\%$, $\varepsilon_c \sim 25\%$

- SV properties (**displacement**, **kinematics**, **multiplicity**, etc) and jet properties combined in **two** BDTs
  - **$BDT_{bc|udsg}$** optimised for heavy flavour versus light discrimination
  - **$BDT_{b|c}$** optimised for b versus c discrimination

JINST 10 (2015) P06013
JHEP 01 (2014) 033

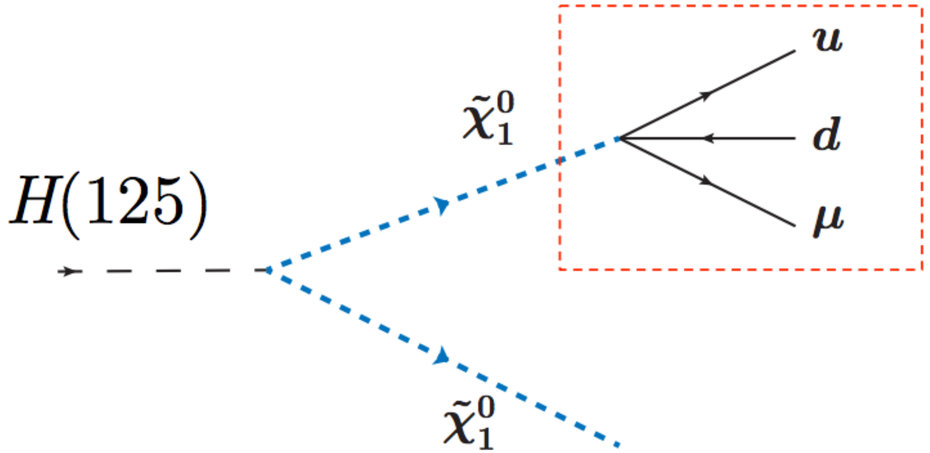





Higgs
boson
H

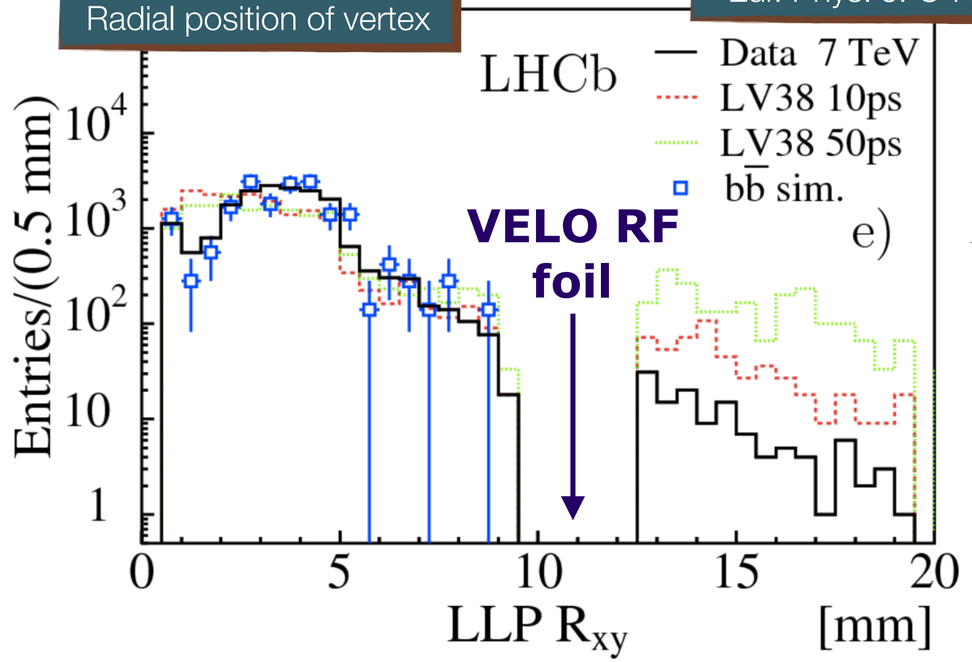
Higgs→LLP→μ+jets / 1

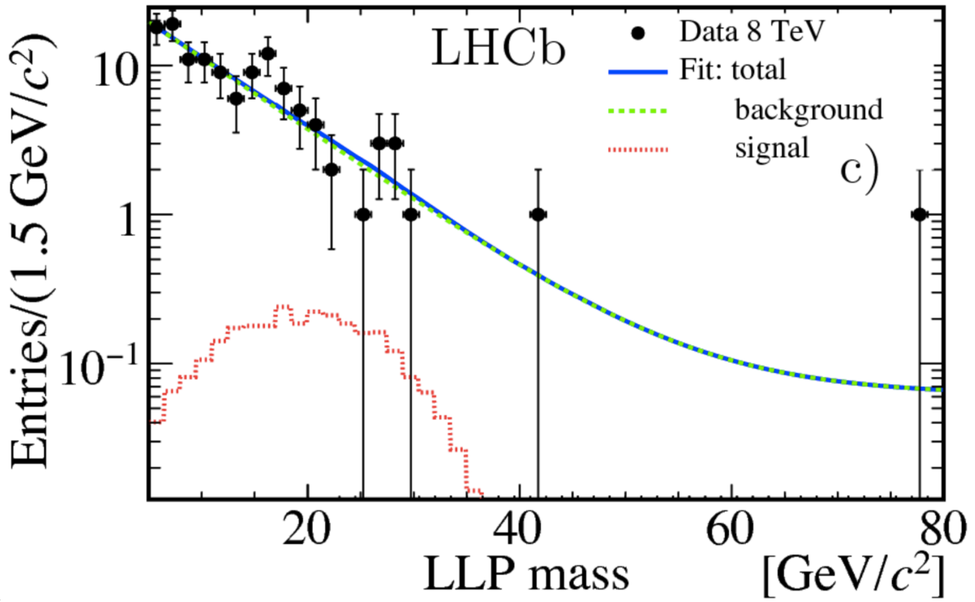
- Massive **LLP** decaying → **μ+jets**
- **Single displaced vertex** with several tracks and a high p_T muon; based on **Run-1** dataset
- Production of LLP could come e.g. from Higgs like particle decaying into pair of LLPs
- **m_{LLP}=[20; 80] GeV** and **τ_{LLP}=[5; 100] ps**
- Background dominated by **QCD**
- No excess found: result interpreted in various models



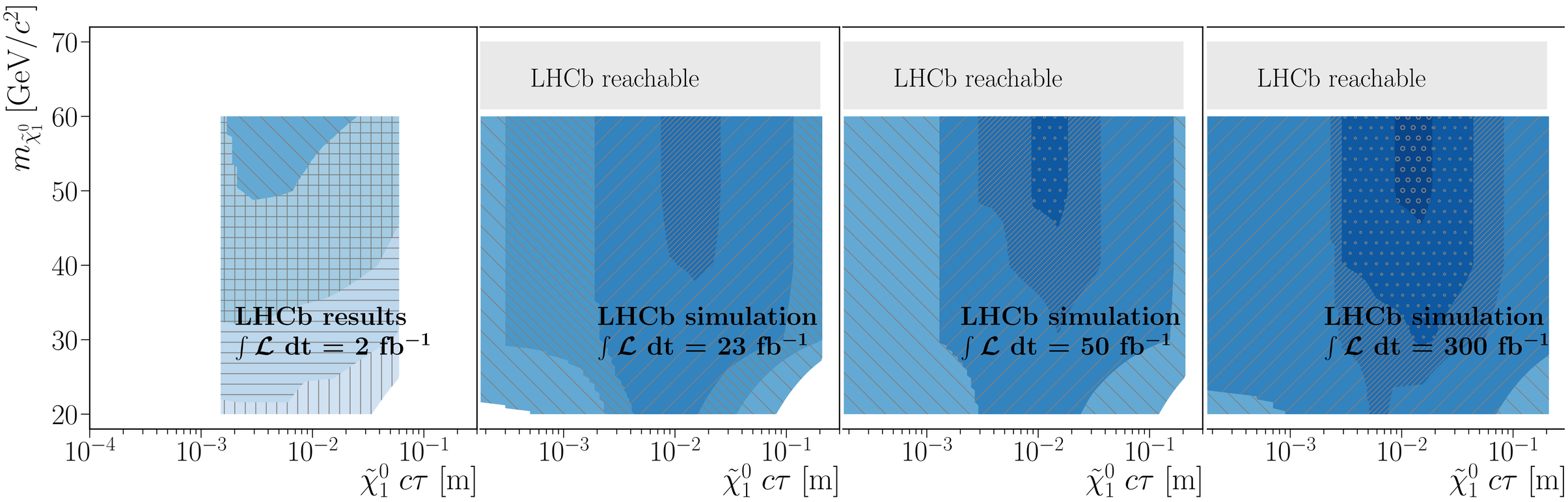
Eur. Phys. J. C 77 224

Radial position of vertex





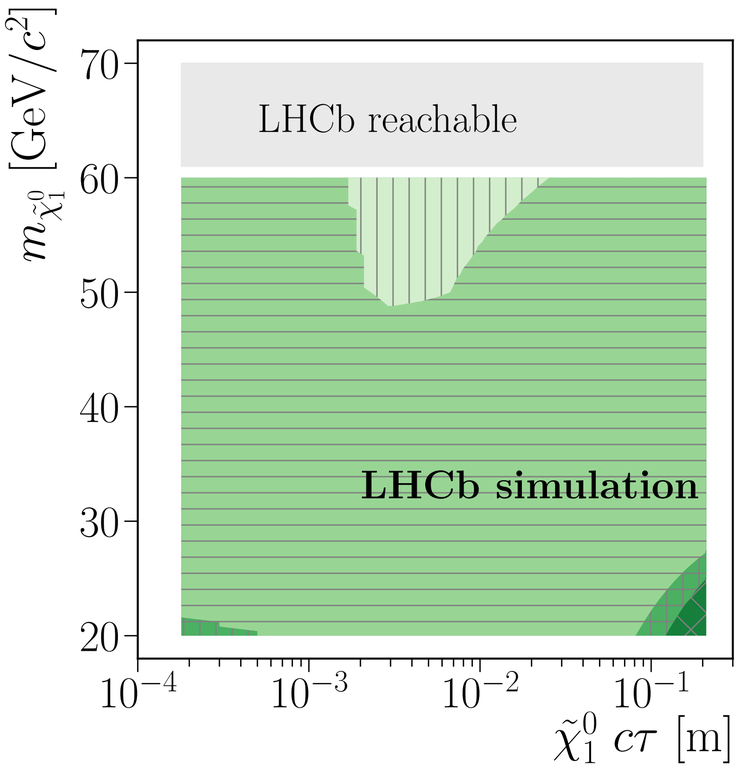
Higgs→LLP→μ+jets / 2



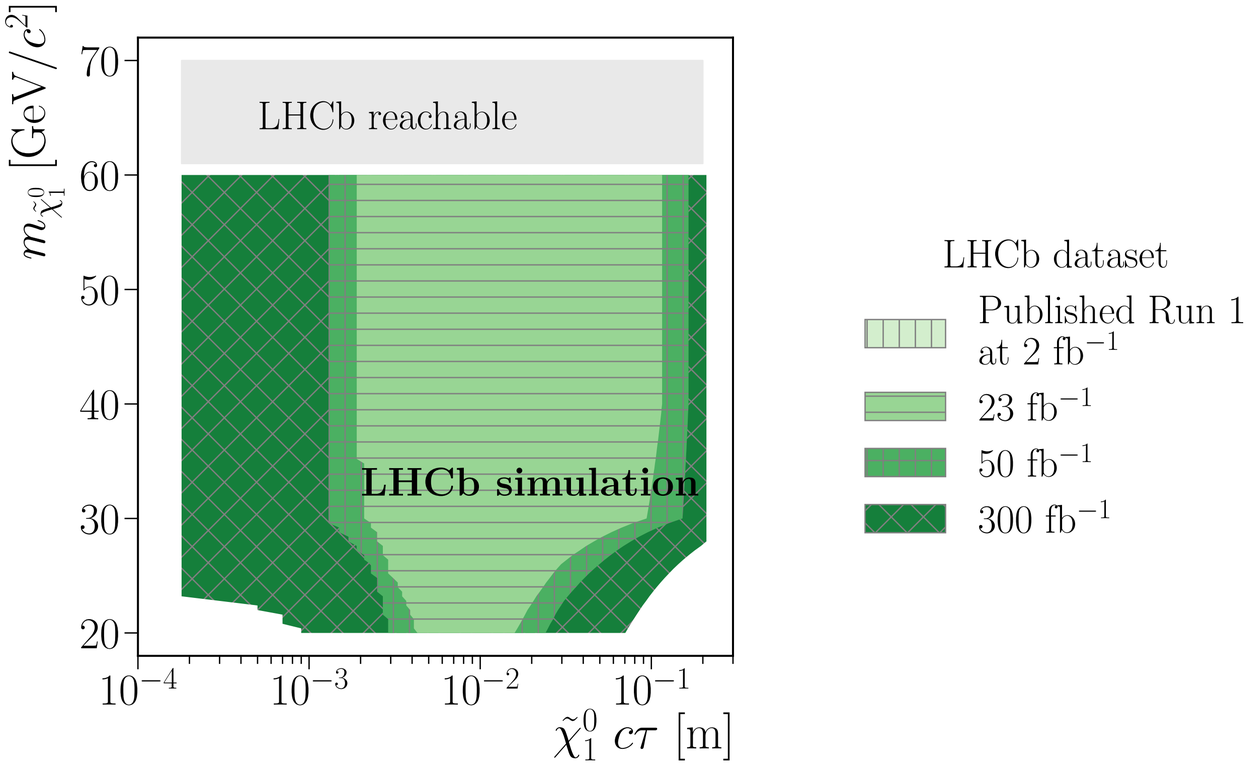
- Model independent scaling of current results to future integrated luminosity for different BFs

Higgs→LLP→μ+jets / 3

- Model dependent scaling of current results to future integrated luminosity for two different BFs



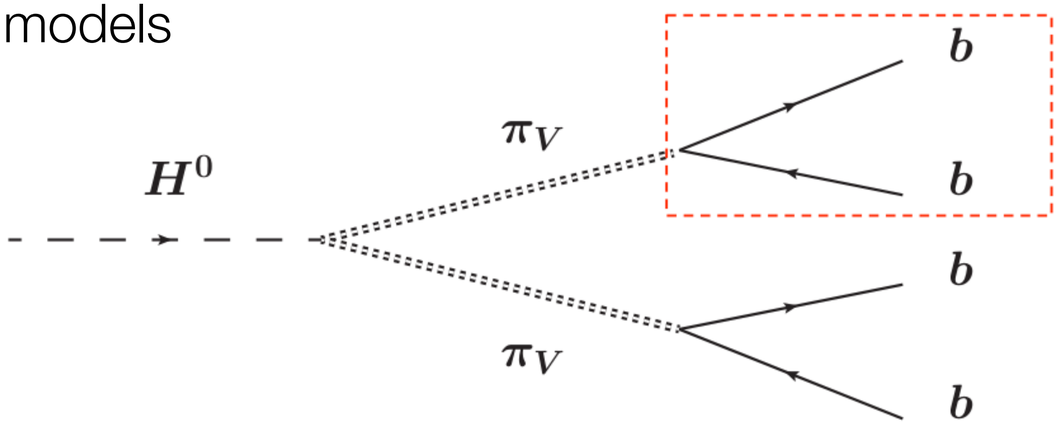
BF(Higgs→LLP+LLP) < 2 %

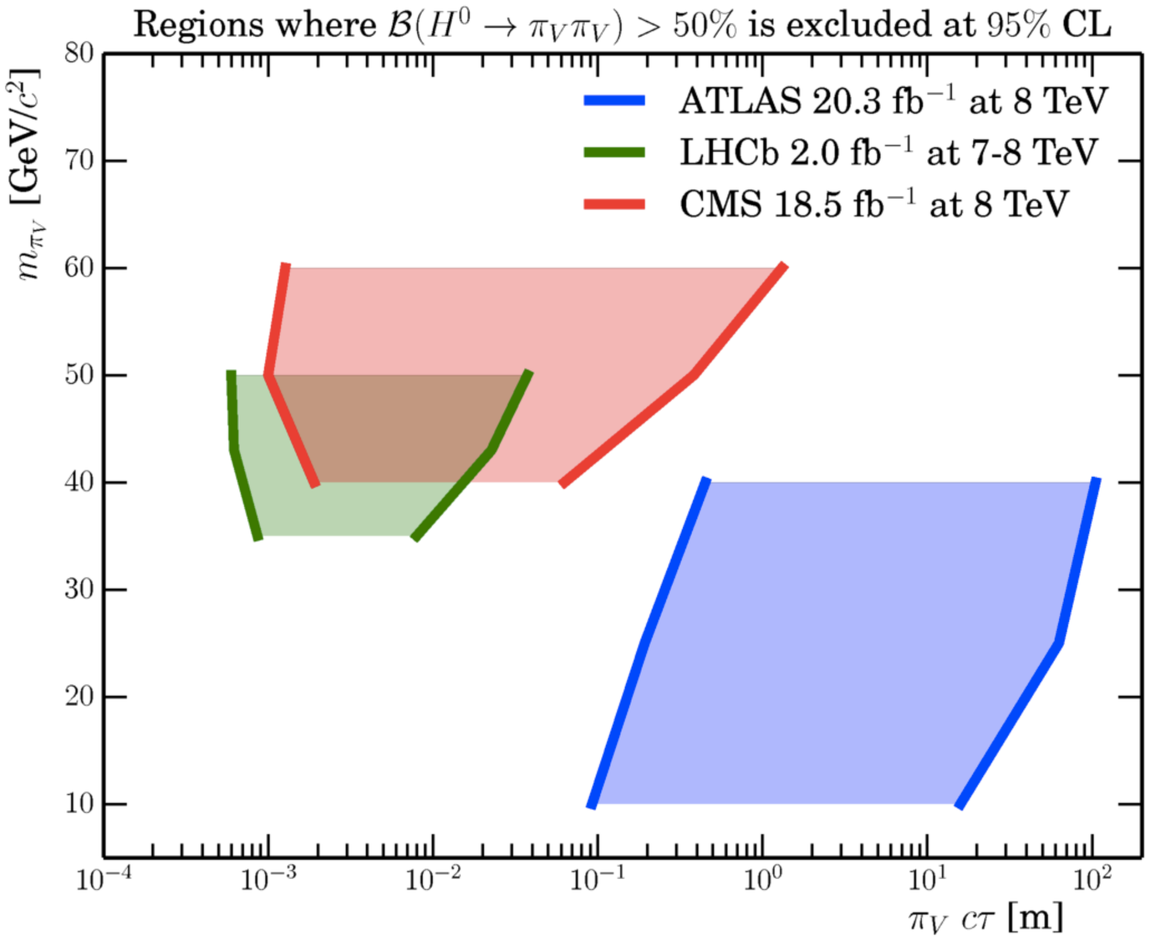


BF(Higgs→LLP+LLP) < 0.5 %

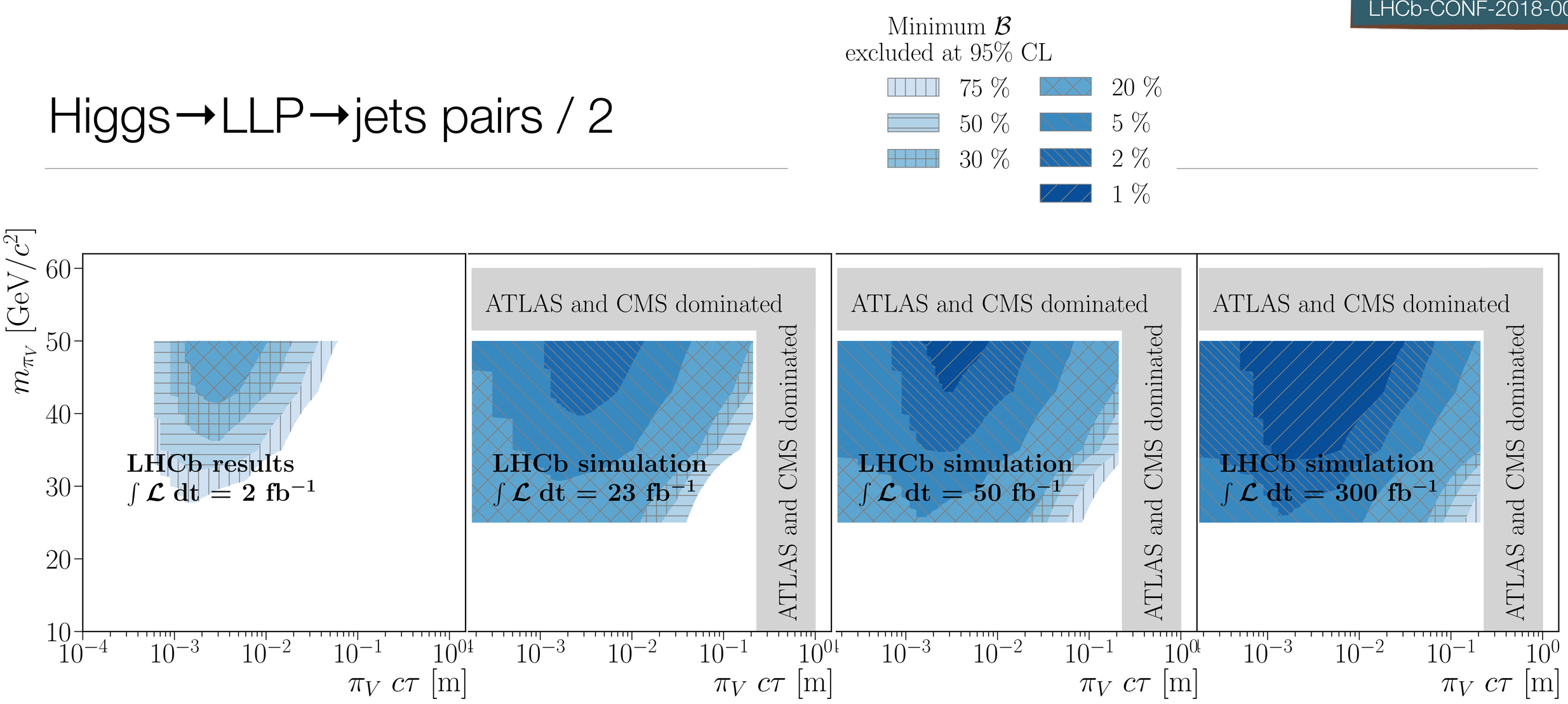
Higgs→LLP→jet pairs / 1

- Massive **LLP** decaying →bb+bb with bb → **jets**
- **Single displaced vertex** with two associated tracks; based on **Run-1** dataset
- Production of LLP could come e.g. from Higgs like particle decaying into pair of LLPs (e.g. π_V)
- **$m_{\pi V}$=[25; 50] GeV** and **$\tau_{\pi V}$=[2; 500] ps**
- Background dominated by **QCD**
- No excess found: result interpreted in various models





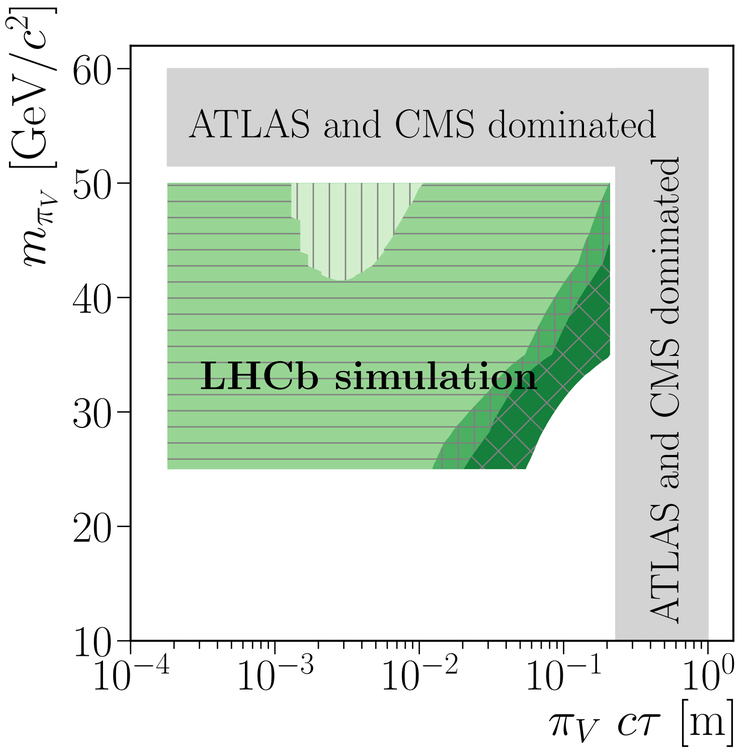
Higgs→LLP→jets pairs / 2



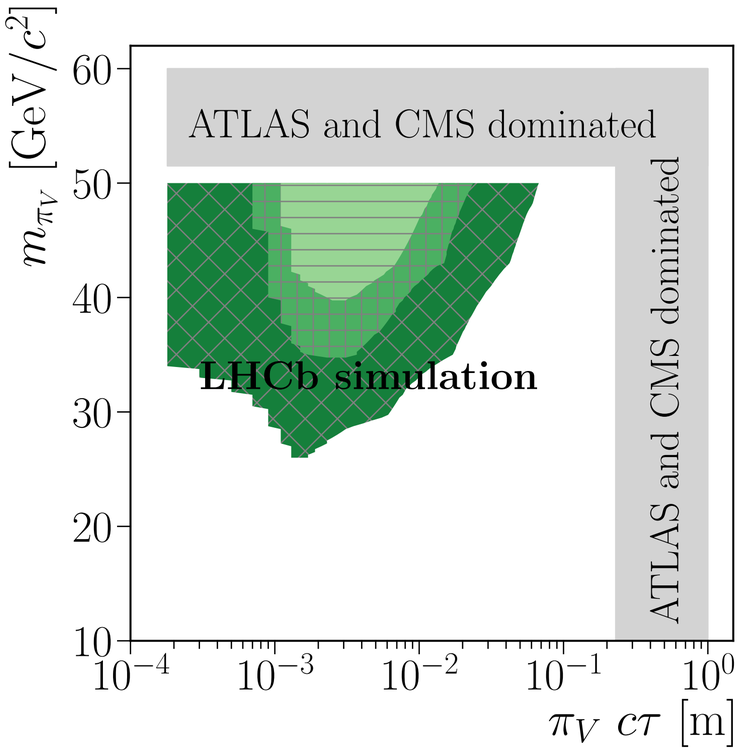
- Model independent scaling of current results to future integrated luminosity for different BFs

Higgs→LLP→jets pairs / 3

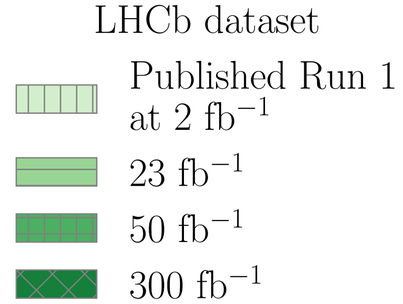
- Model dependent scaling of current results to future integrated luminosity for two different BFs



BF(Higgs→πV+πV) < 20 %



BF(Higgs→πV+πV) < 2 %

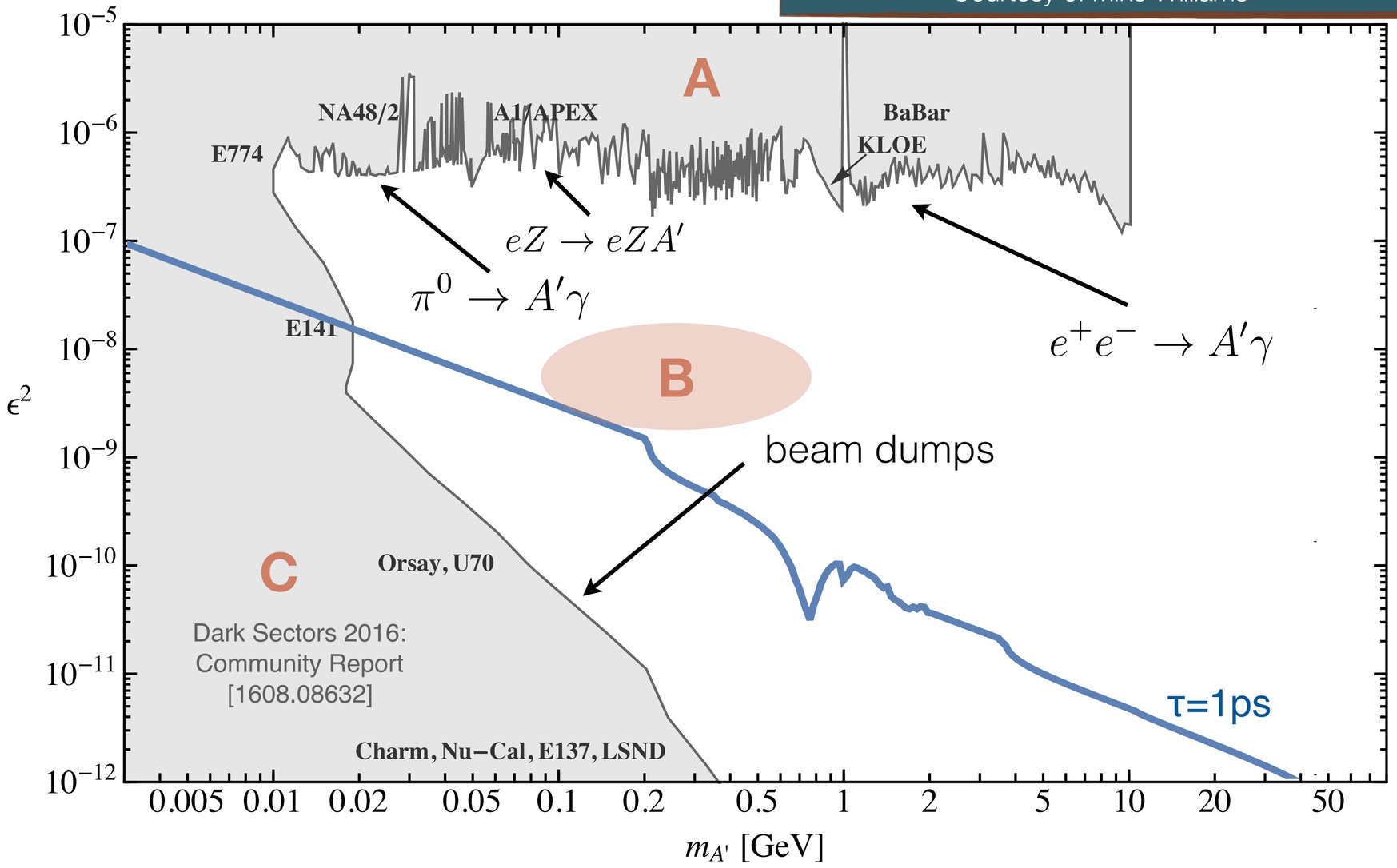



photon

Visible dark photons

- **Pre LHCb**
- **A**: Bump hunts, visible or invisible
- **B**: Displaced vertex searches, short decay lengths
- **C**: Displaced vertex

Dark Sectors 2016: Community Report [1608.08632]
Courtesy of Mike Williams

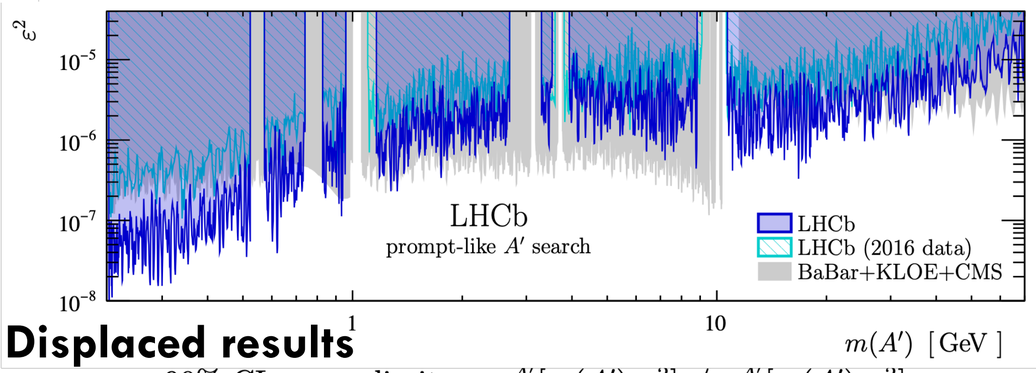


PRL 120 (2018) 061801
PRL 124 (2020) 041801

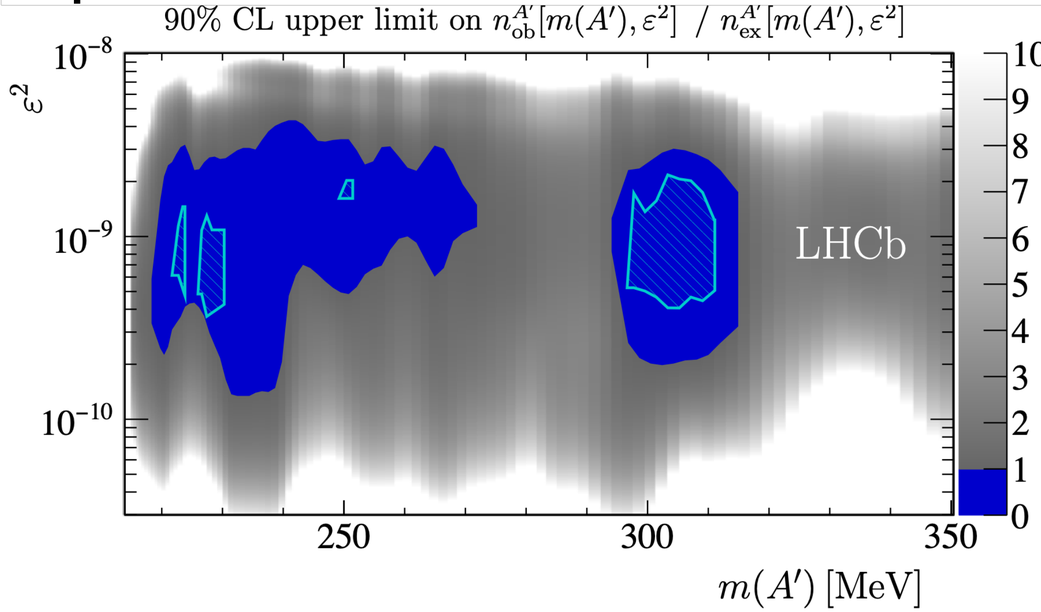
Searching for Dark Photons / 1

- Search for dark photons decaying into **a pair of muons**
- Used **5.5 fb^{-1}** of Run 2 LHCb data (13 TeV)
- Kinetic mixing of the dark photon (A′) with **off-shell photon** (γ^*) by a factor ε:
  - A′ inherits the production mode mechanisms from γ^*
  - A′ → $\mu^+\mu^-$ can be **normalised** to $\gamma^* \to \mu^+\mu^-$
  - No use of MC → no systematics from MC → fully **data-driven** analysis
- Separate γ^* signal from background and measure its fraction
- Prompt-like search (up to 70 GeV/c^2) → displaced search (214-350 MeV/c^2)
  - A′ is long-lived only if the mixing factor is really small
- No significant excess found - exclusion regions at 90% C.L.

Prompt results



Displaced results



Taken from one of Martino's talks

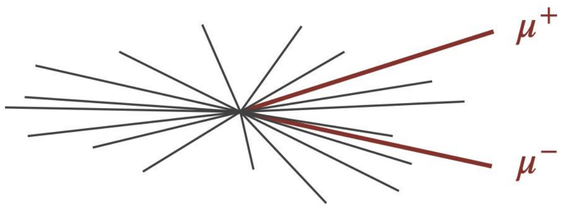
JHEP 10 (2020) 156

Low-mass dimuon resonances / 1

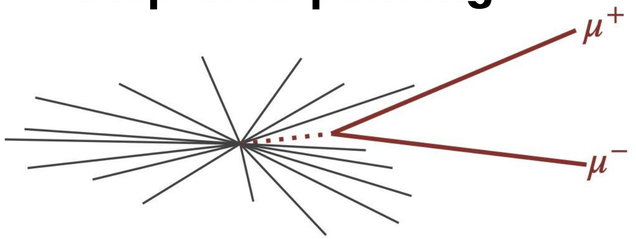
- Non-minimal searches, example signatures:

+ no isolation requirement
+ non-zero width considered

Inclusive Prompt

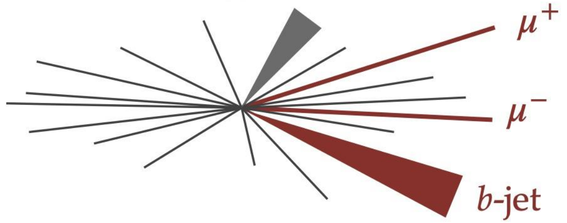


Displaced pointing

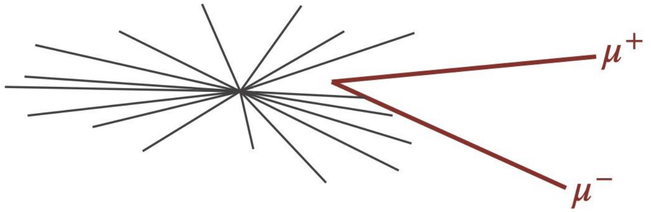


+ non-zero width considered

Prompt + b-jet



Displaced non-pointing



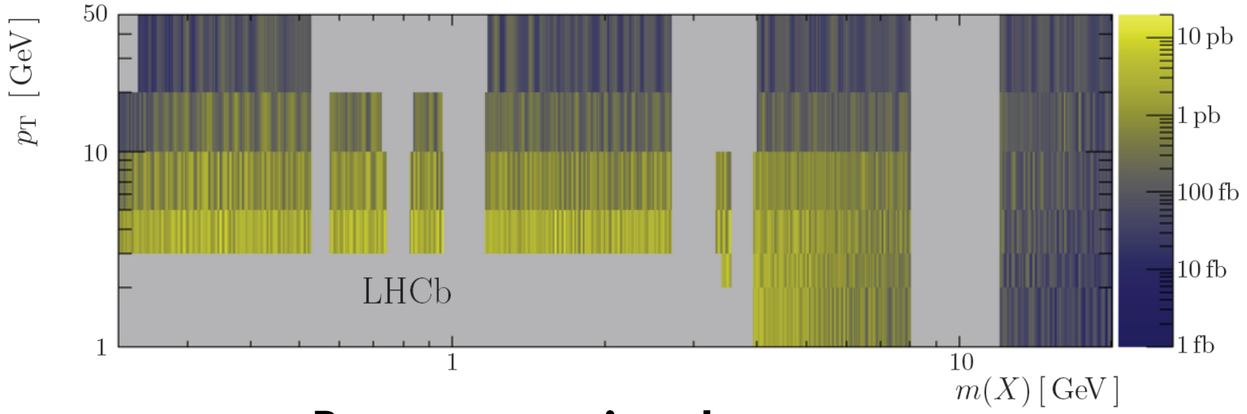
Taken from I. Kostiuk's talk

JHEP 10 (2020) 156

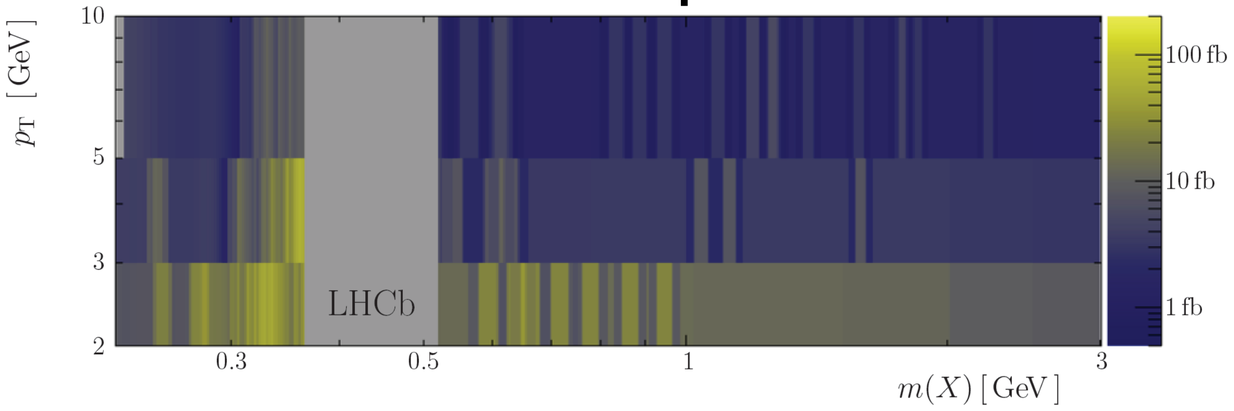
Low-mass dimuon resonances / 2

- Upper limits at 90% CL on $\sigma(X \to \mu\mu)$

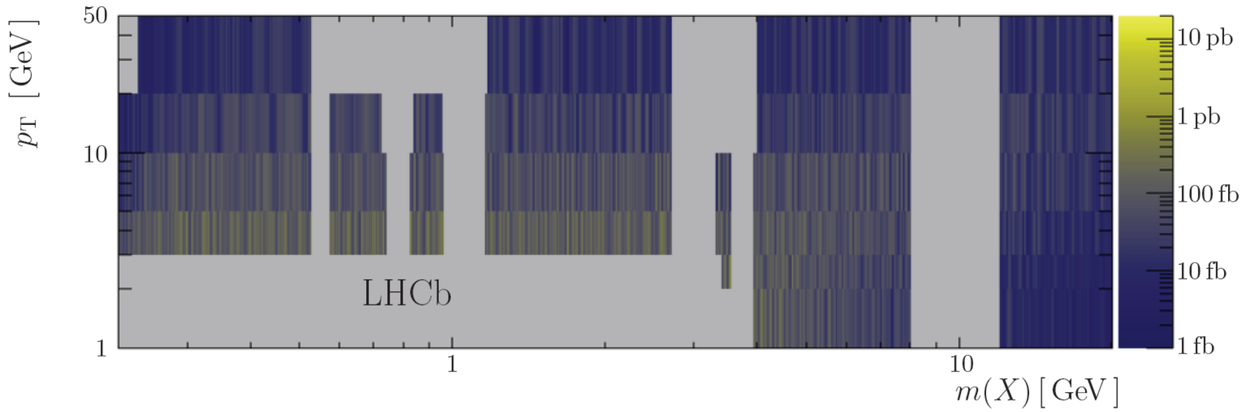
Inclusive prompt



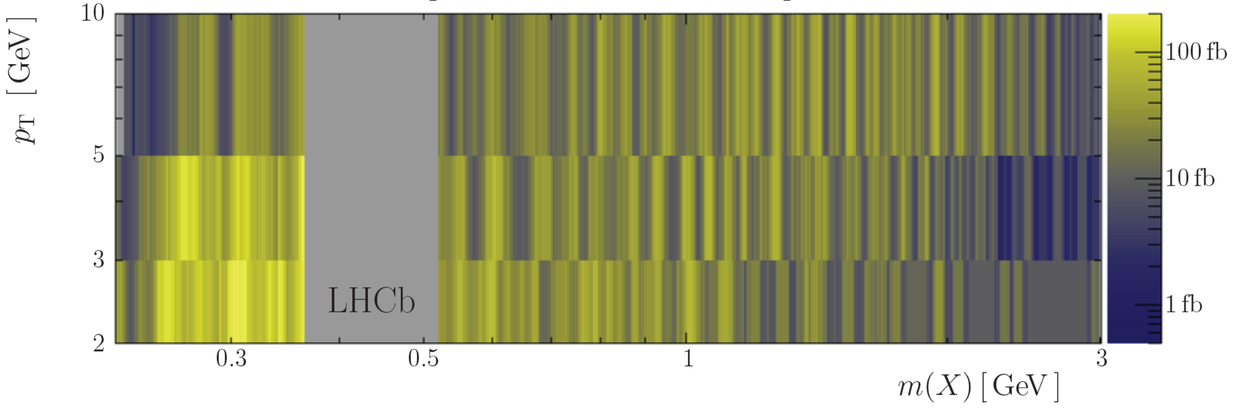
Inclusive displaced



Beauty associated prompt



Beauty associated displaced



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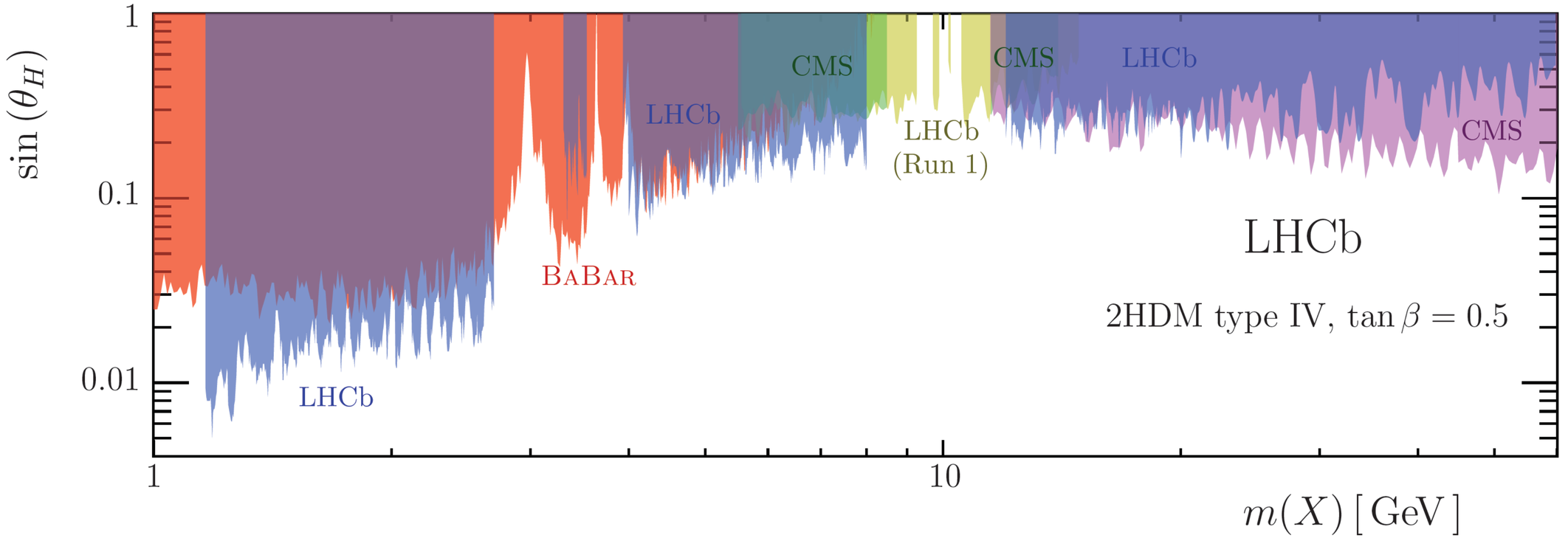
Low-mass dimuon resonances / 3

- A complex scalar singlet is added to the two-Higgs doublet (2HDM) potential
- E.g. a scenario where the pseudoscalar boson acquires all of its couplings to SM fermions through its mixing with the Higgs doublets; the corresponding X–H mixing angle is denoted as θ_H



Conclusions

- **LHCb can be a key player in the search for displaced signatures**
- The upcoming Run 3 with the new Upgraded detector will introduce many positive modifications
- **Most importantly the removal of the hardware trigger**
- What will the future be?

- 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 [SIC] 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

ASPEN2014 Theoretical summary - M. Mangano

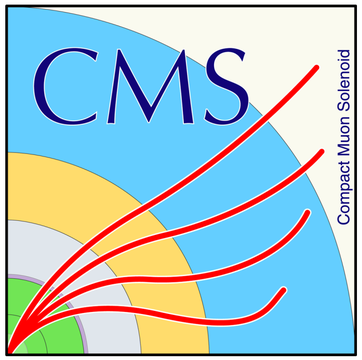
2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	203?
LS2		**RUN 3**			LS3			**RUN 4**			LS4	**RUN 5**
LHCb 40 MHz Upgrade Ia		$L = 2x10^{33}$			LHCb Upgrade Ib			$L = 2x10^{33}$; **50 fb^{-1}**			LHCb Upgrade II (proposed)	$L = 2x10^{34}$; **300 fb^{-1}** (proposed)

Thanks

Federico Leo Redi

Summary of results

Disclaimer this is not an up to date list!

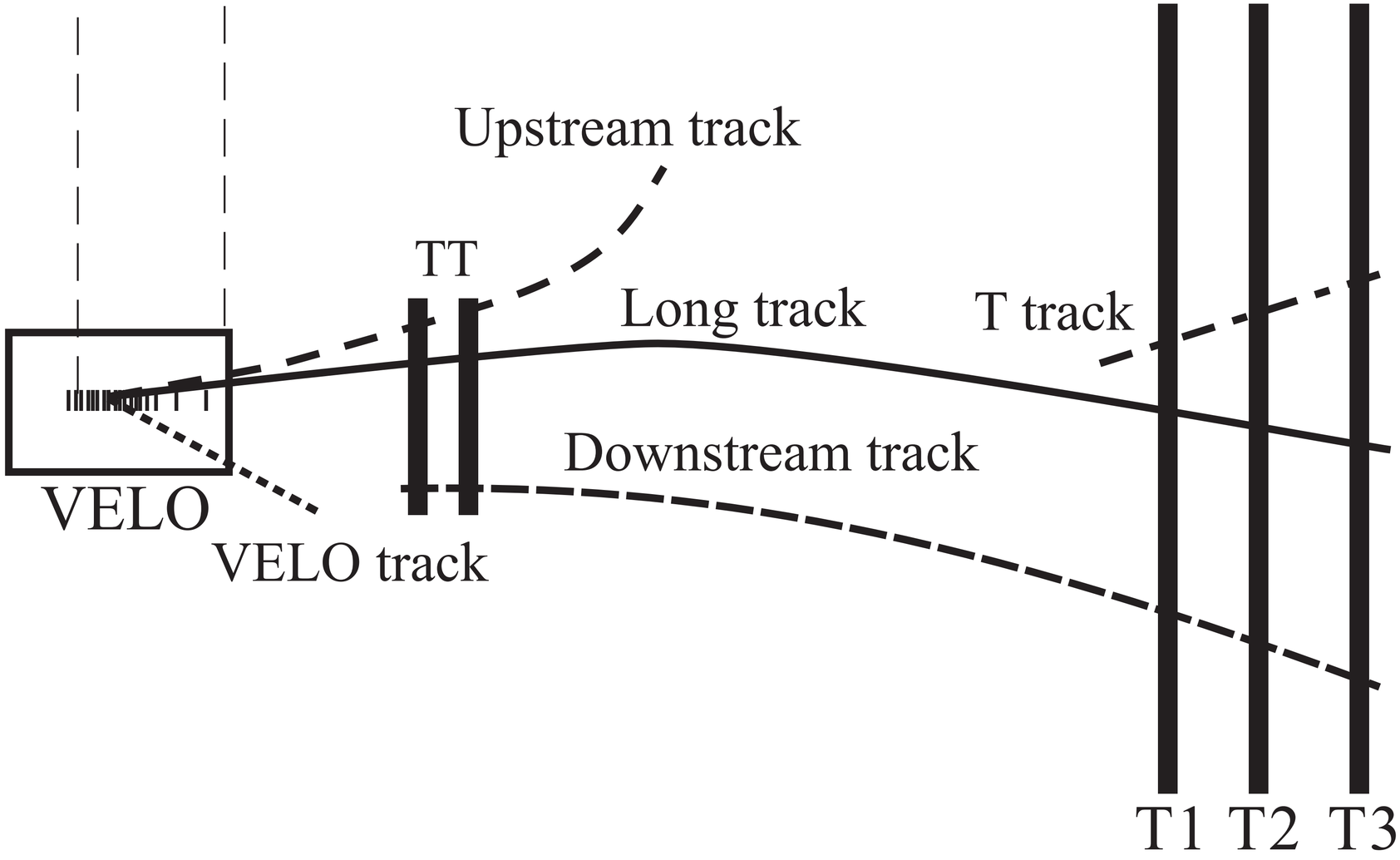


- Searching for long lived particles at the LHC 4π detectors:
  - At CMS
    - Nonprompt jets
      Phys. Lett. B 797 (2019) 134876
    - Delayed photons
      Phys. Rev. D 100, 112003 (2019)
    - Displaced jets
      CERN-EP-2020-202
    - *LLPs to trackless jets*
      CMS-PAS-EXO-17-010
    - *LLPs to jets*
      CMS-PAS-EXO-19-013
    - *Disappearing tracks [other talks]*
      Phys. Lett. B 806 (2020) 135502

- Searching for long lived particles at the LHC 4π detectors:
  - At ATLAS
    - *LLP + Z*
      Phys. Rev. Lett. 122, 151801 (2019)
    - *Multi-charged LLPs*
      Phys. Rev. D 99, 052003 (2019)
    - LLPs to light hadrons or collimated leptons
      Eur. Phys. J. C 80 (2020) 450
    - Magnetic monopoles
      Phys. Rev. Lett. 124, 031802 (2020)
    - *LLPs to hadronic jets*
      Phys. Rev. D 101, 052013 (2020)
    - *LLPs to μ jet(s)*
      Phys. Rev. D 102, 032006 (2020)
    - *LLPs to leptons*
      CERN-EP-2020-205

- **Searching for long lived particles at the LHC in the forward region:**
  - **At LHCb**
    - **Displaced leptons**
      - **Dark Photons:**
        Phys. Rev. Lett. 120, 061801 (2018)
        Phys. Rev. Lett. 124, 041801 (2020)
      - **Low-mass dimuon resonances**
        JHEP 10 (2020) 156
      - LLPs in eμν
        CERN-EP-2020-212
      - HNLs
        Phys. Rev. Lett. 112, 131802 (2014)
      - Light bosons in b to s
        Phys. Rev. Lett. 115, 161802 (2015)
        Phys. Rev. D 95, 071101 (2017)
    - **Displaced jets**
      - HNLs
        CERN-EP-2020-194
      - **LLPs to jet jet**
        Eur. Phys. J. C (2017) 77:224
      - **LLPs to μ jets**
        Eur. Phys. J. C77 (2017) 812

LHCb track types



Mass resolution

JHEP 1511 (2015) 103

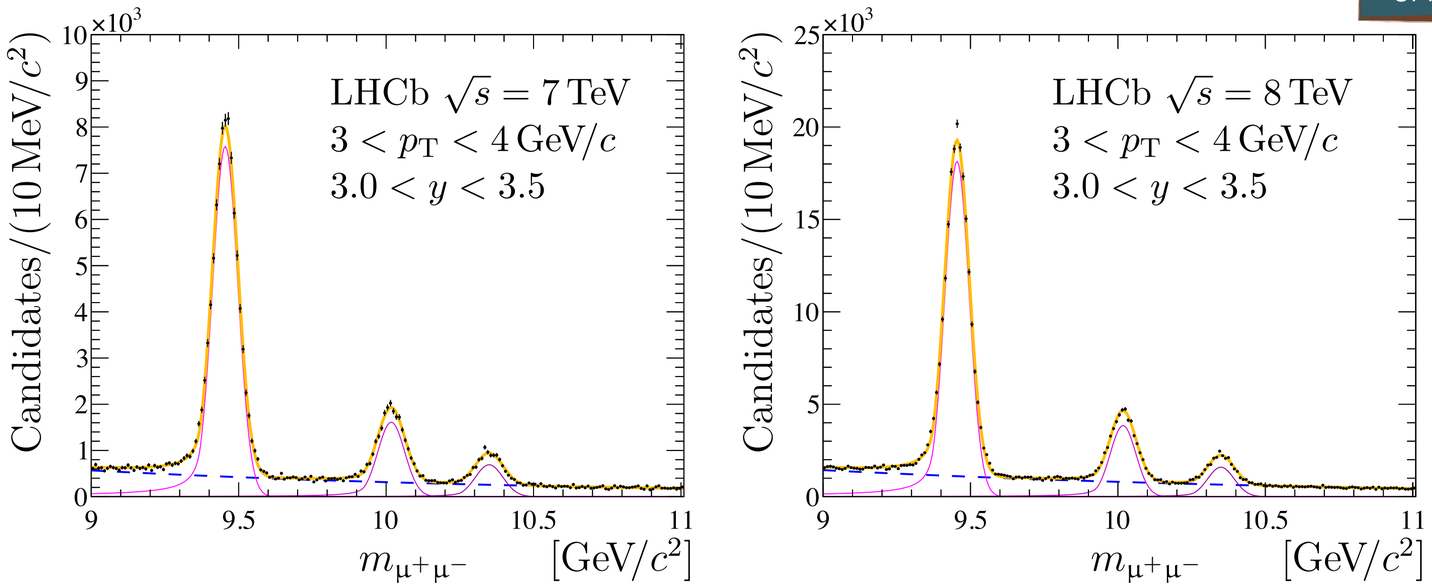


Figure 1: Efficiency-corrected dimuon mass distributions for (left) $\sqrt{s} = 7\,\text{TeV}$ and (right) $\sqrt{s} = 8\,\text{TeV}$ samples in the region $3 < p_\text{T} < 4\,\text{GeV}/c$, $3.0 < y < 3.5$. The thick dark yellow solid curves show the result of the fits, as described in the text. The three peaks, shown with thin magenta solid lines, correspond to the $\Upsilon(1\text{S})$, $\Upsilon(2\text{S})$ and $\Upsilon(3\text{S})$ signals (left to right). The background component is indicated with a blue dashed line. To show the signal peaks clearly, the range of the dimuon mass shown is narrower than that used in the fit.

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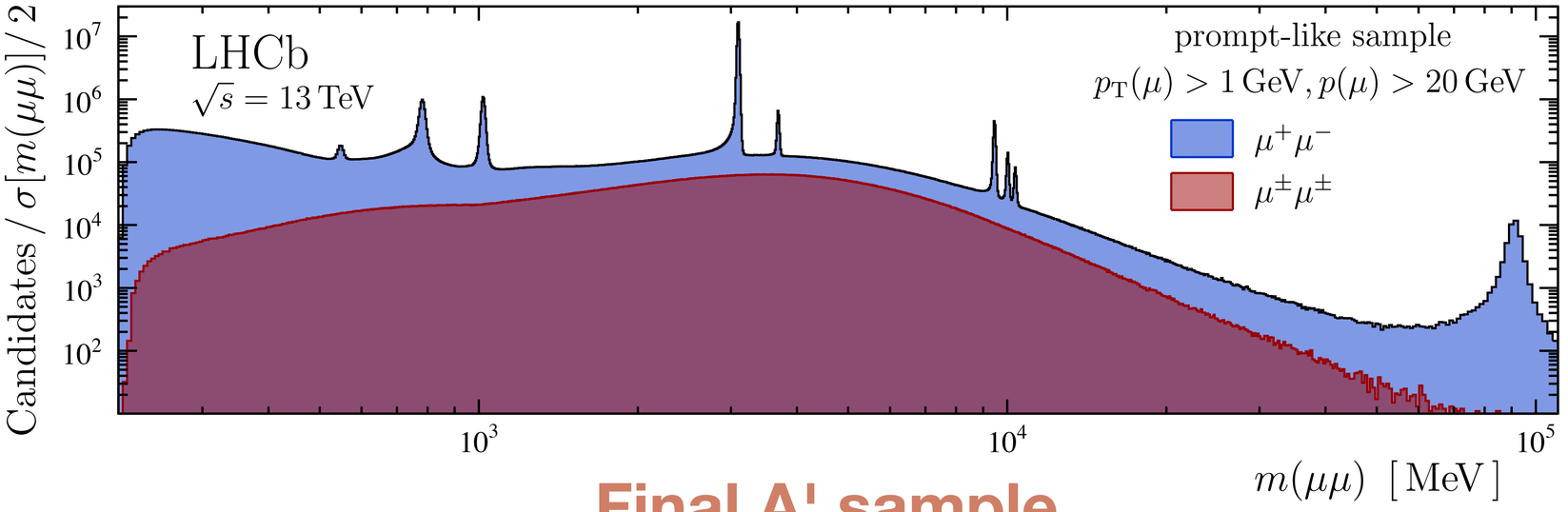
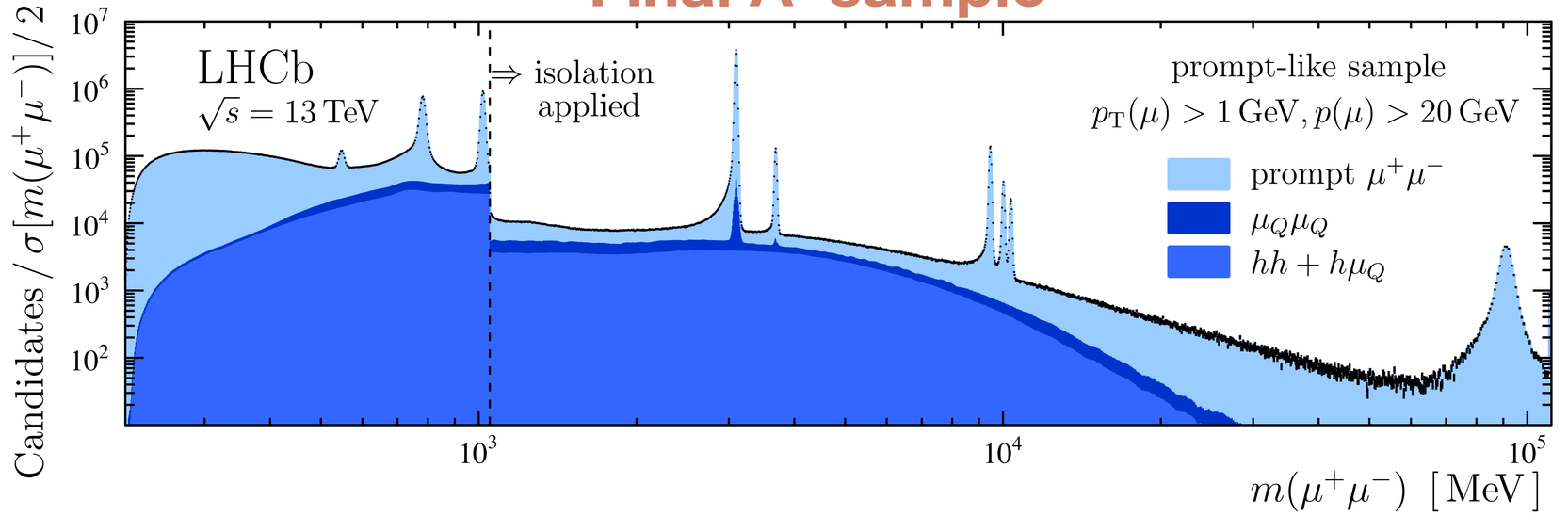
Phys. Rev. Lett. 120, 061801 (2018)

- Suppressing misidentified (non-muon) backgrounds and reducing the event size enough to record the **prompt-dimuon sample**
- Accomplished these by moving to **real-time calibration** in Run 2
- Hardware trigger is still there, and only ~10% efficient at low pT

Trigger output



Final A' sample



Searching for Dark Photons / 2

arXiv:[1803.07466]

- Background dominated by **material interactions** for displaced searches at LHCb
- Precise knowledge of the location of the material in the LHCb VELO is essential to reduce the background in searches for long-lived exotic particles
- LHCb data calibration process can align active sensor elements, an **alternative approach** is required to fully map the VELO material