Dark photons at ATLAS / CMS / LHCb

Federico Leo Redi

on behalf of the ATLAS, CMS, and LHCb collaborations

9th Edition of the Large Hadron Collider Physics Conference

Jun 2021

Summary of results

ATLAS EXPERIMENT

- CONF-2021-004
- Eur. Phys. J. C 80 (2020) 450
- PHYS-PUB-2020-007

CMS Compact Muon Solenoid

- **PAS EXO-20-014 NEW**
- JHEP 03 (2021) 011
- Phys. Rev. Lett. 124 (2020) 131802
- JHEP 10 (2019) 139

LHCb

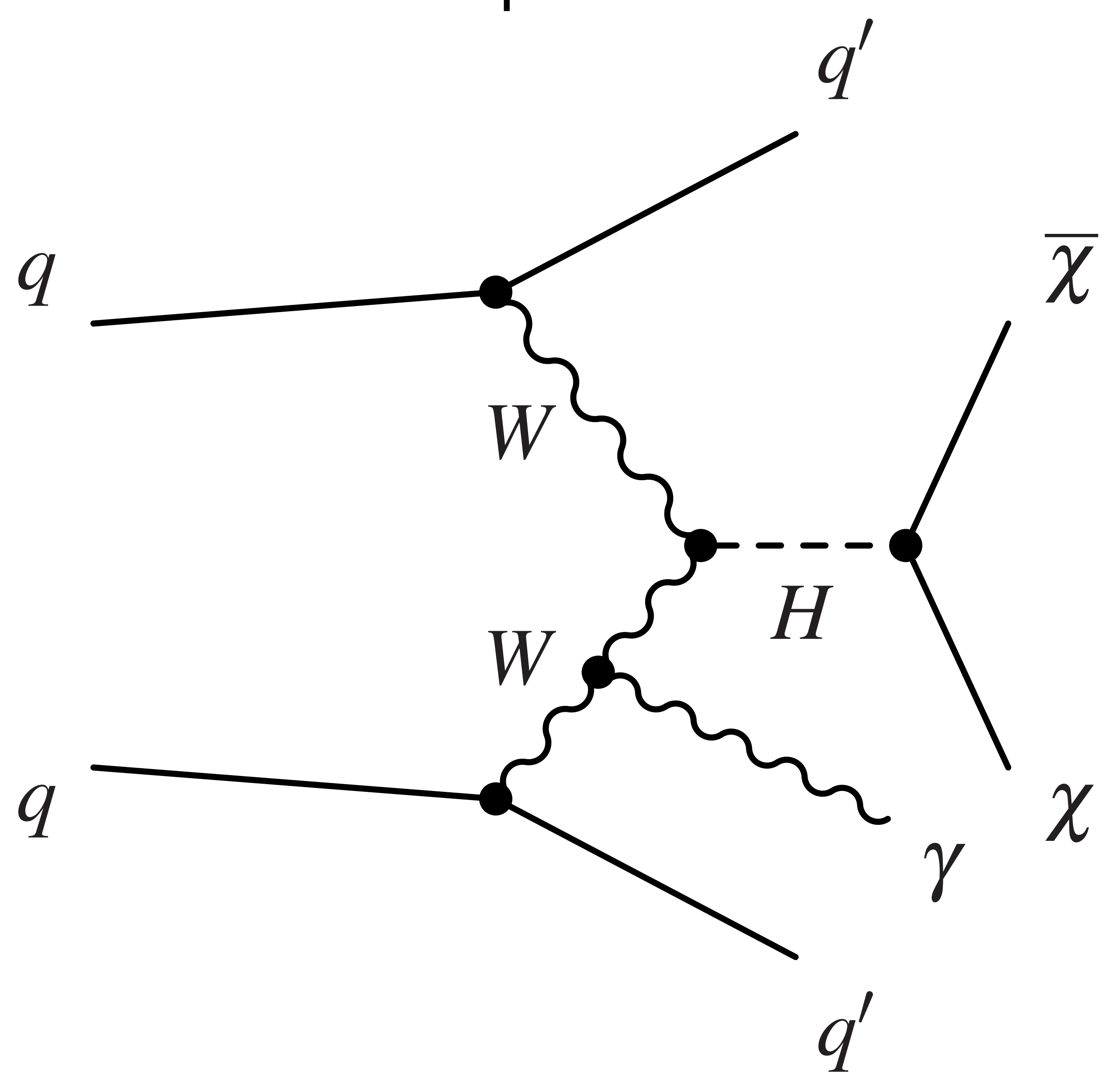
- Phys. Rev. Lett. 124, 041801 (2020)
- Phys. Rev. Lett. 120, 061801 (2018)

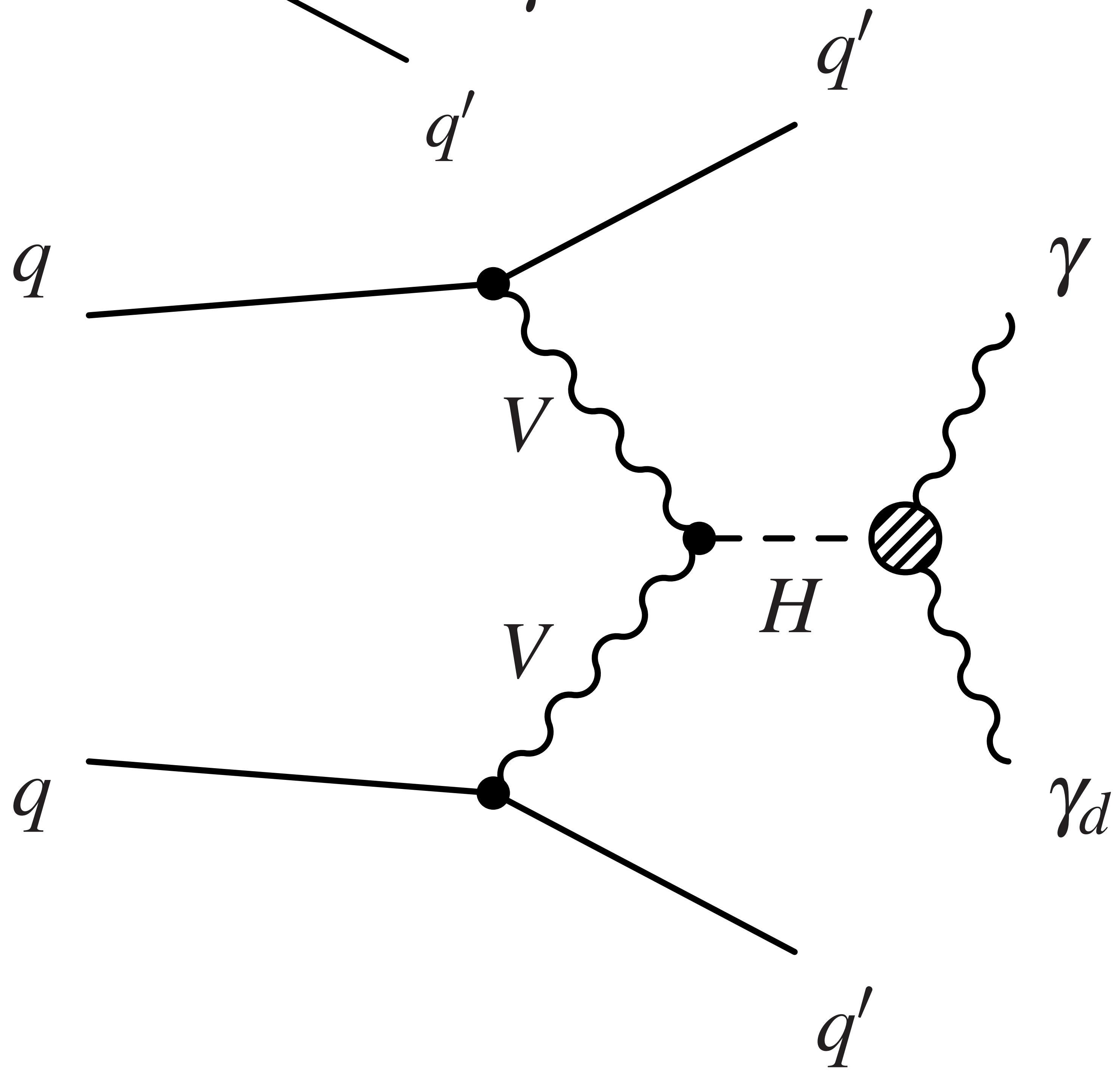
CONF-2021-004

ATLAS: Searches for electroweak production of two jets in association with a Higgs boson decaying fully or partially to invisible particles, including a final state photon

using proton-proton collisions at 13 TeV

- Search using 2015 to 2018 dataset ~ 139 fb^{-1}
- Signal selected using the powerful **ATLAS MET triggers**: Trigger algorithms based on the presence of missing transverse momentum, E^{miss}_T
- Probing decays of the Higgs to invisible particles when produced through the SM-predicted vector boson fusion (VBF) **in association with an emitted photon** (top)
  - Higgs boson decays to a photon and an invisible dark photon with a branching ratio $B(H \rightarrow \gamma\gamma_d)$
- This makes it sensible also to probe a dark photon model which predicts a massless dark photon (γ_d) coupled with the Higgs boson through a U(1) unbroken dark sector (bottom)



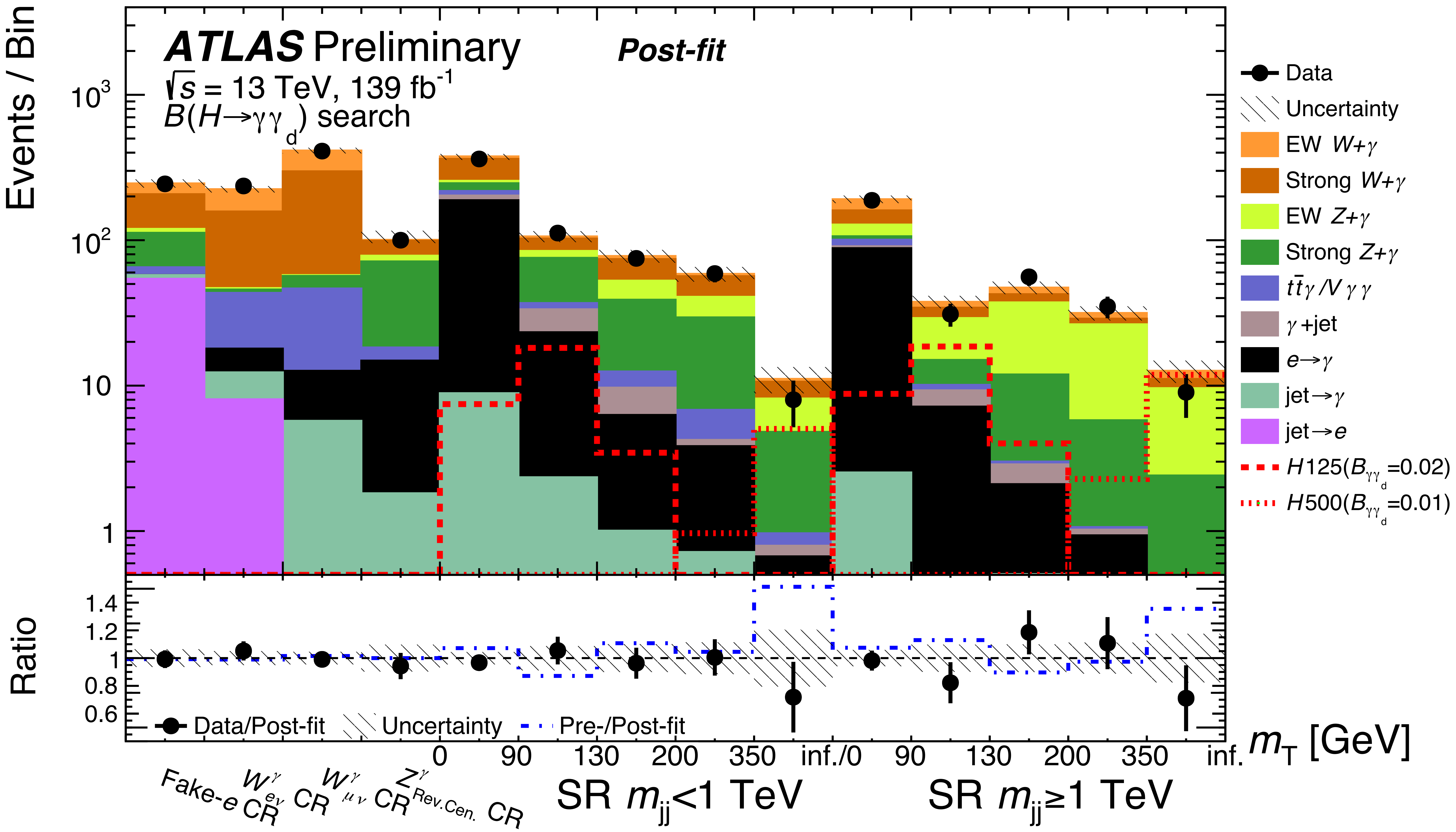


ATLAS: Searches for electroweak production of two jets in association with a Higgs boson decaying fully or partially to invisible particles, including a final state photon

- Jacobian peak of $H \rightarrow \gamma\gamma_d$ decays signature characterised by the use of **transverse mass**
  - Transverse missing energy
  - Transverse photon momentum
  - Azimuthal angle around the z-axis
- Maximum likelihood fit with the $\mathbf{B(H \rightarrow \gamma\gamma_d)}$ signal normalisation floating in the ten [m_{jj},m_T] SR bins
- Four inclusive CRs as a function of $m_T(\gamma, E^{miss}_T)$

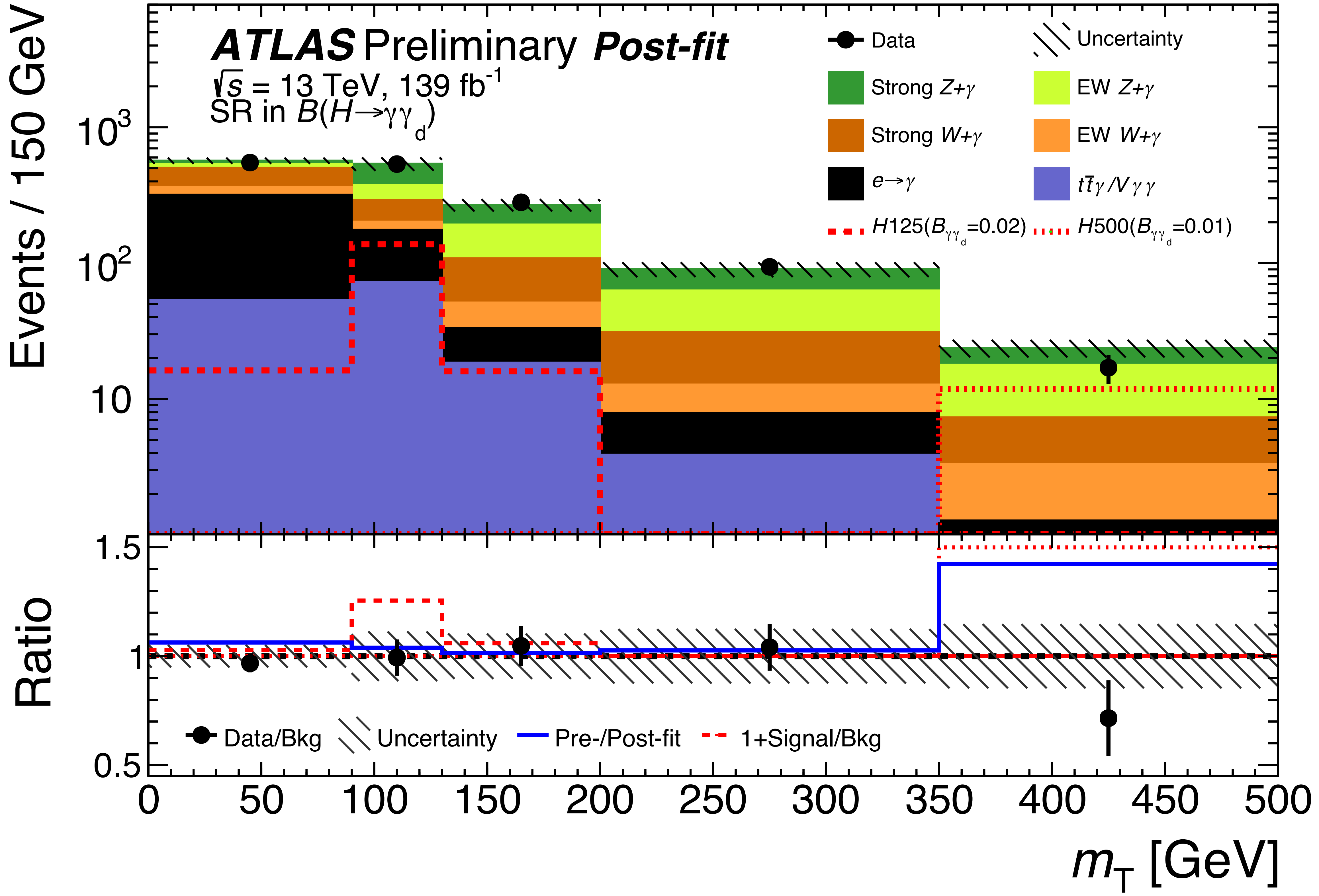
S(C)R := Signal (Contro) Region

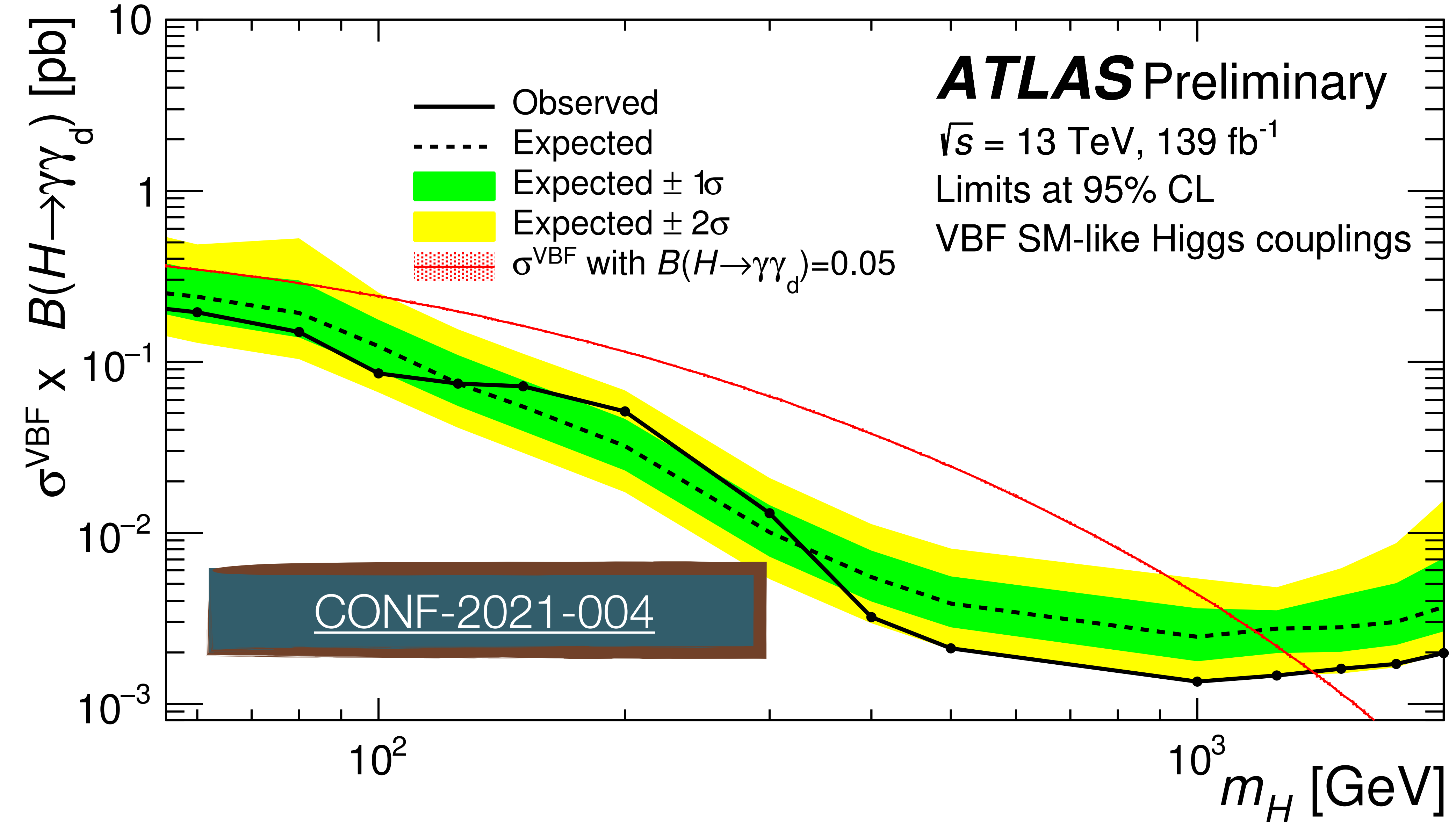
$$m_T(\gamma, E_T^{miss}) = \sqrt{2 p_T^{\gamma} E_T^{miss} \left[1 - \cos(\phi_\gamma - \phi_{E_T^{miss}})\right]}$$



ATLAS: Searches for electroweak production of two jets in association with a Higgs boson decaying fully or partially to invisible particles, including a final state photon

- **TOP**
  - Post-fit m_T (γ,E^{miss}_T) distribution in the inclusive signal region
  - As before the H → $\gamma\gamma_d$ decay signal is shown for two different mass hypotheses, 125 GeV and 500 GeV, and scaled to a B(H → $\gamma\gamma_d$) of 2% and 1%, respectively
- **BOTTOM**
  - At an observed (expected) upper limit on B(H → $\gamma\gamma_d$)
  - 95% CL limit on σ^{VBF} * B(H → $\gamma\gamma_d$) calculated for dominant VBF-produced production mode with different mass hypotheses

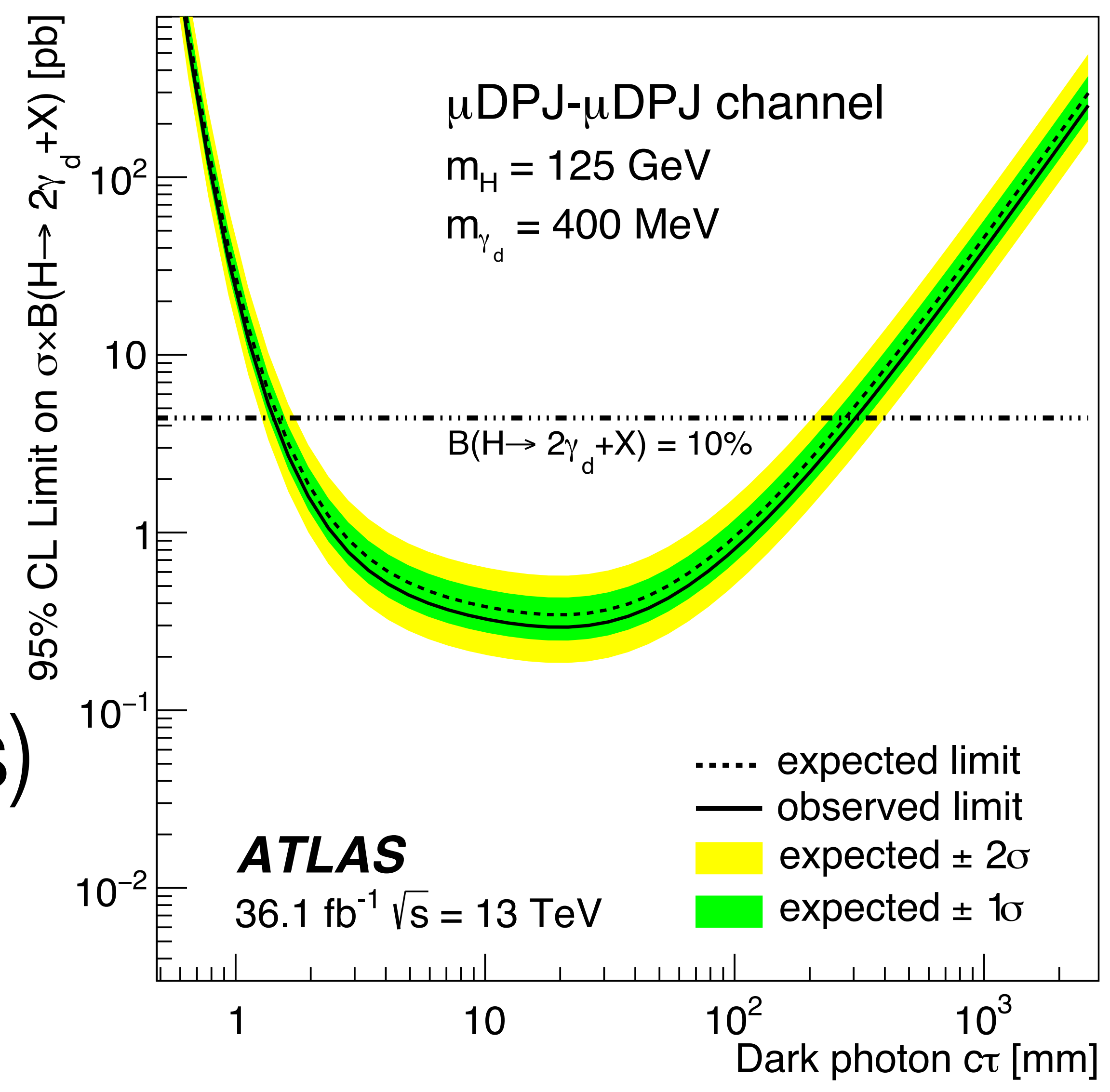


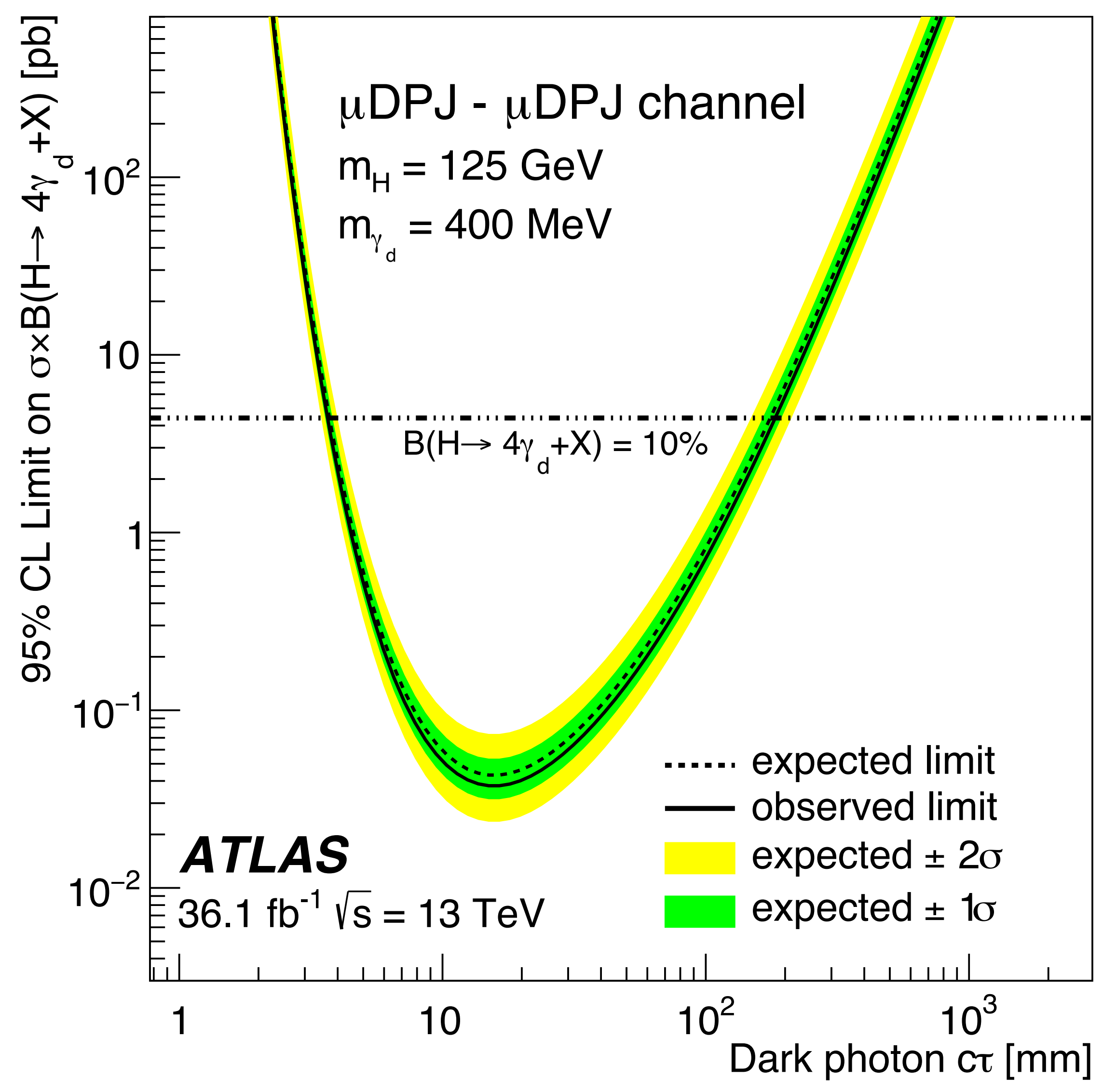


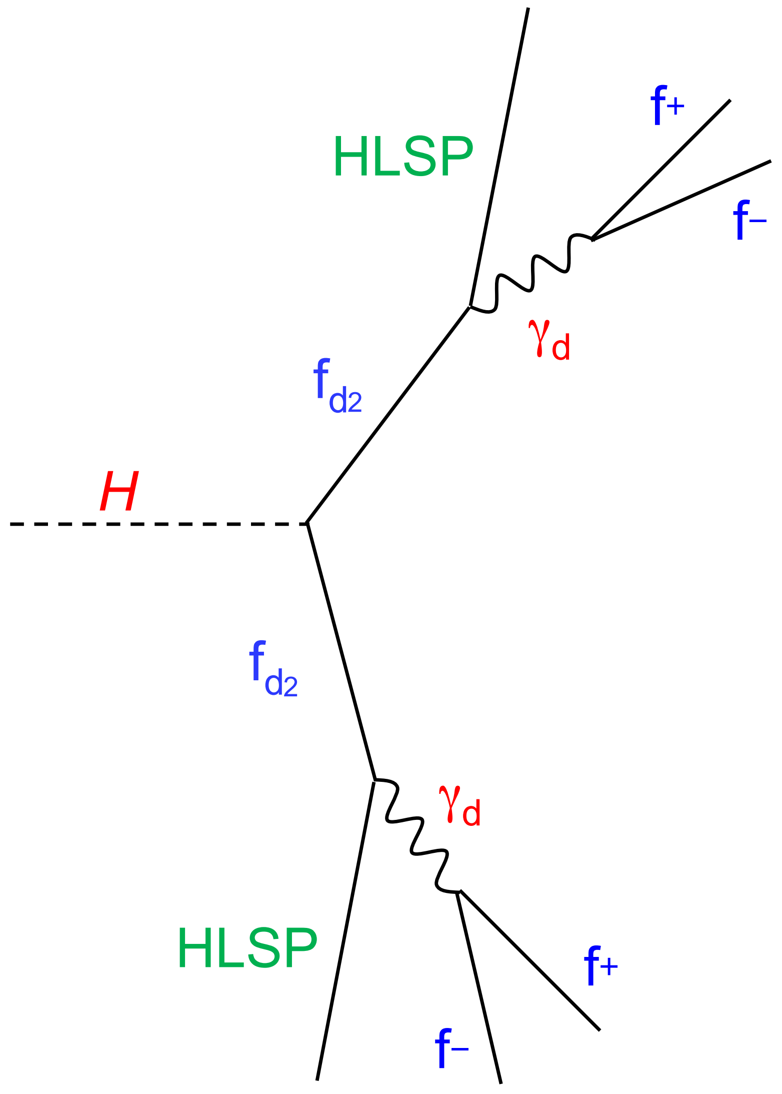
ATLAS: LLPs to light hadrons or collimated leptons

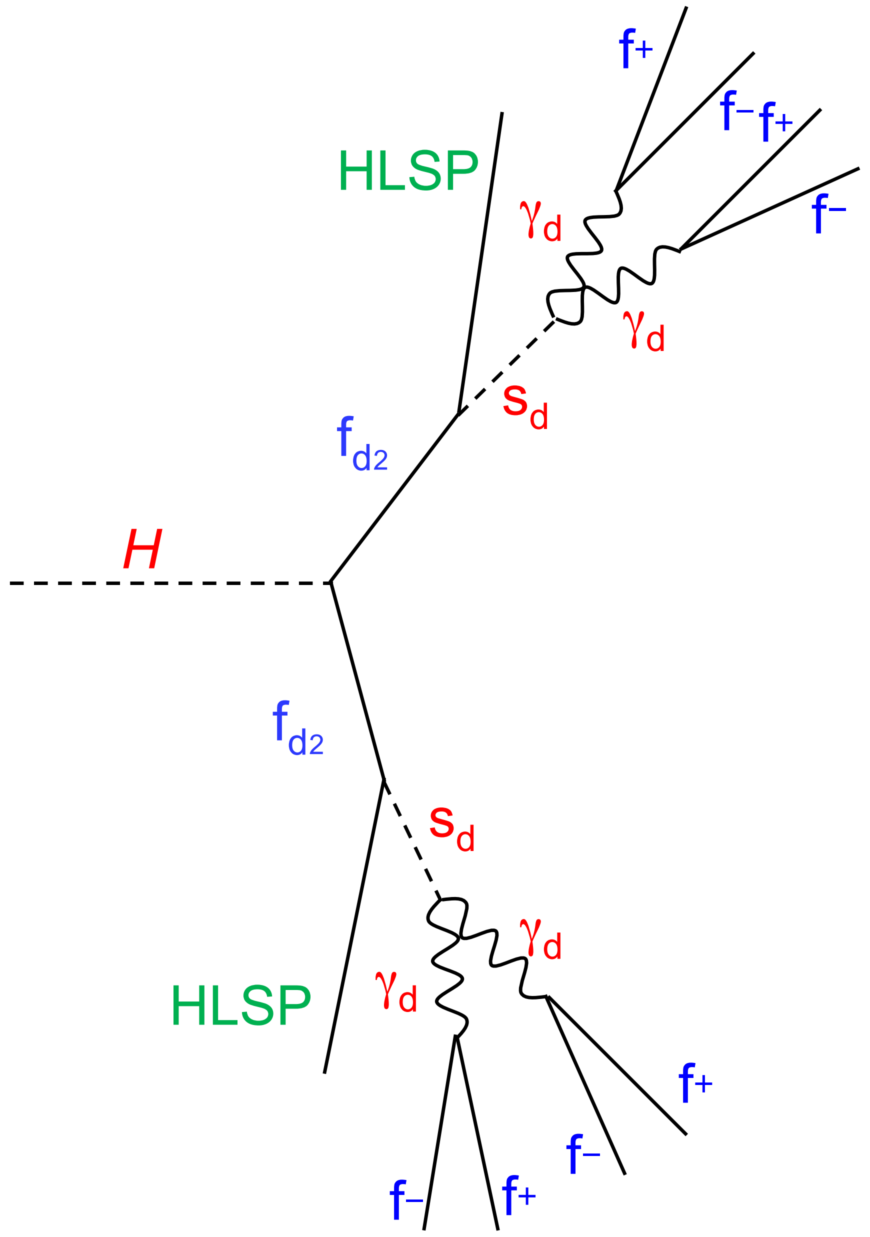
- Collimated groups of leptons and light hadrons in a jet-like structure == Dark photon jets (DPJs)
- **μDPJ or hDPJ (e and pions)**
- ABCD used and not excess measured
- Extrapolated signal efficiency for the
  - H → 2γ_d + X

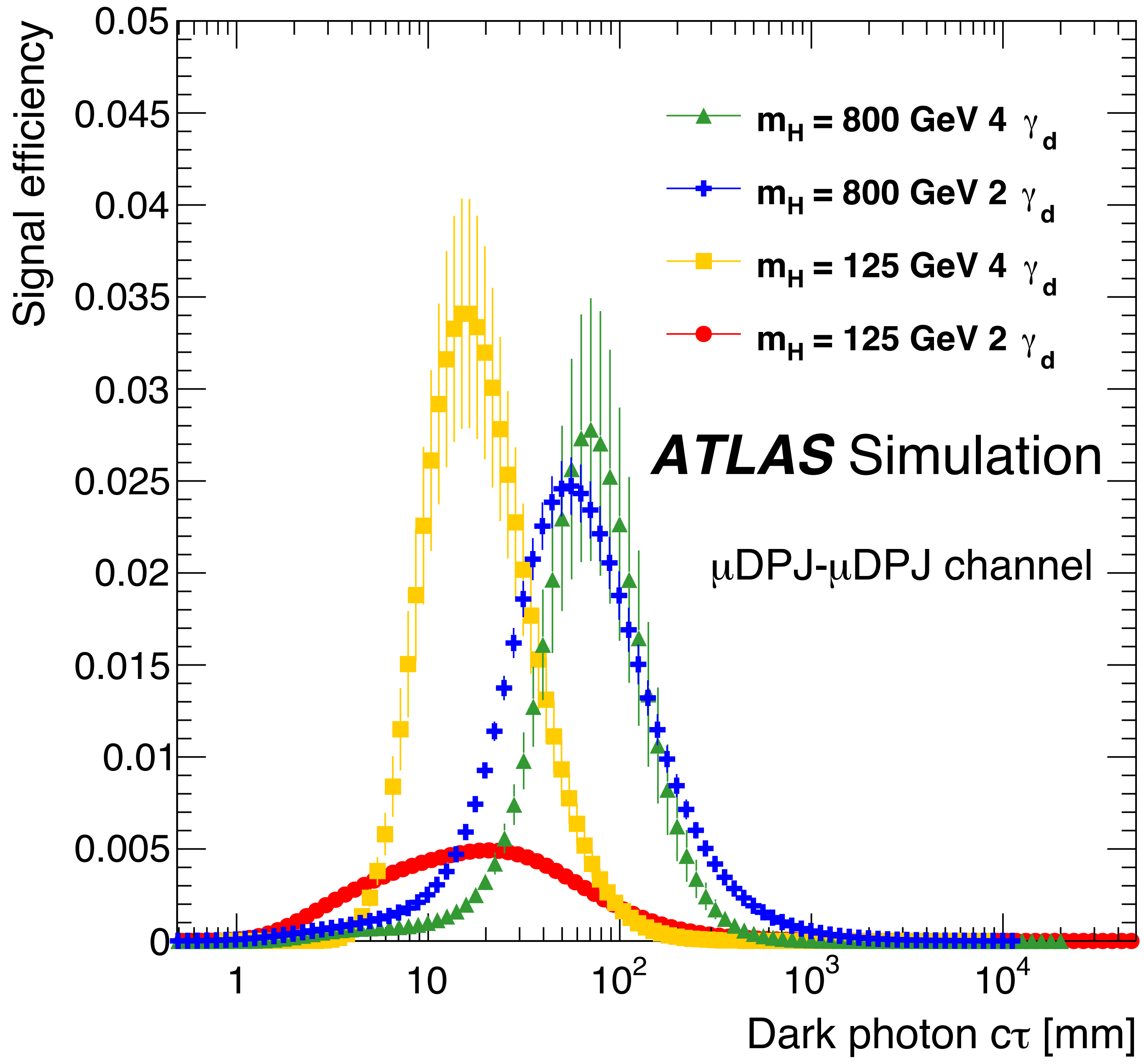
    (HLSP: hidden lightest stable particle)
  - H → 4γ_d + X (Sd: dark scalars)
- **as a function of cτ of the dark photon in the**
  - μDPJ–μDPJ
  - μDPJ–hDPJ
  - hDPJ–hDPJ channels







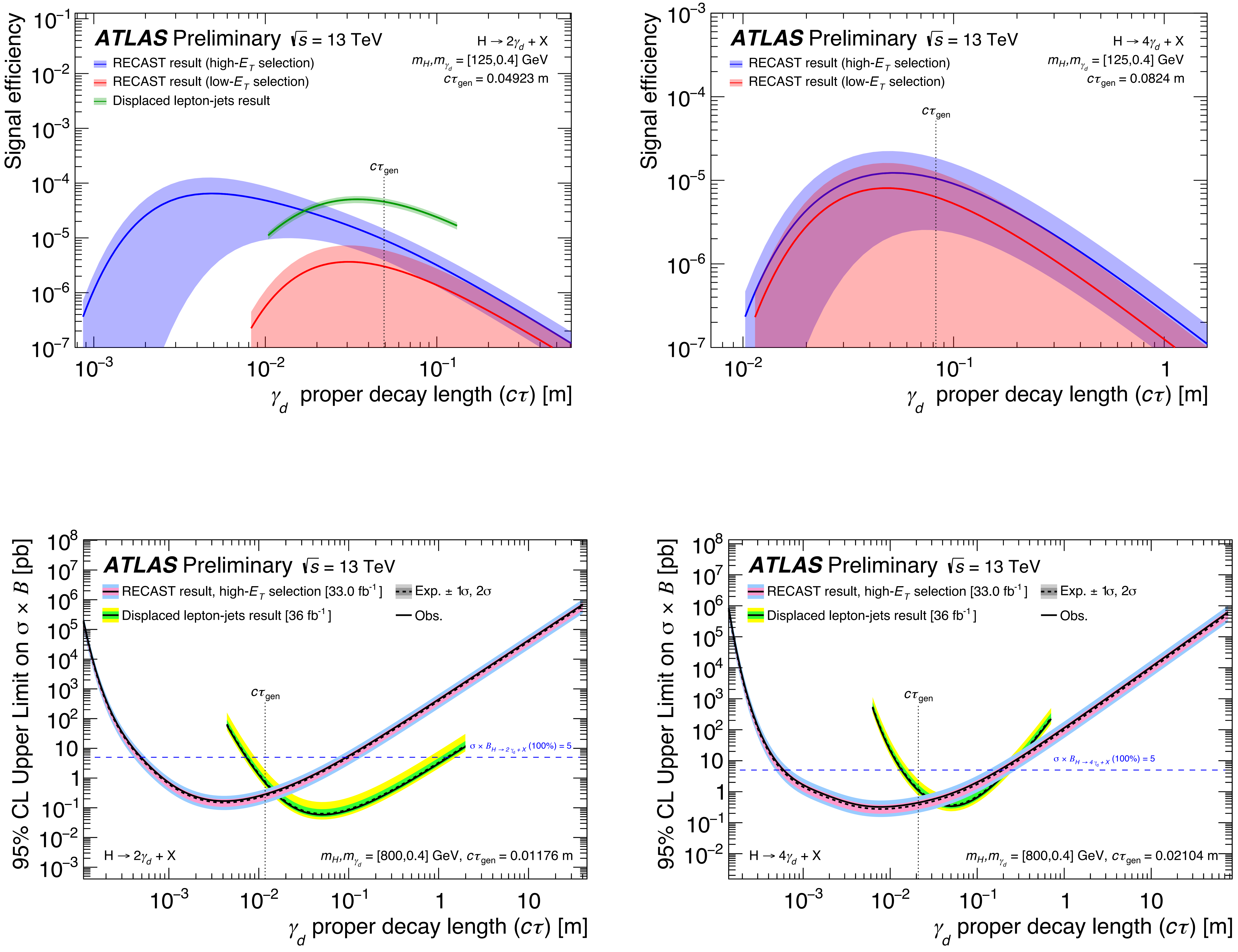




Eur. Phys. J. C 80 (2020) 450

ATLAS: Reinterpretation of the ATLAS Search for Displaced Hadronic Jets with the **RECAST** Framework

- An ATLAS search for displaced jets in the HCAL is **reinterpreted and used to constrain three NP models ⊄ of the original paper**
- Original signal ϕ→ss→ff′f′f’
  - Heavy neutral boson: ϕ; Neutral scalar boson: s
- **RECAST** is a framework designed to reuse estimates of backgrounds, systematic uncertainties and observations in the data from the original search to test alternative signal hypotheses
- Diff from previous analysis since using pairs of displaced **jets in the HCAL**



PHYS-PUB-2020-007

Summary of results

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- Phys. Rev. Lett. 124, 041801 (2020)
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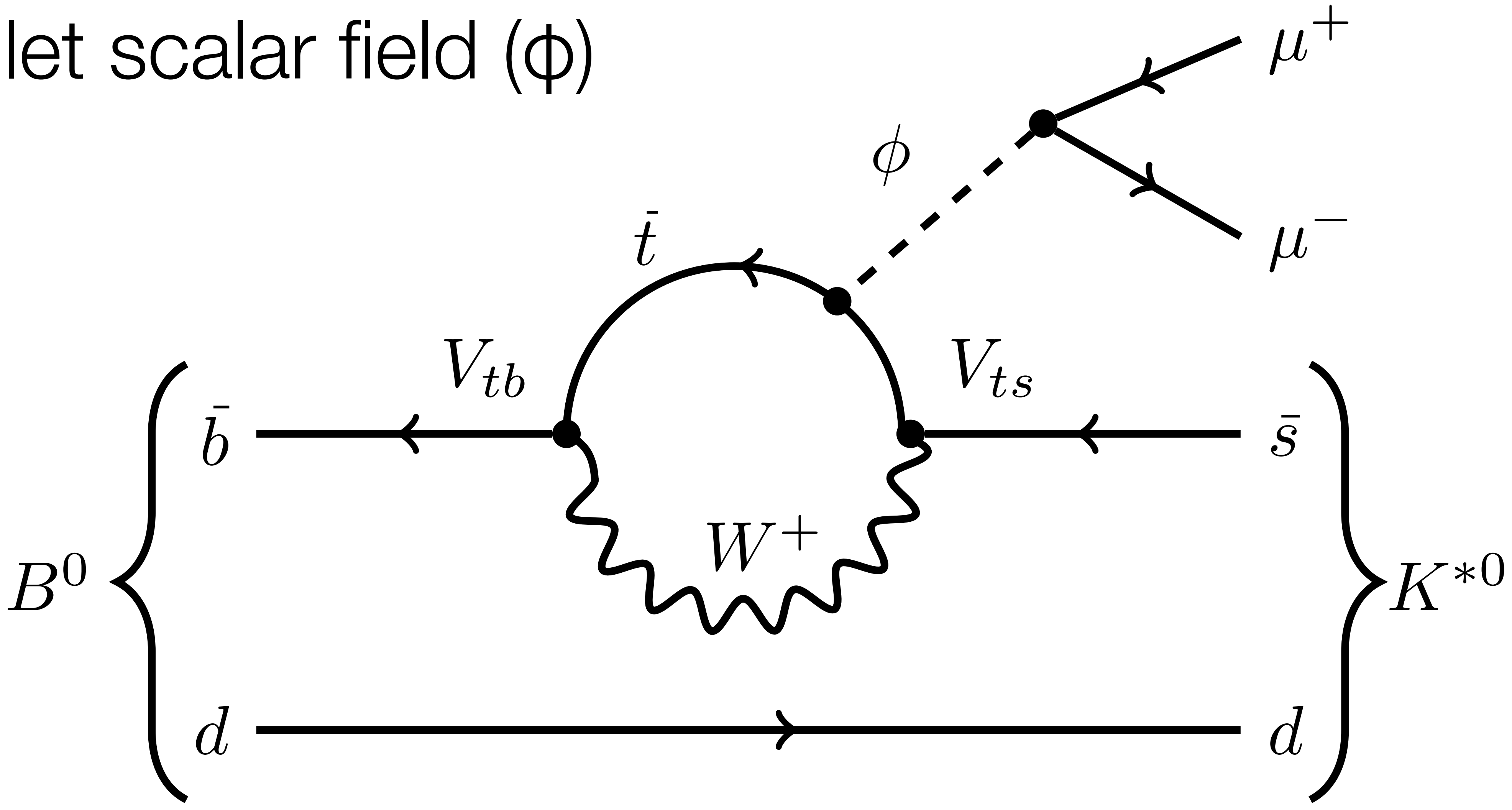
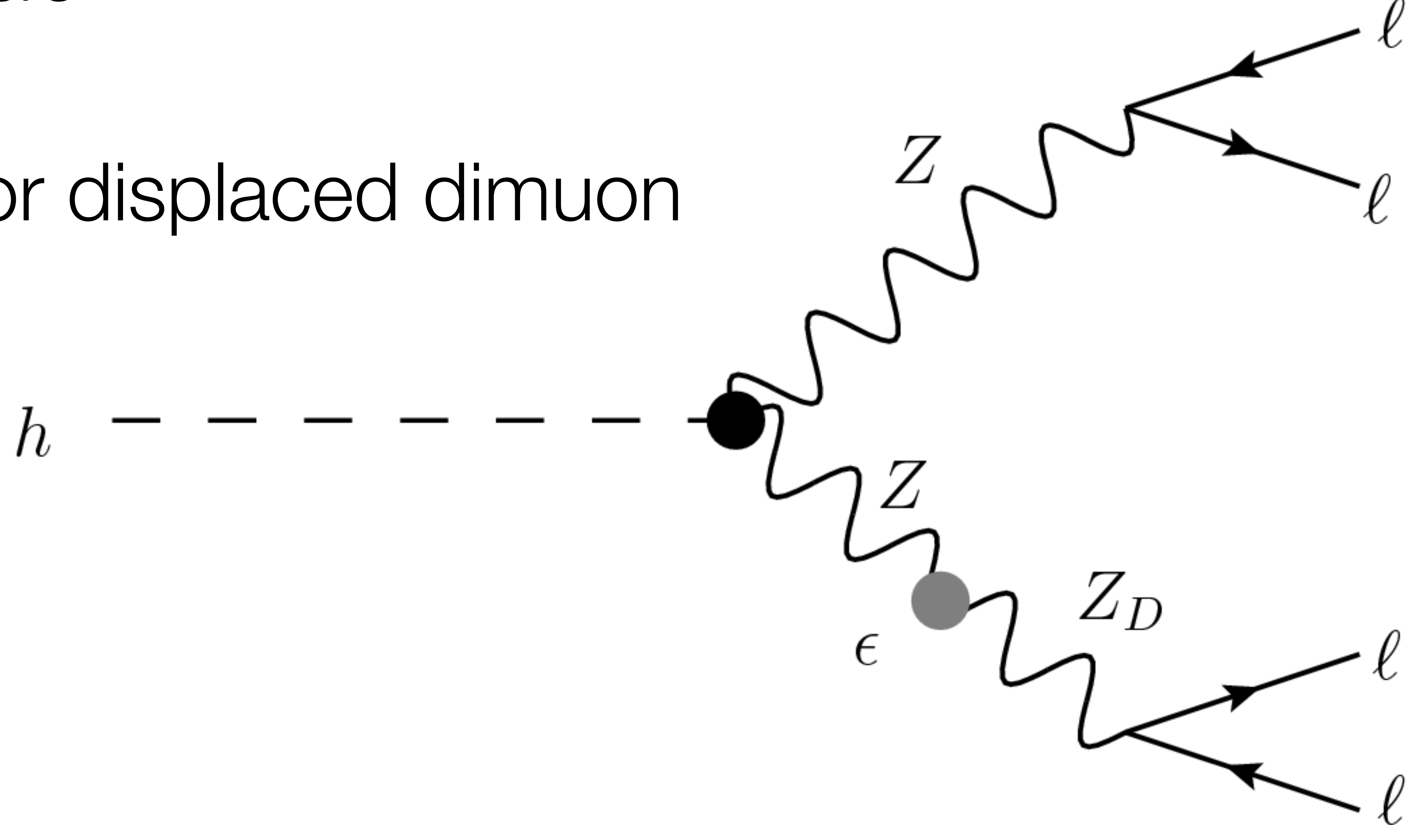
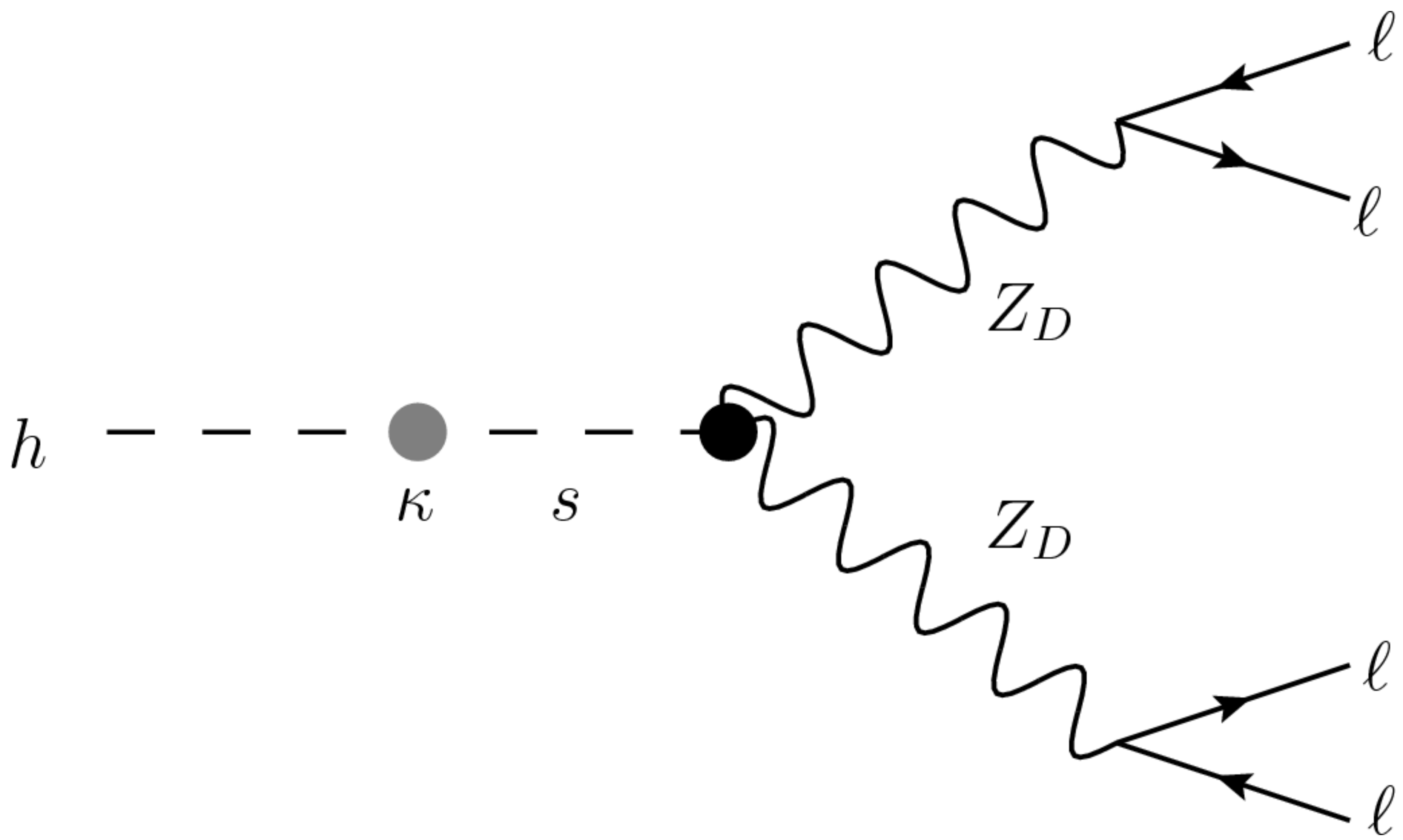
CMS: Search for long-lived particles decaying into two muons

in pp collisions at √s = 13 TeV using data collected with high rate triggers

- **NEW**: Available on CERN CDS information server: search for displaced dimuon resonances (also as a preliminary public page)
- 2017 and 2018 which is 101 fb^{-1} scouting data
- Sensitive to DP (Zd)
  - via the Higgs mixing (denoted as κ)
  - via the kinetic mixing coupling (denoted as ε)
- And a singlet scalar field (ϕ)

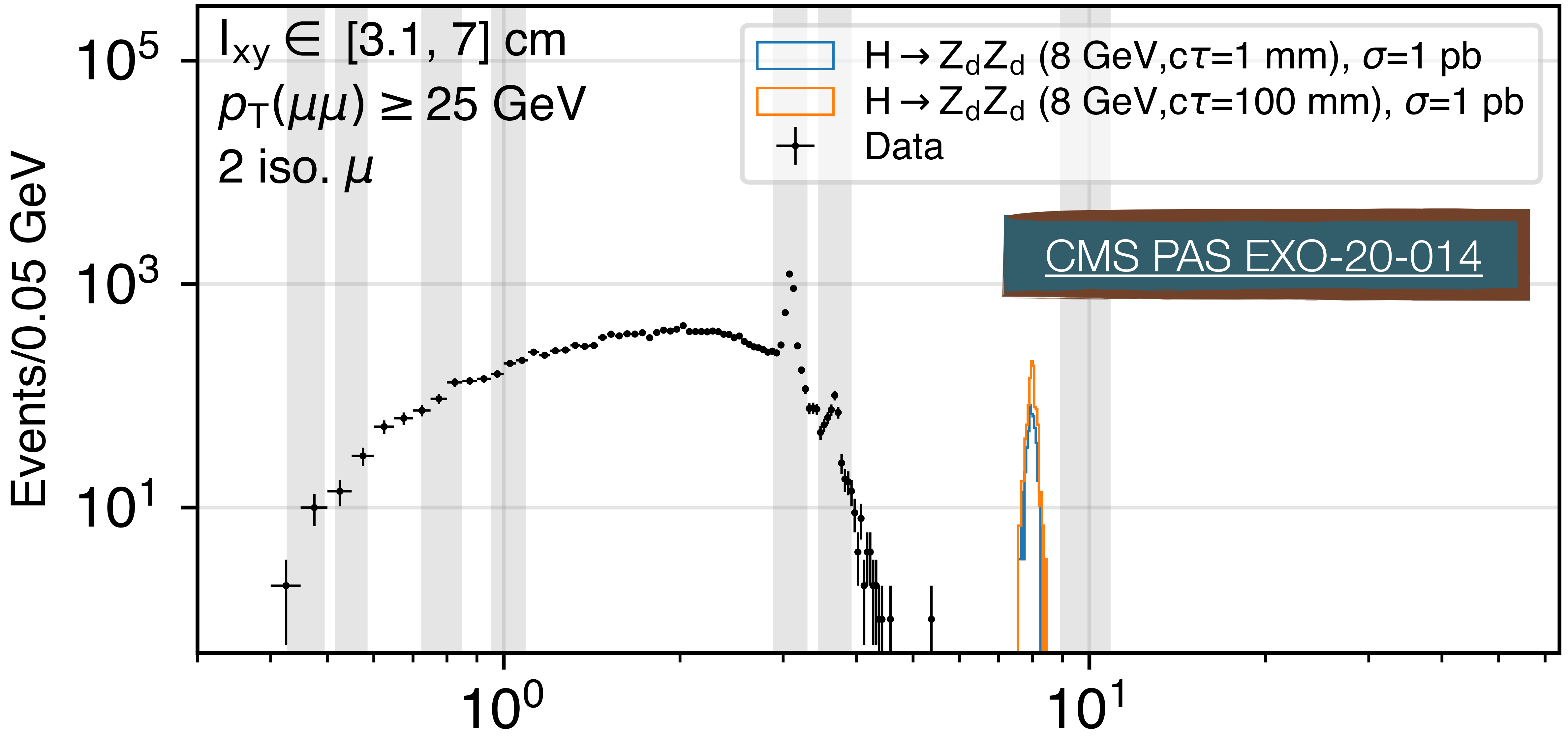


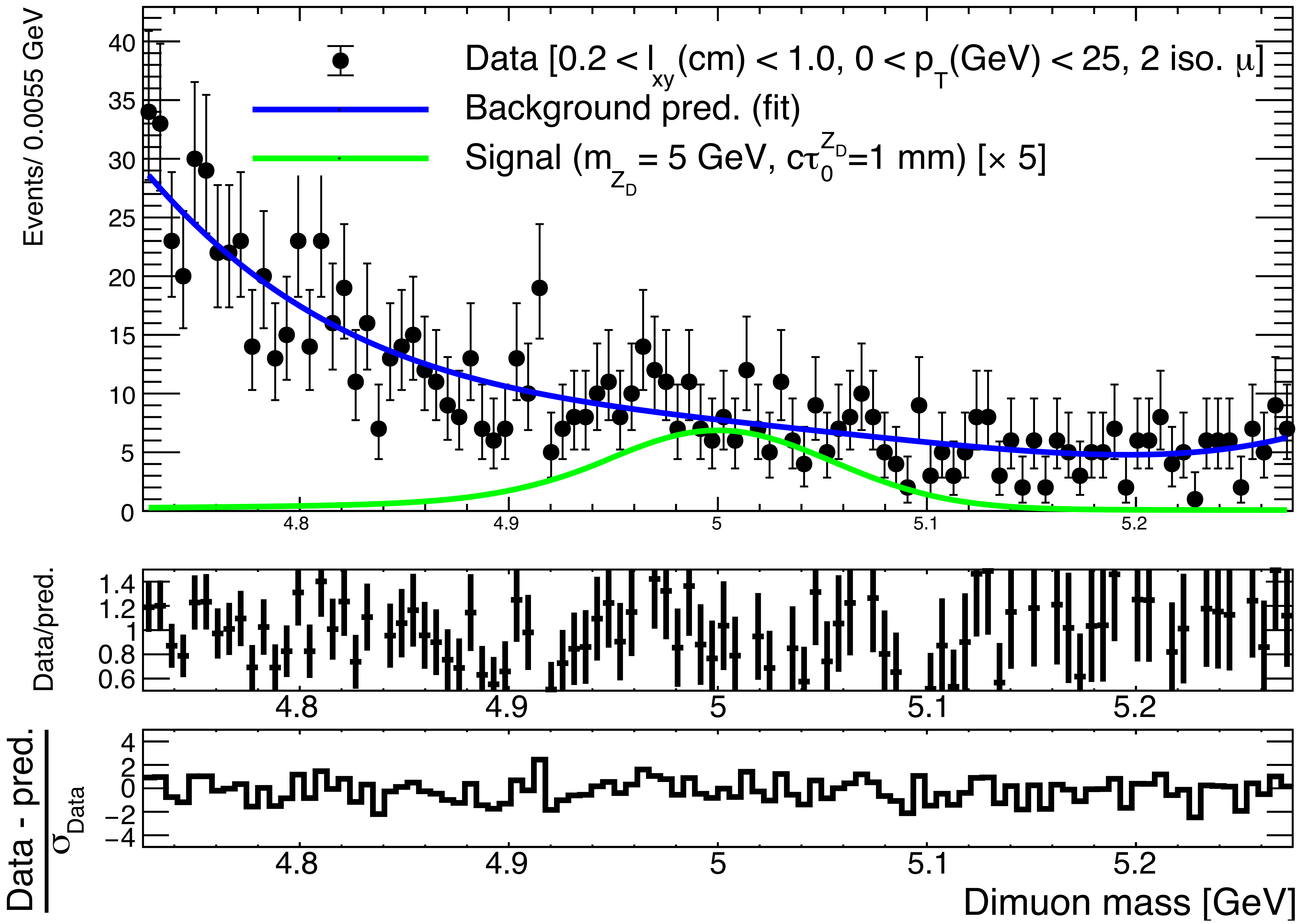




CMS: Search for long-lived particles decaying into two muons

- Importance of scouting trigger (like TURBO in LHCb)
- **Efficiency of such triggers measured as a function of the dimuon** transverse displacement l_{xy} from the interaction point and of the minimum p_T^{μ} of the pair, using events with at least two muons selected with orthogonal standard triggers
- **CMS pixel tracker geometry** used for an l_{xy} categorisation plus bins of dimuon transverse momentum brings maximisation of the sensitivity to different signal topologies
- A search for a resonant dimuon peak in each mass window is performed

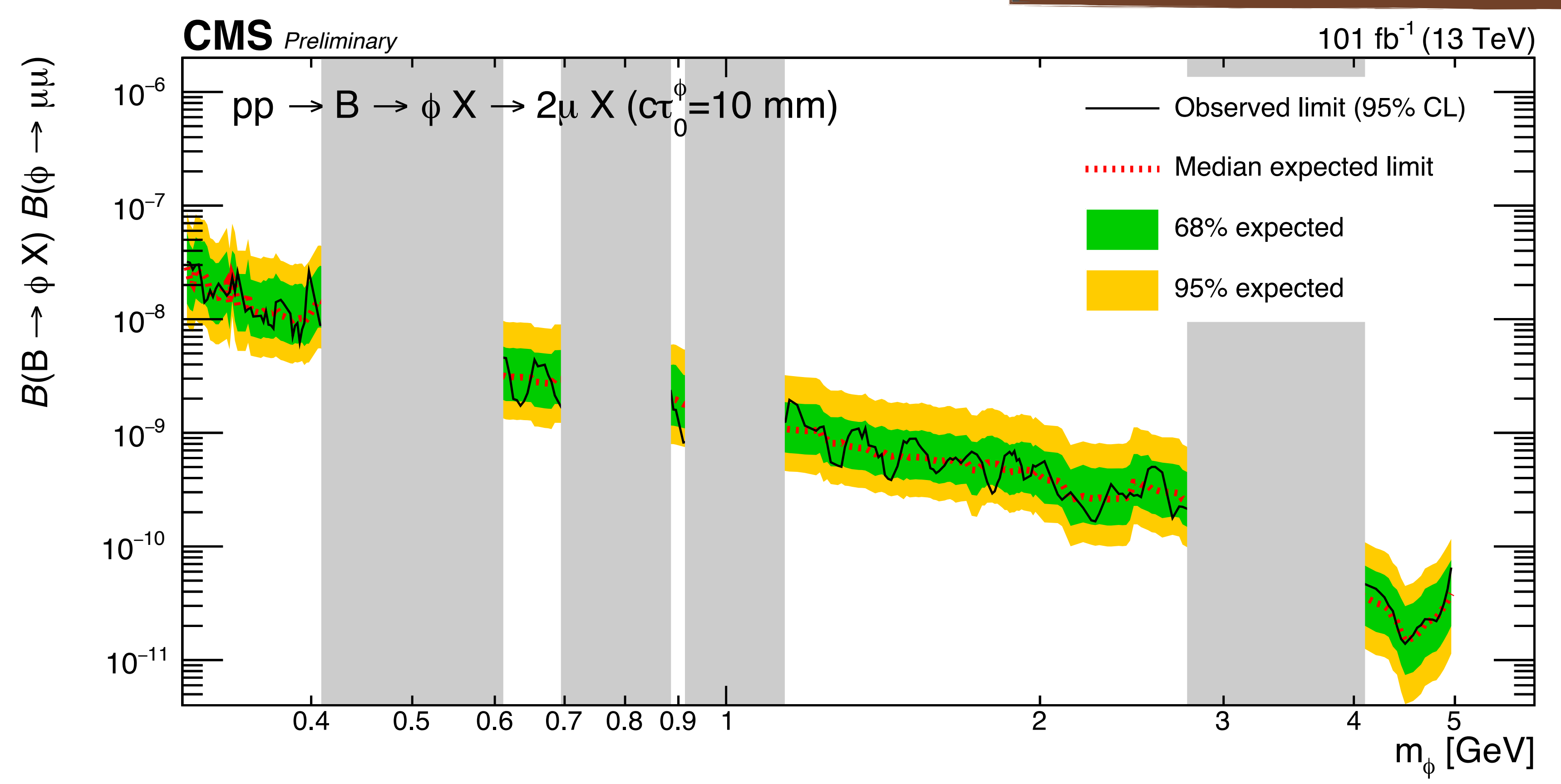


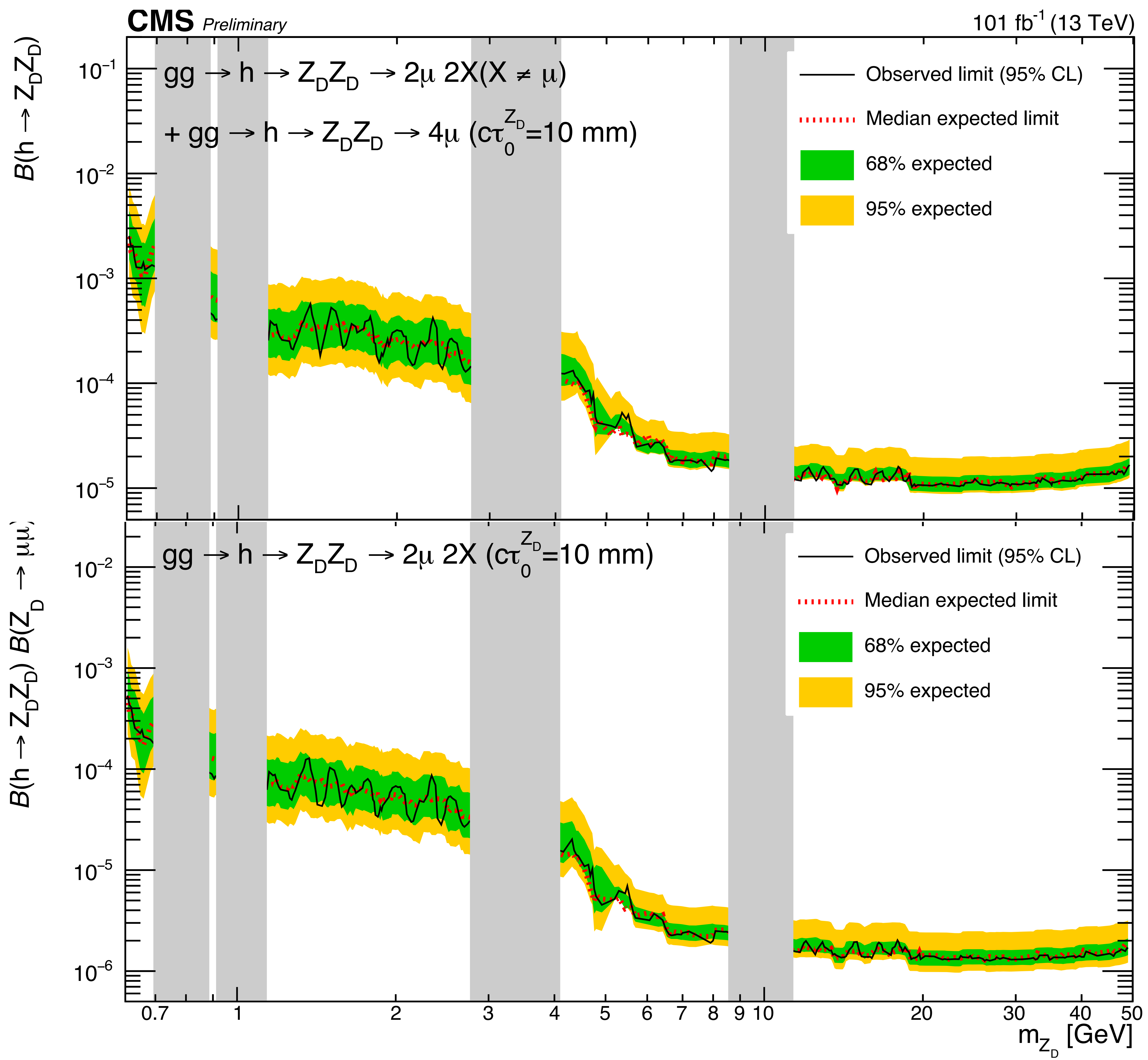


CMS PAS EXO-20-014

CMS: Search for long-lived particles decaying into two muons

- Very competitive constraints on models of BSM physics
  - Theorists will have access to a state-of-the-art dataset for reinterpretation
- **Bonus**: Exclusion limits at 95% CL on the branching fraction B(B → ϕX) * B(ϕ → μμ) as a function of the signal mass (m_ϕ) hypothesis for a given lifetime: **LHCb, careful!**
  - Not easy to compare since CMS limits are on the inclusive B → ϕX branching ratio, while the LHCb limits are on the exclusive B0 → ϕK* and B^+ → ϕK^+ branching ratios
- Exclusion limits at 95% CL on the branching fractions for h → $Z_D Z_D$
- **B(h → $Z_D Z_D$) and as B(h → $Z_D Z_D$) × B(Z_D → μμ)**



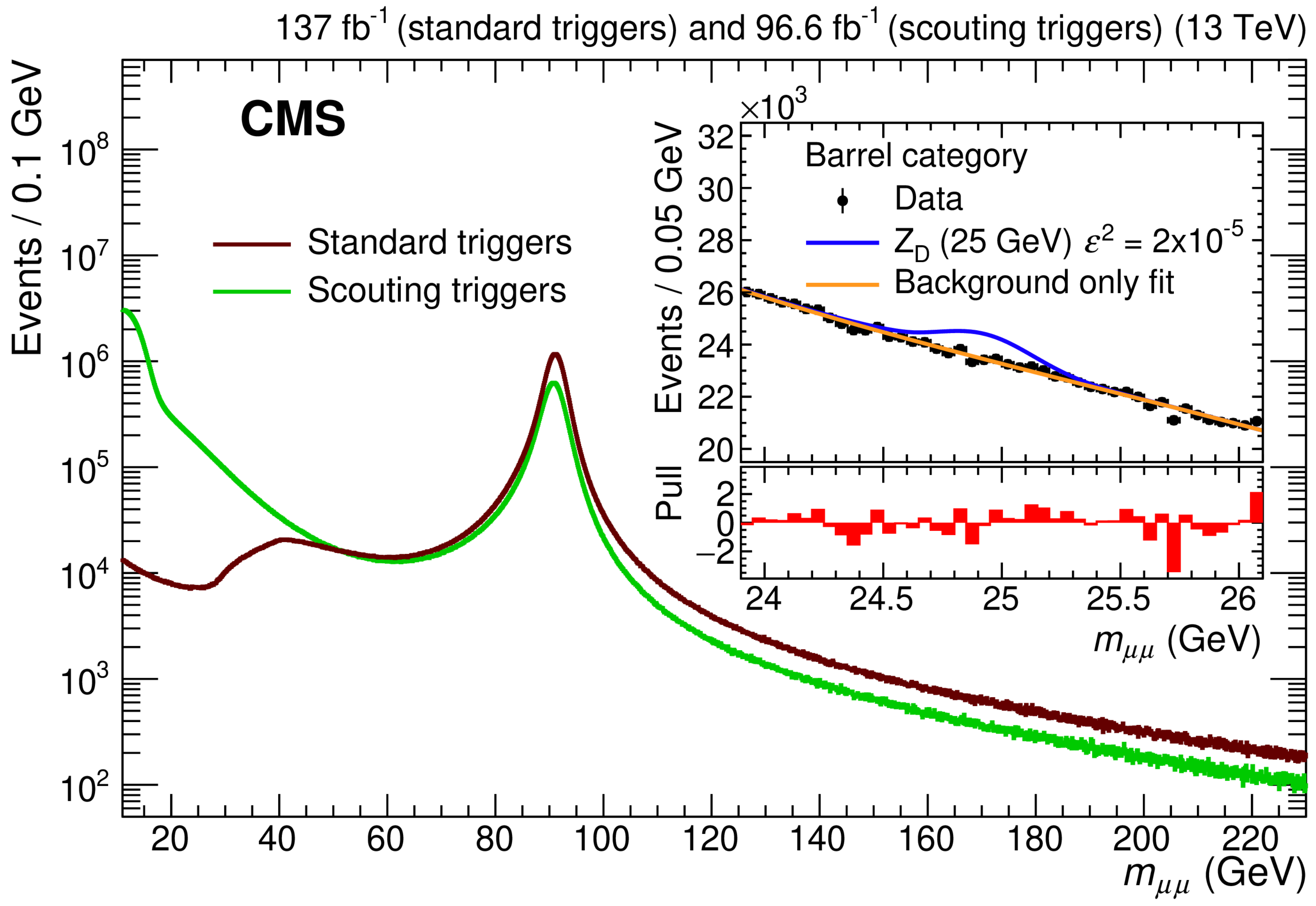


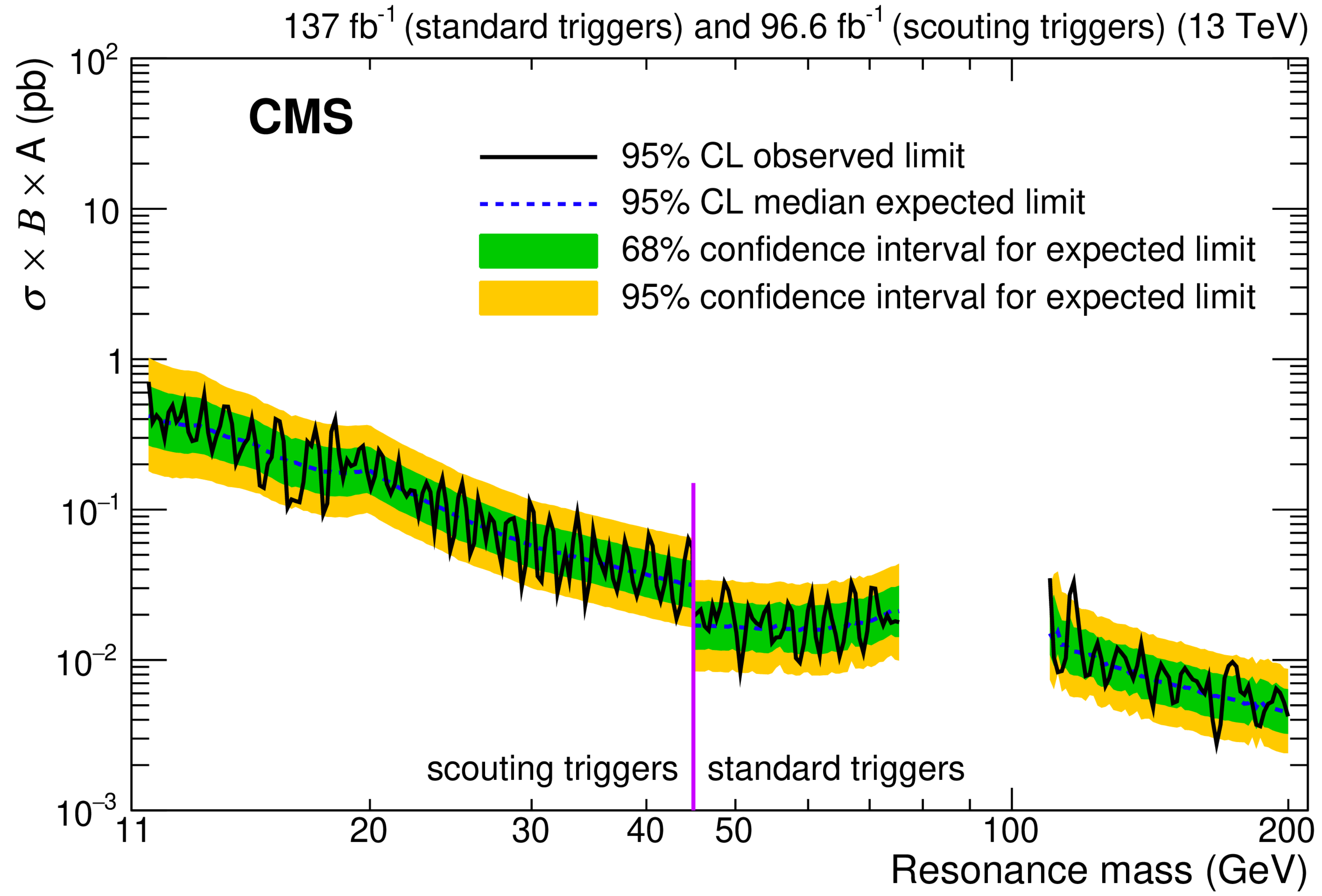
Phys. Rev. Lett. 124 (2020) 131802

CMS: Search for a narrow resonance lighter than 200 GeV decaying to a pair of muons

in proton-proton collisions at $\sqrt{s}$=13 TeV

- Search for a narrow resonance decaying to a pair of oppositely charged muons
- **The search looks for a narrow resonance in the 11.5–200 GeV mass range, omitting the 75–110 GeV range where Z boson production dominates**
- For dimuon resonance masses below ~40 GeV *scouting*!
- E.g. “barrel” (|η| < 0.9) search for a 25 GeV resonance (**TOP**)
- In order to extract the signal from data, a simultaneous binned maximum likelihood fit is performed to the $m_{\mu\mu}$ distributions in the “barrel” and “forward” (0.9 < |η| < 1.9) event categories
- Expected and observed upper limits at 95% CL on the product of the signal cross section (σ) for a narrow resonance, branching fraction to a pair of muons (B), and acceptance (A) as a function of the mass of a narrow resonance (**BOTTOM**)



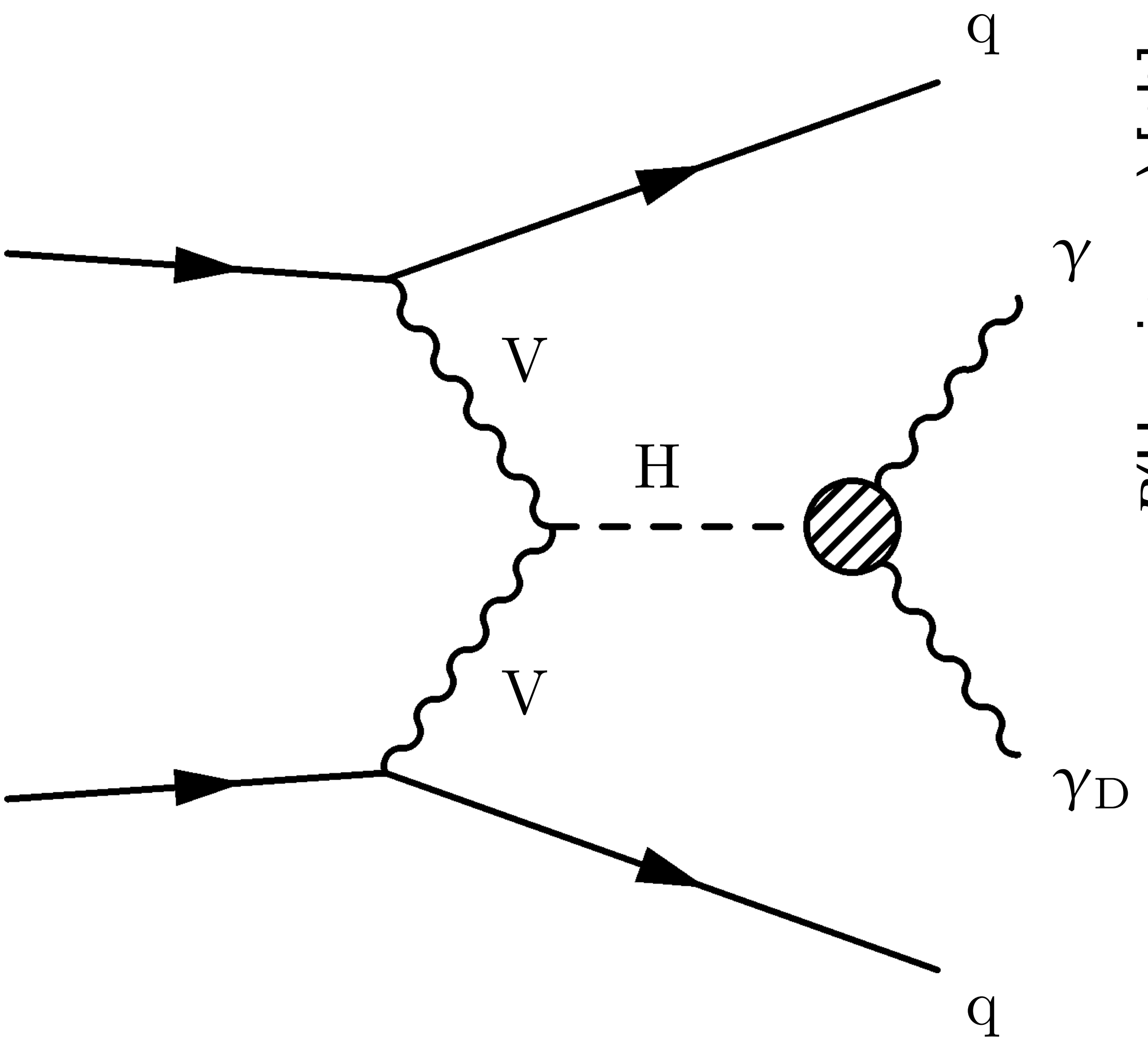


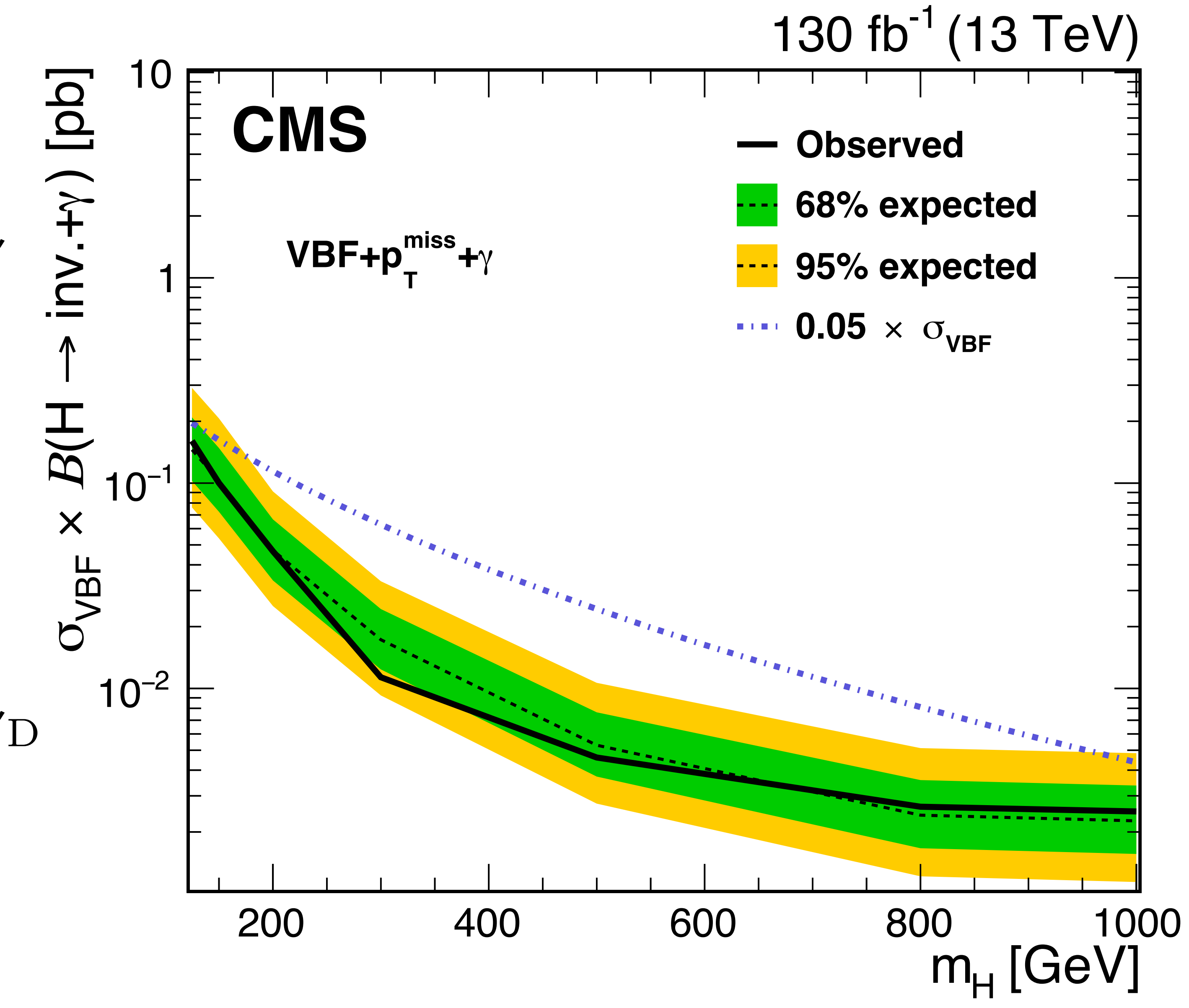
CMS: Search for dark photons in Higgs boson production via vector boson fusion

in proton-proton collisions at $\sqrt{s}$ = 13 TeV

JHEP 03 (2021) 011

- **Search using 2016 to 2018 datasets (analysed independently) ~ 130 fb^{-1}**
- Similar to what previously present for ATLAS (**but this published before**)
- Expected and observed upper limits at 95% CL



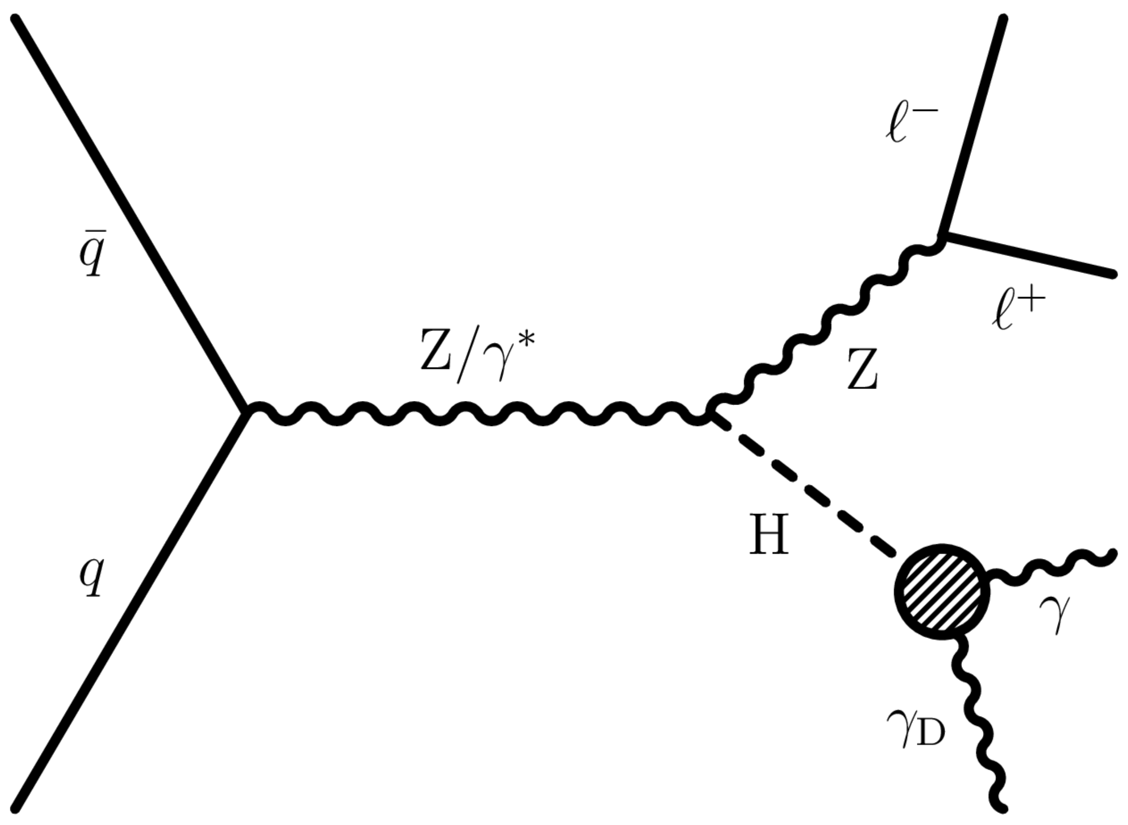


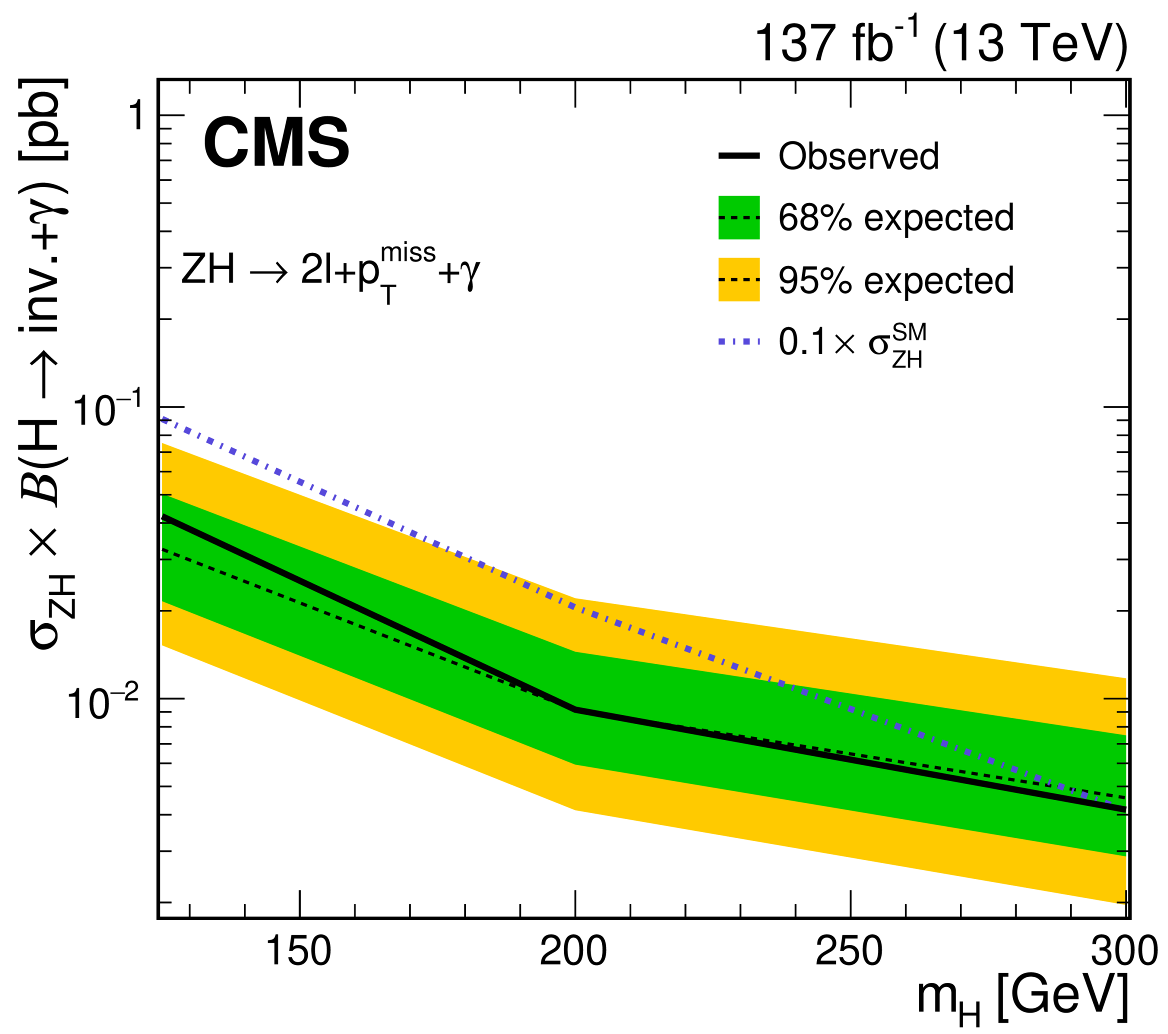
CMS: Search for dark photons in Higgs boson produced in association with Z bosons

in proton-proton collisions at $\sqrt{s}$ = 13 TeV

JHEP 10 (2019) 139

- **Search using 2016 to 2018 datasets (analysed independently) ~ 139 fb^{-1}**
- Signal topology: two oppositely charged same-flavour high p_T isolated leptons, electrons or muons, compatible with a Z boson decay, large p miss T , an isolated high p_T photon, and little jet activity
- Expected and observed upper limits at 95% CL





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LHCb

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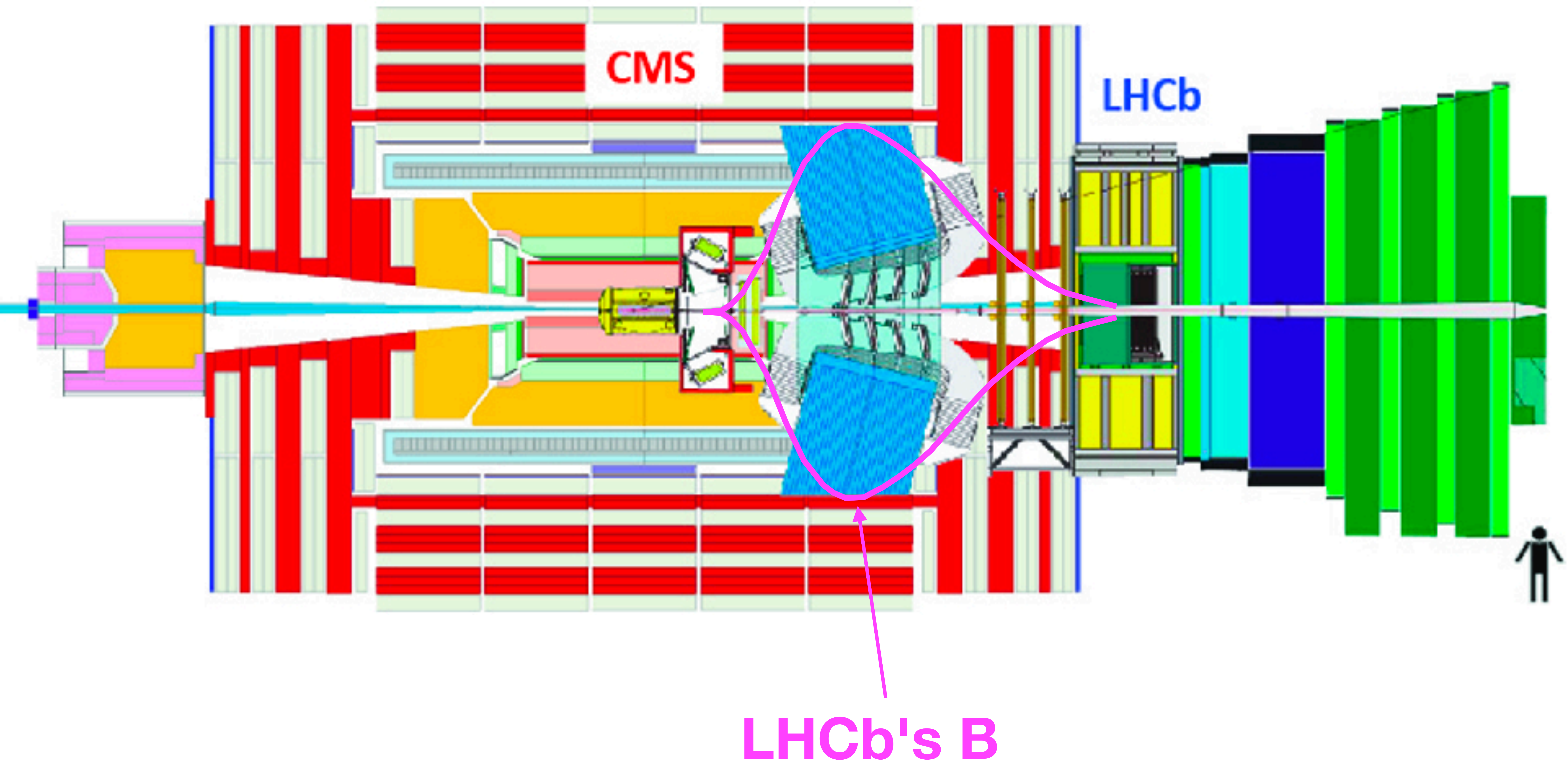
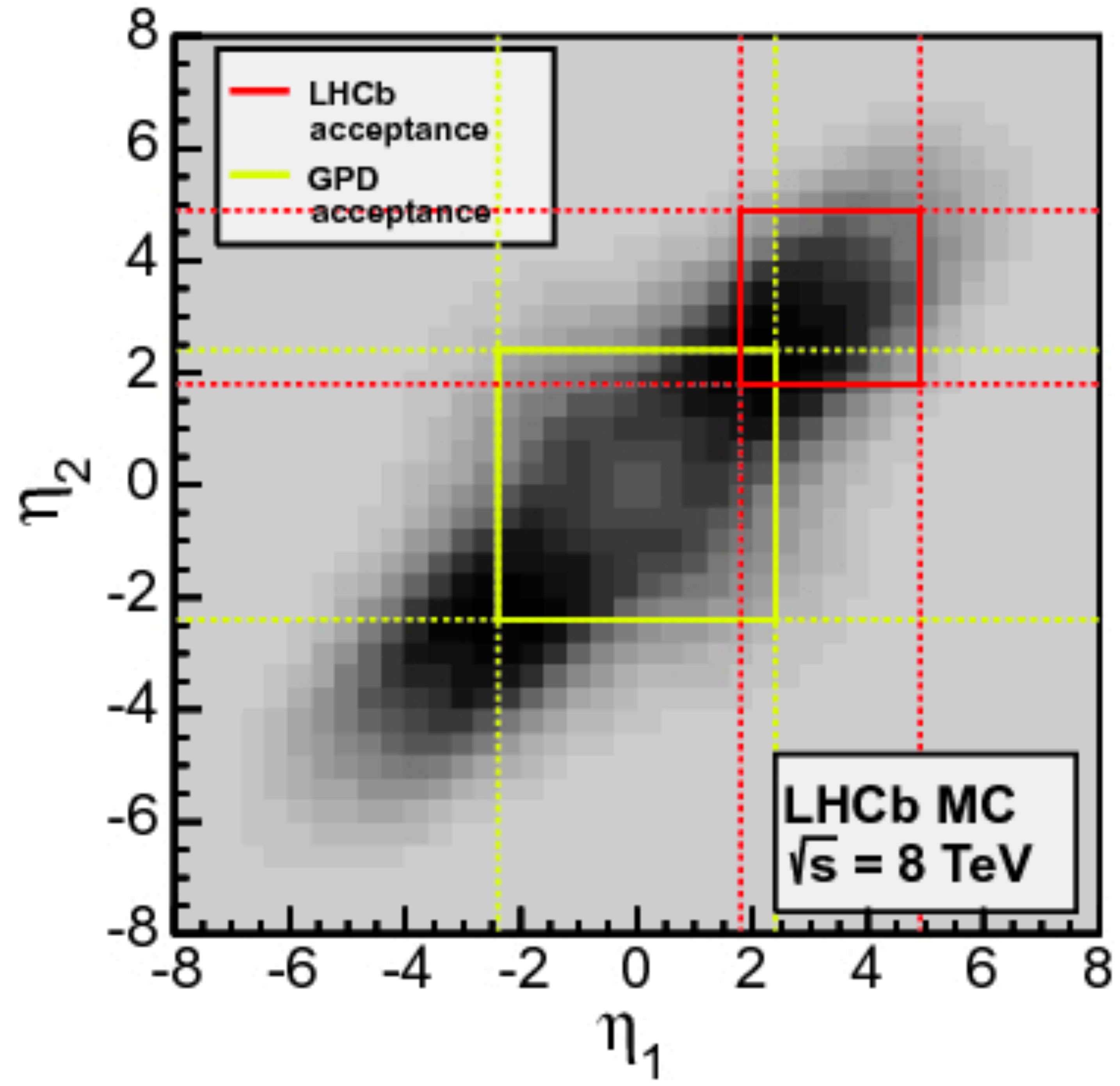
LHCb: is CMS so much different?





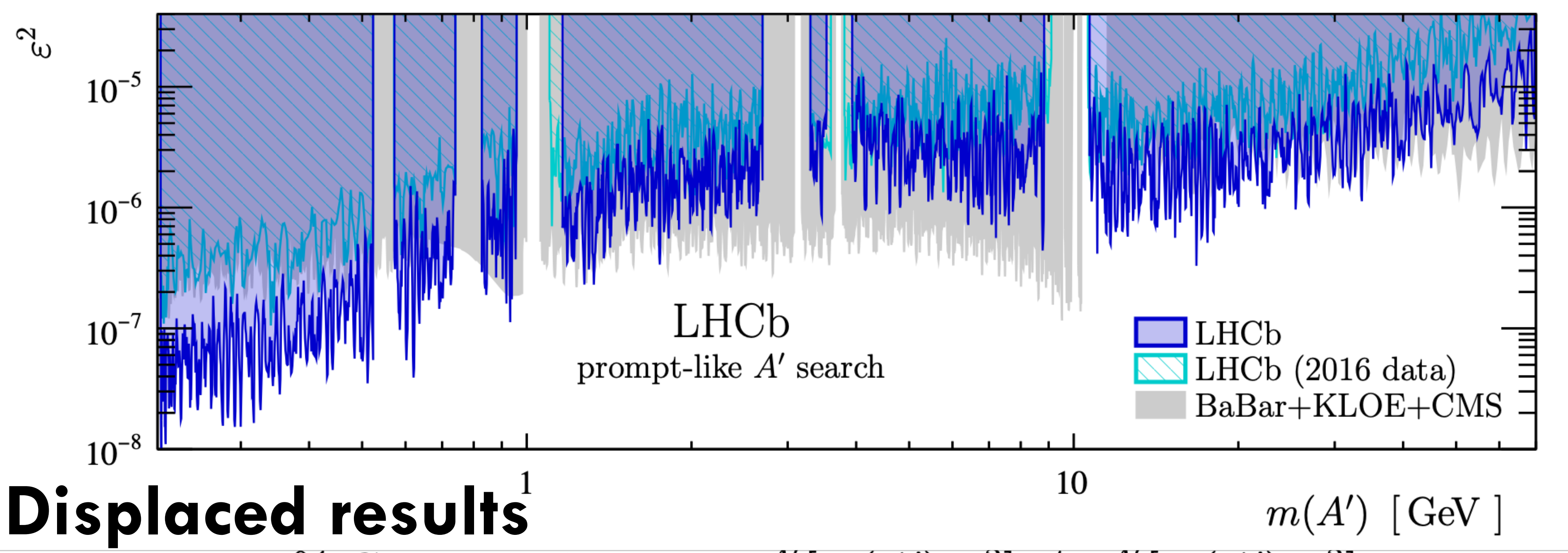
Link 1 and 2

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

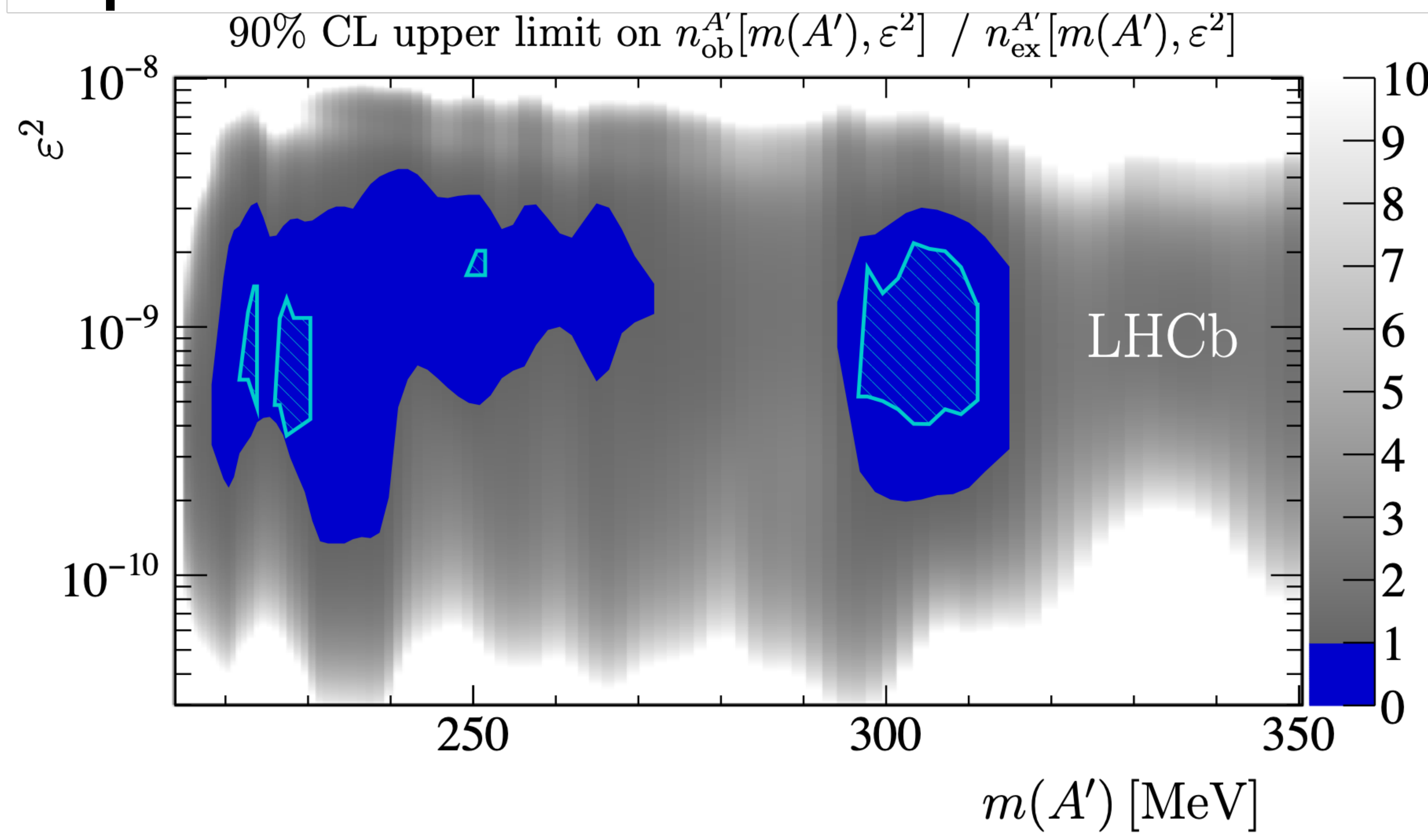
LHCb: Searching for Dark Photons

- 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^*
  - $A' \rightarrow \mu^+\mu^-$ can be **normalised** to $\gamma^* \rightarrow \mu^+\mu^-$
  - 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

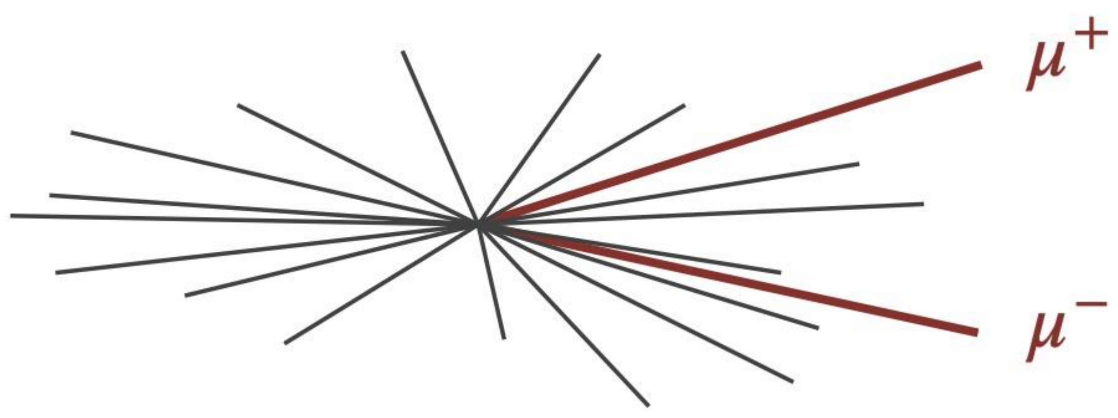
JHEP 10 (2020) 156

LHCb: Low-mass dimuon resonances / 1

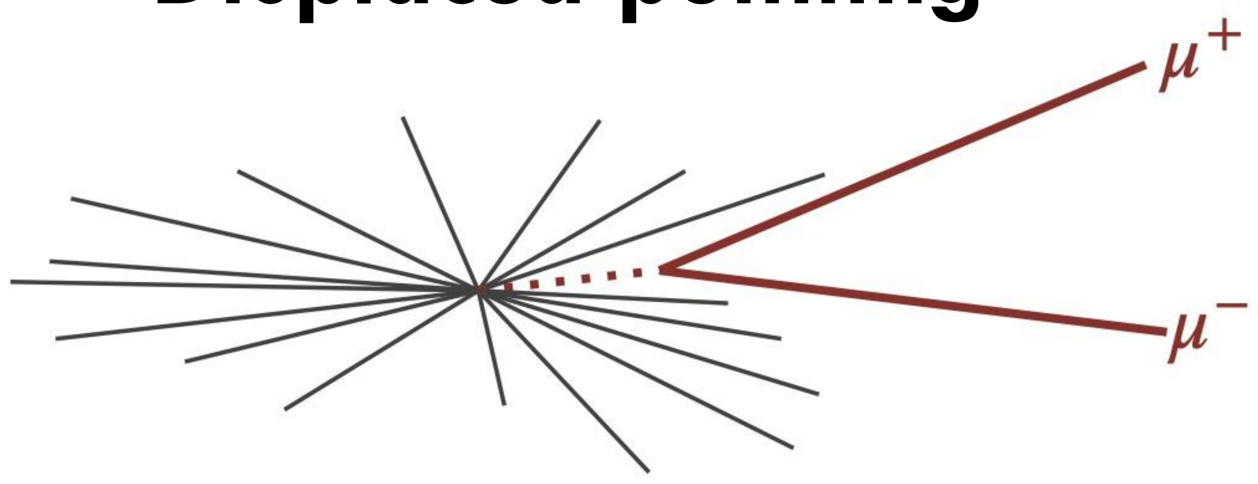
- Non-minimal searches, example signatures:

+ no isolation requirement
+ non-zero width considered

Inclusive Prompt

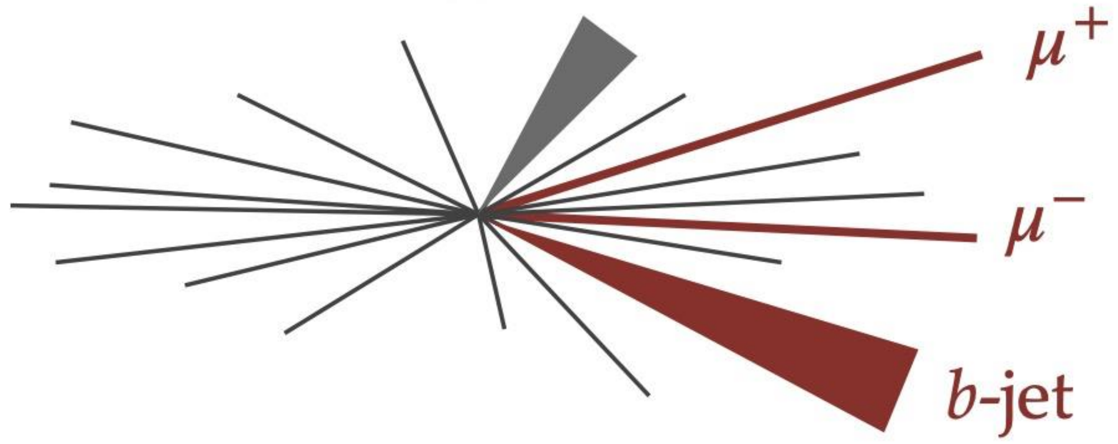


Displaced pointing

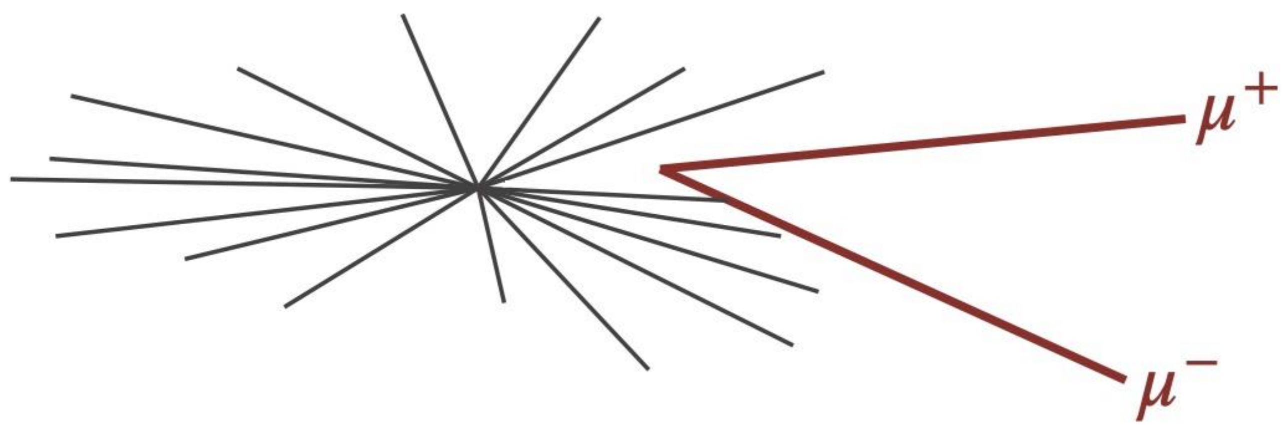


+ non-zero width considered

Prompt + b-jet



Displaced non-pointing



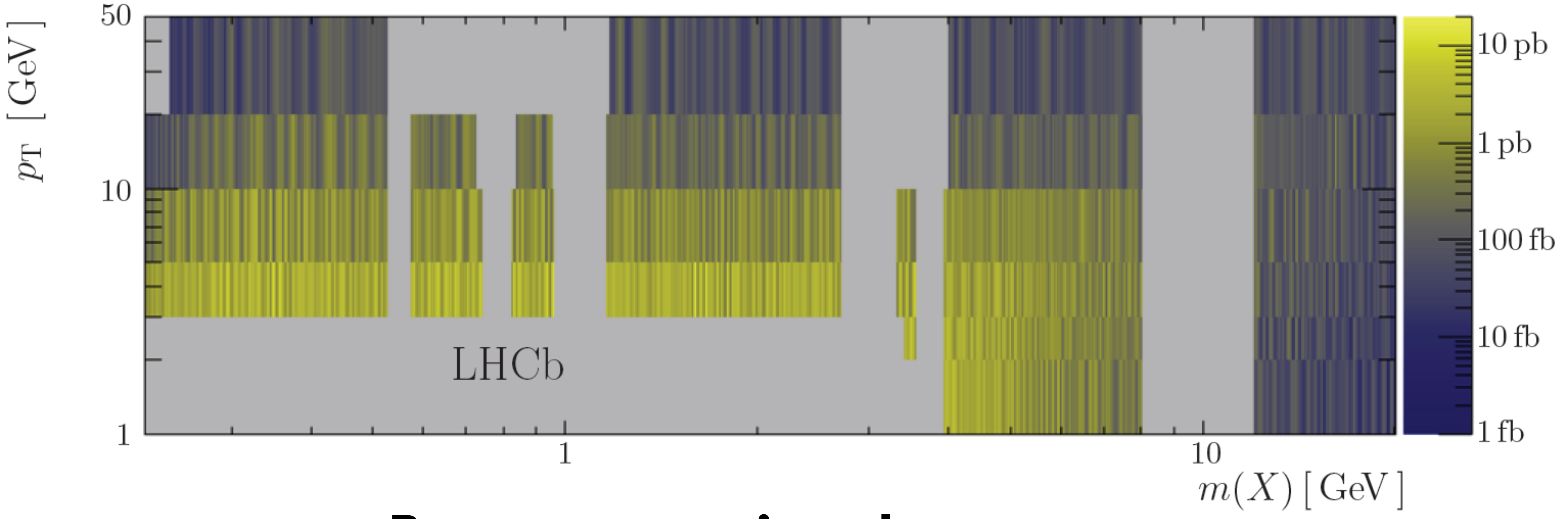
[Taken from I. Kostiuk's talk](#)

[JHEP 10 (2020) 156](#)

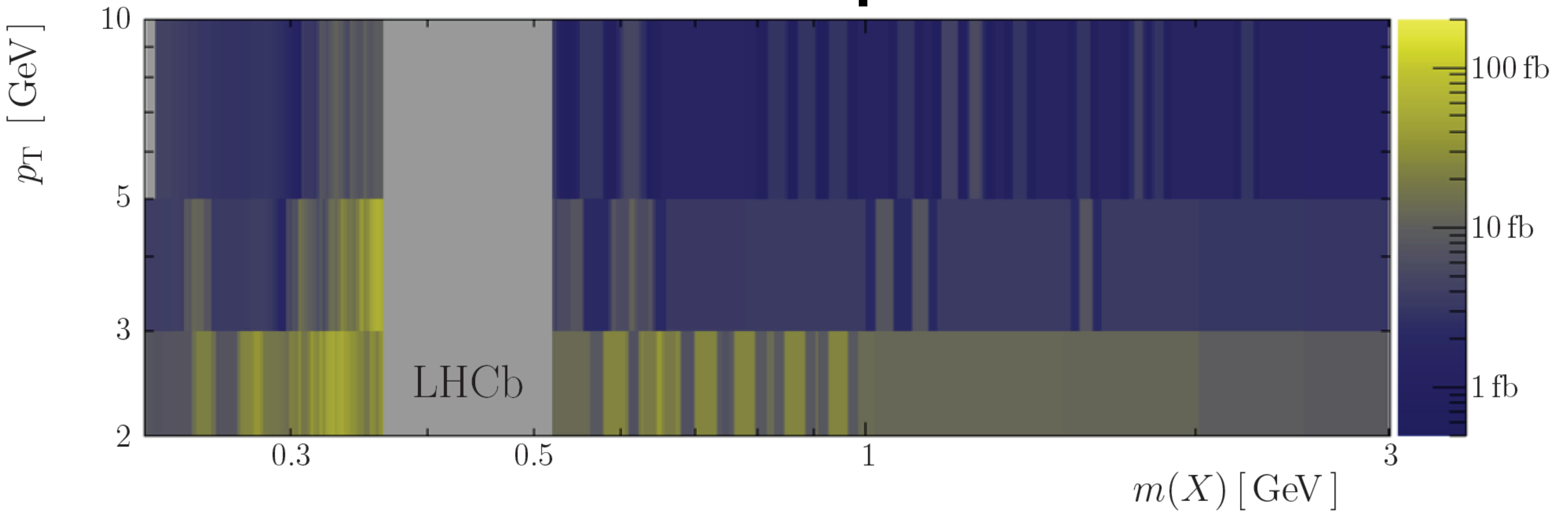
LHCb: Low-mass dimuon resonances / 2

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

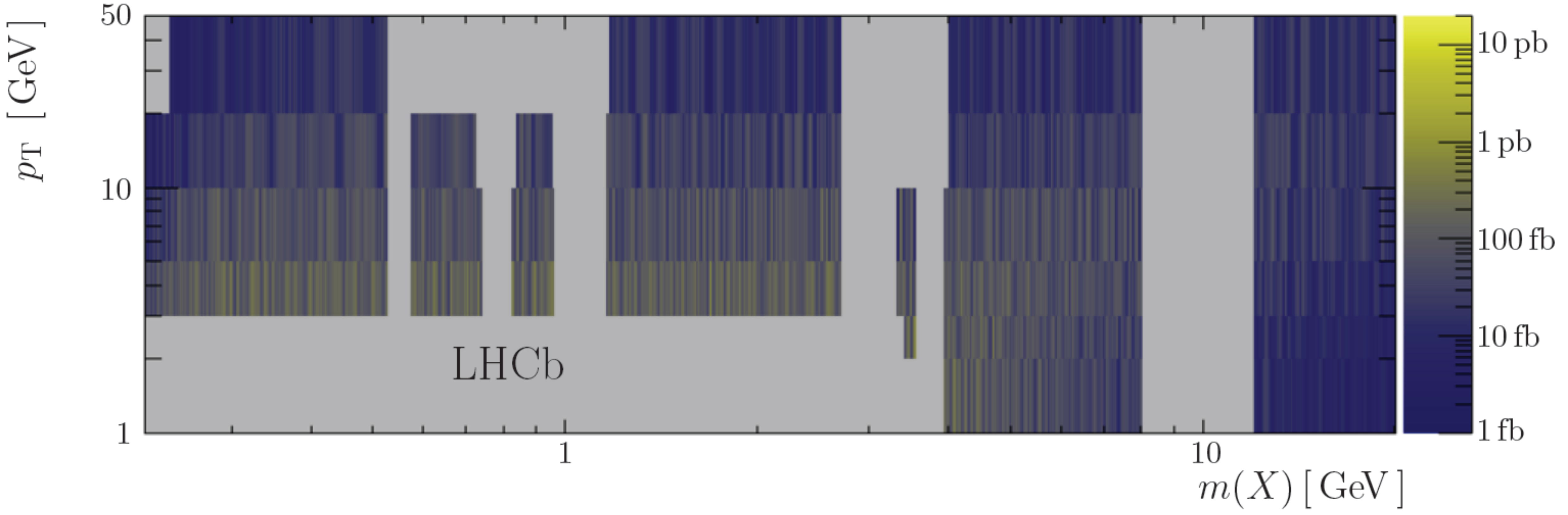
Inclusive prompt



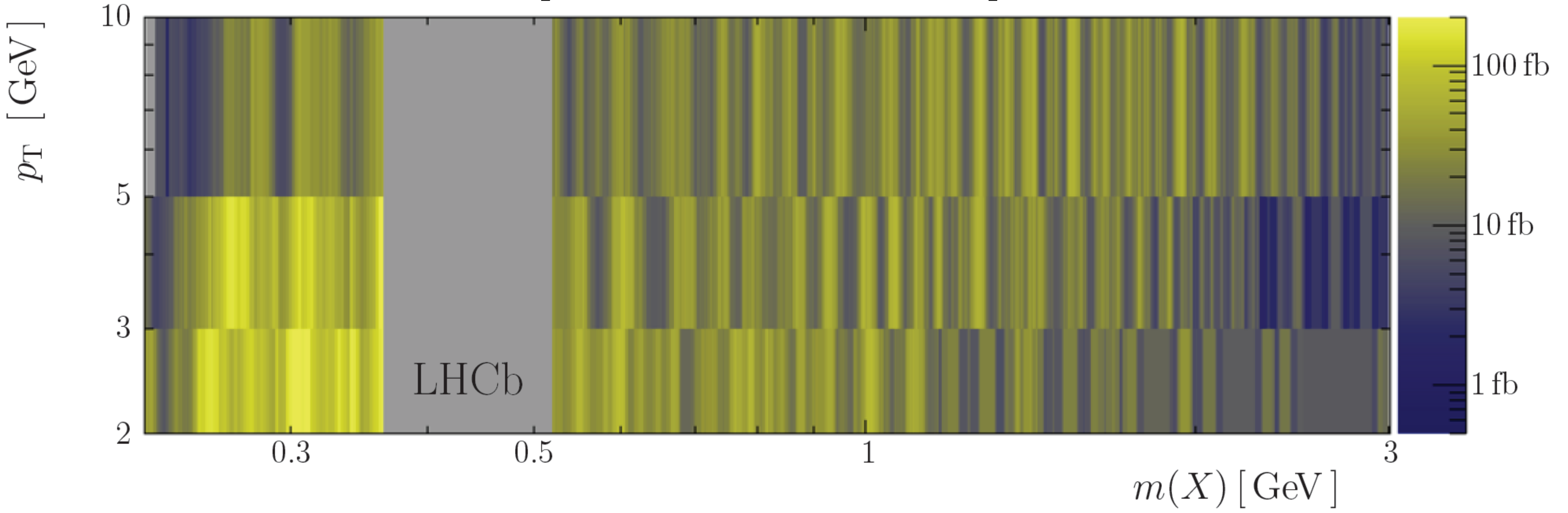
Inclusive displaced



Beauty associated prompt



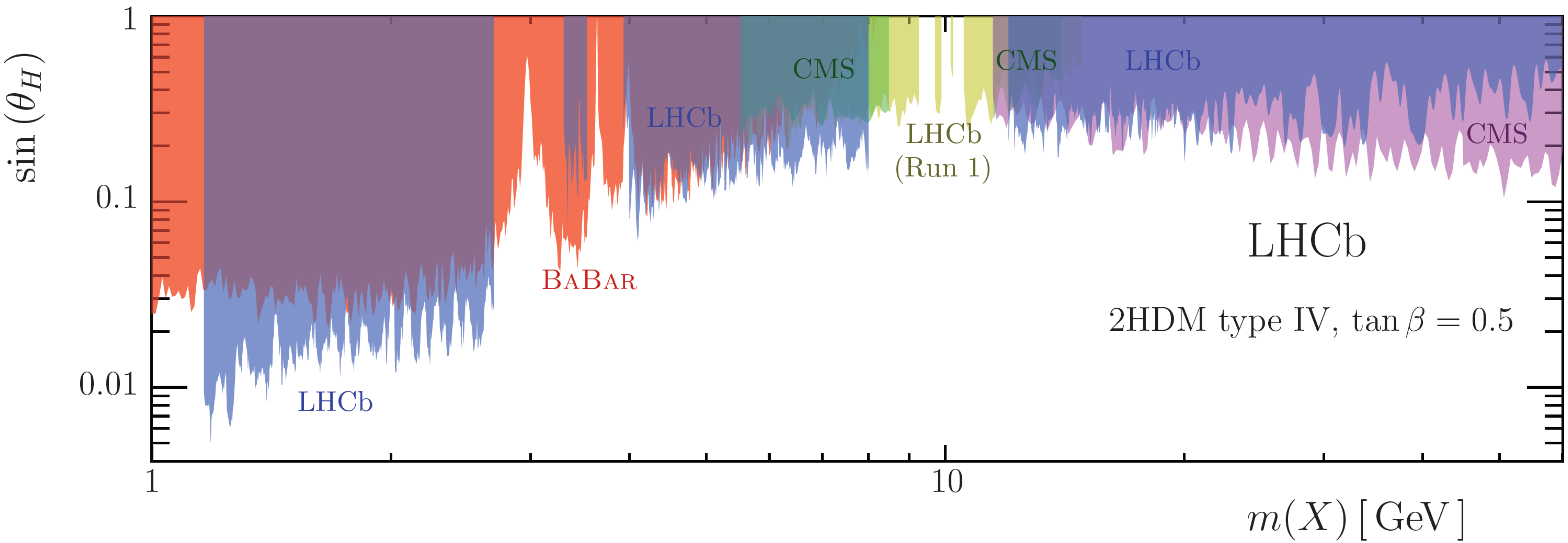
Beauty associated displaced



JHEP 10 (2020) 156

LHCb: 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

- Plenty of results, really hard to cover everything in 15 minutes, so sorry to the people whose analyses I have missed!

- *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

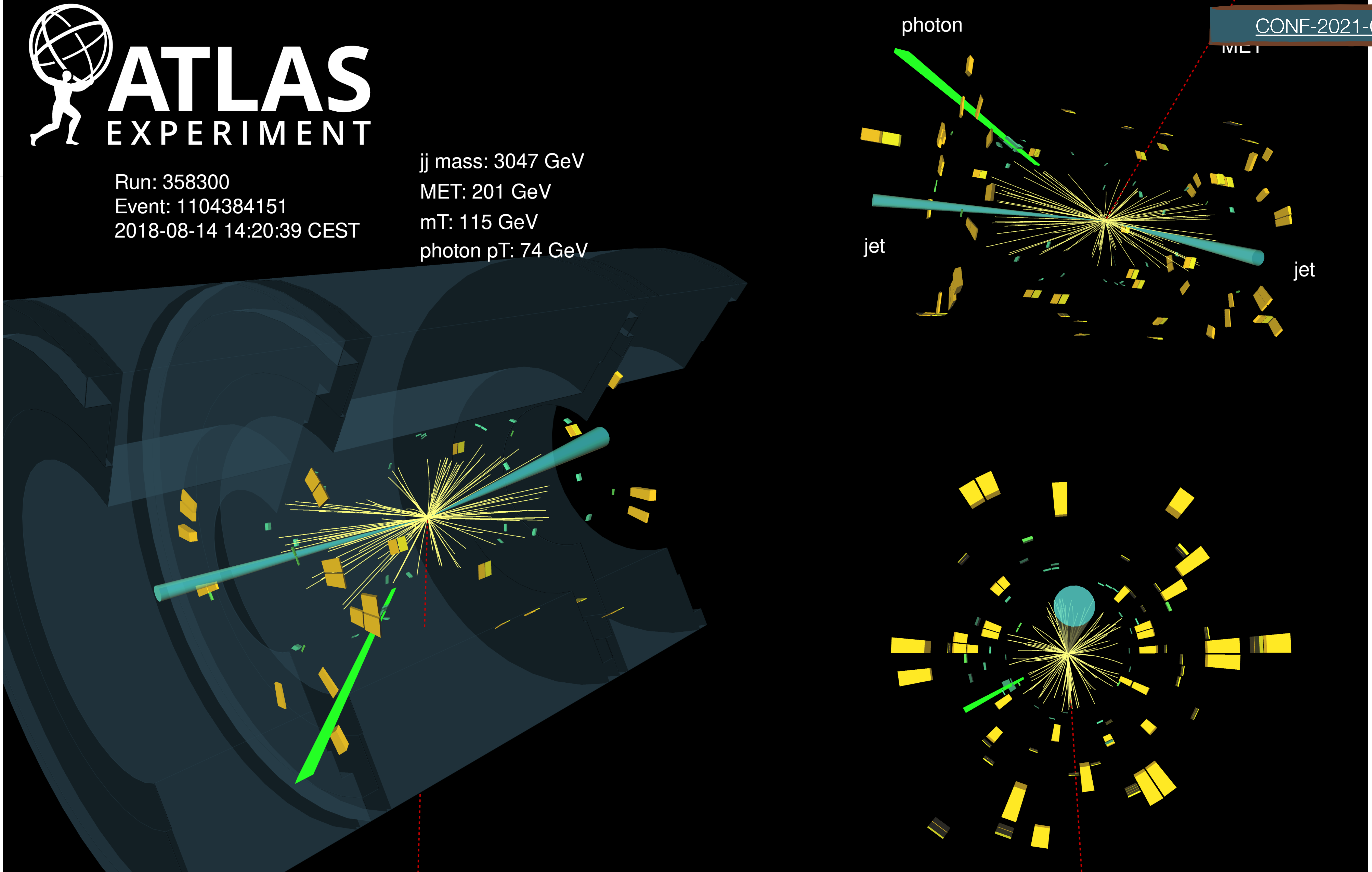
2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	203?

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

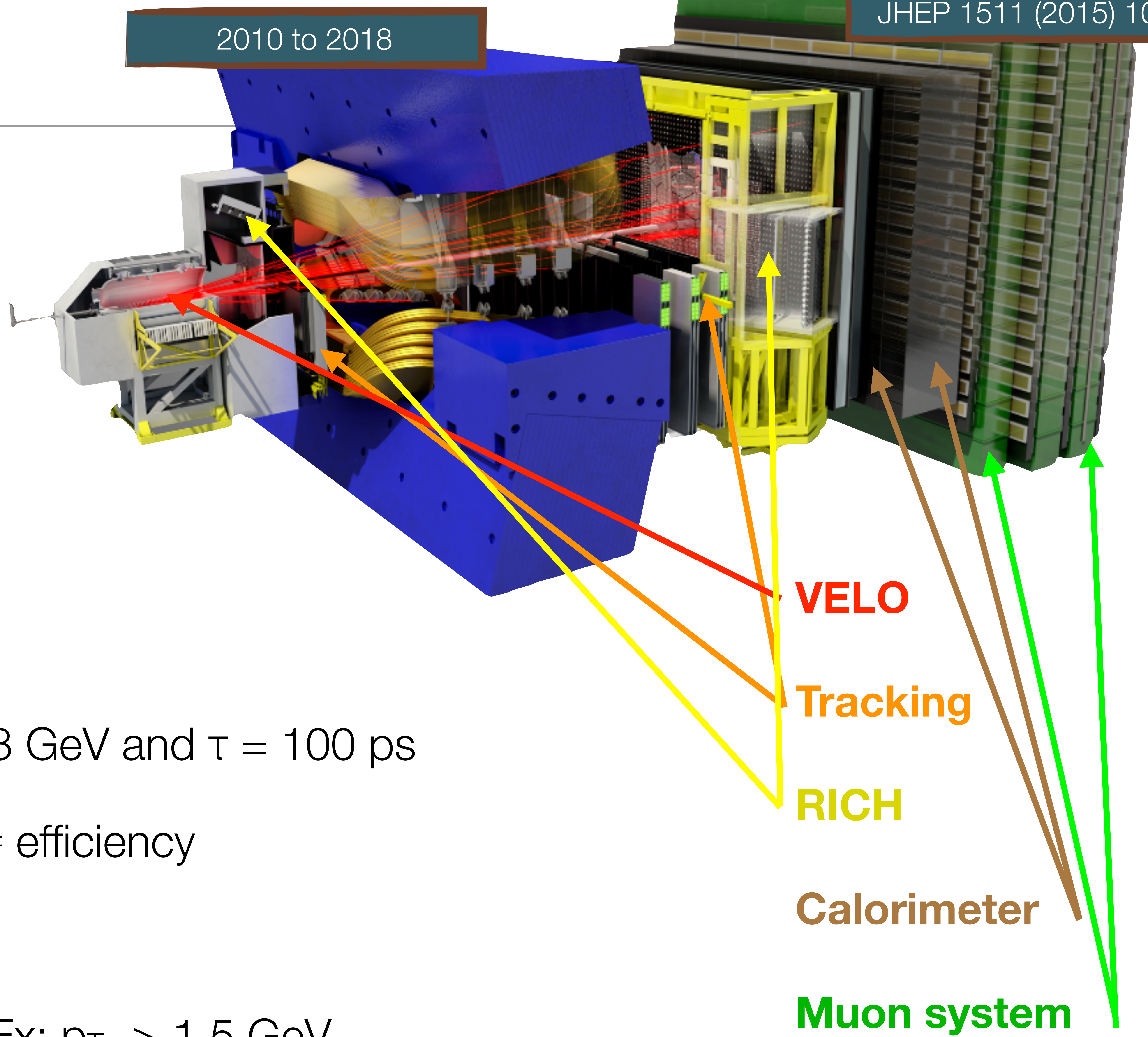
CONF-2021-004



The LHCb detector

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

- **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
  - ~ 50 fs for a J/ψ
  - ~ 0.2 ps for long lived neutral particle of m = 3 GeV and τ = 100 ps
- **Muons** clearly identified and triggered: ~ 90% $\mu^{\pm}$ efficiency
- Great **mass resolution**: e.g. 15 MeV for J/ψ
- **Low p_T trigger** means low masses accessible. Ex: $p_{T\mu} > 1.5$ GeV

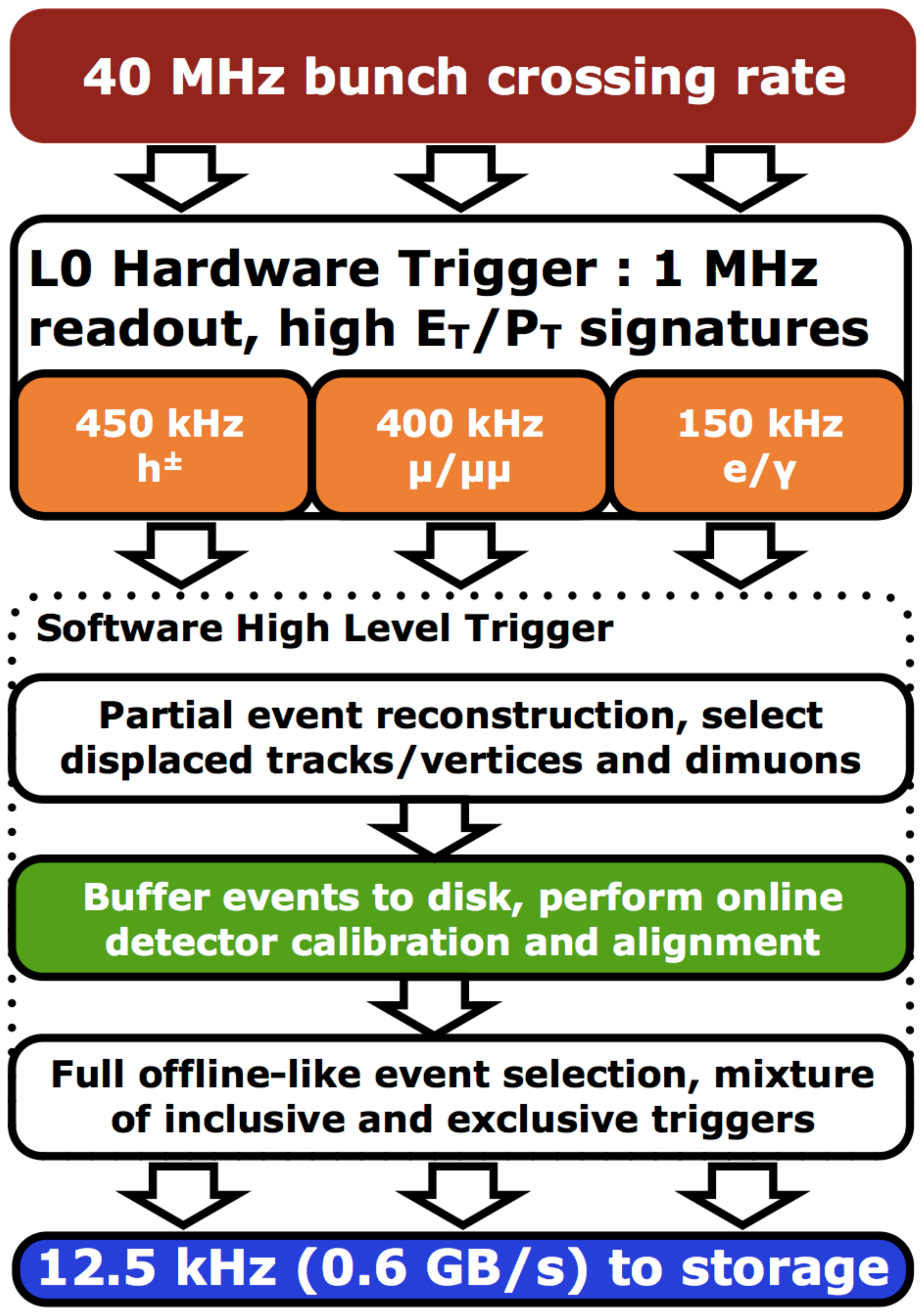


CERN-LHCC-2014-016
LHCB-TDR-016

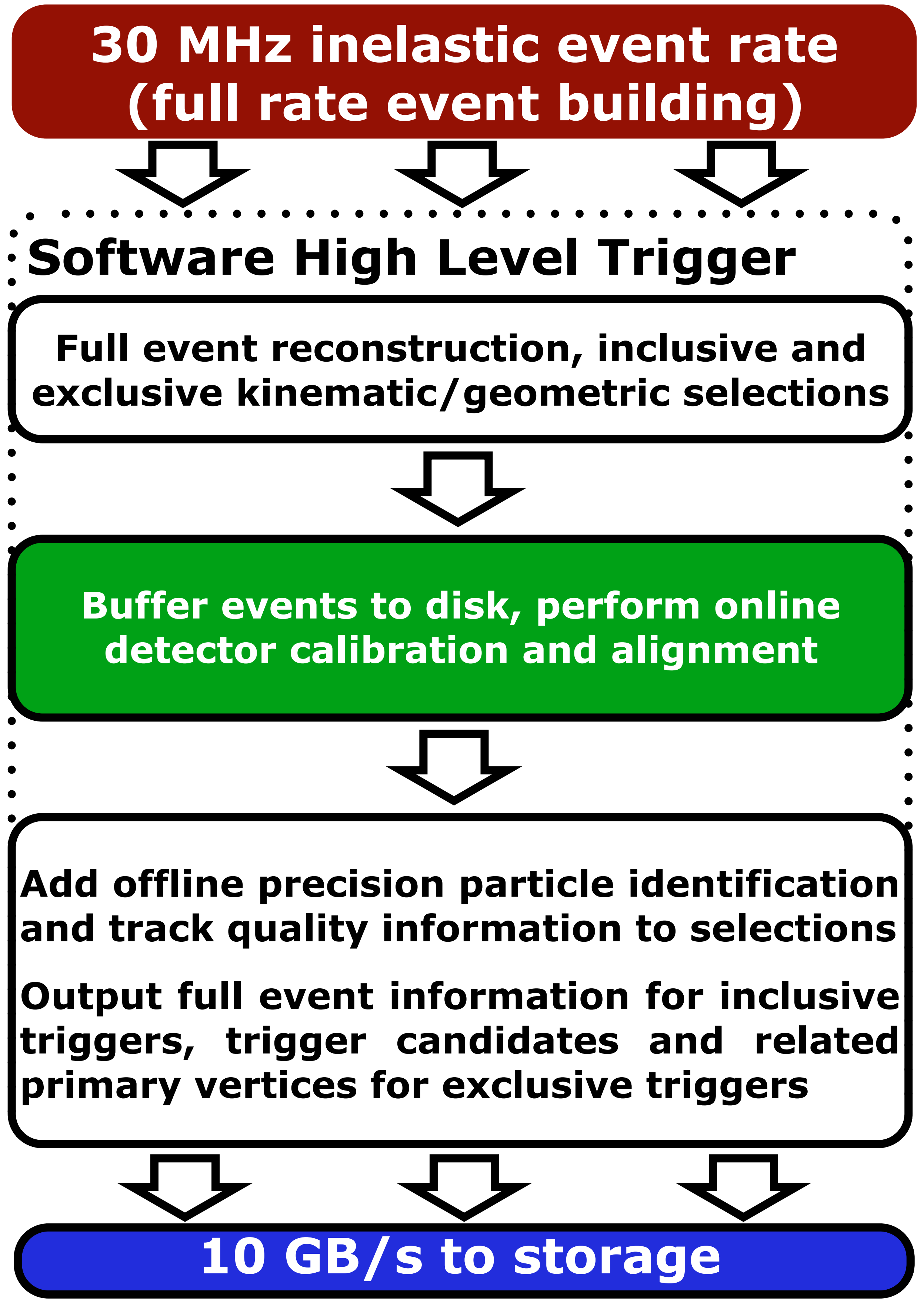
LHCb: Trigger

- Lower luminosity (and low pile-up)
  - **~1/8** of ATLAS/CMS in **Run 1**
  - **~1/20** of ATLAS/CMS in **Run 2**
- **Run 2:**
  - **Full real-time reconstruction** (since 2015) for all charged particles with p_T > 0.5 GeV
  - We go from 1 TB/s (post zero suppression) to 0.6 GB/s (mix of full + partial events)
- **Run 3**:
  - LHCb will move to a **hardware-less readout system** for LHC Run 3 (2022-2024), and process 5 TB/s in real time to get 10 GB/s to storage

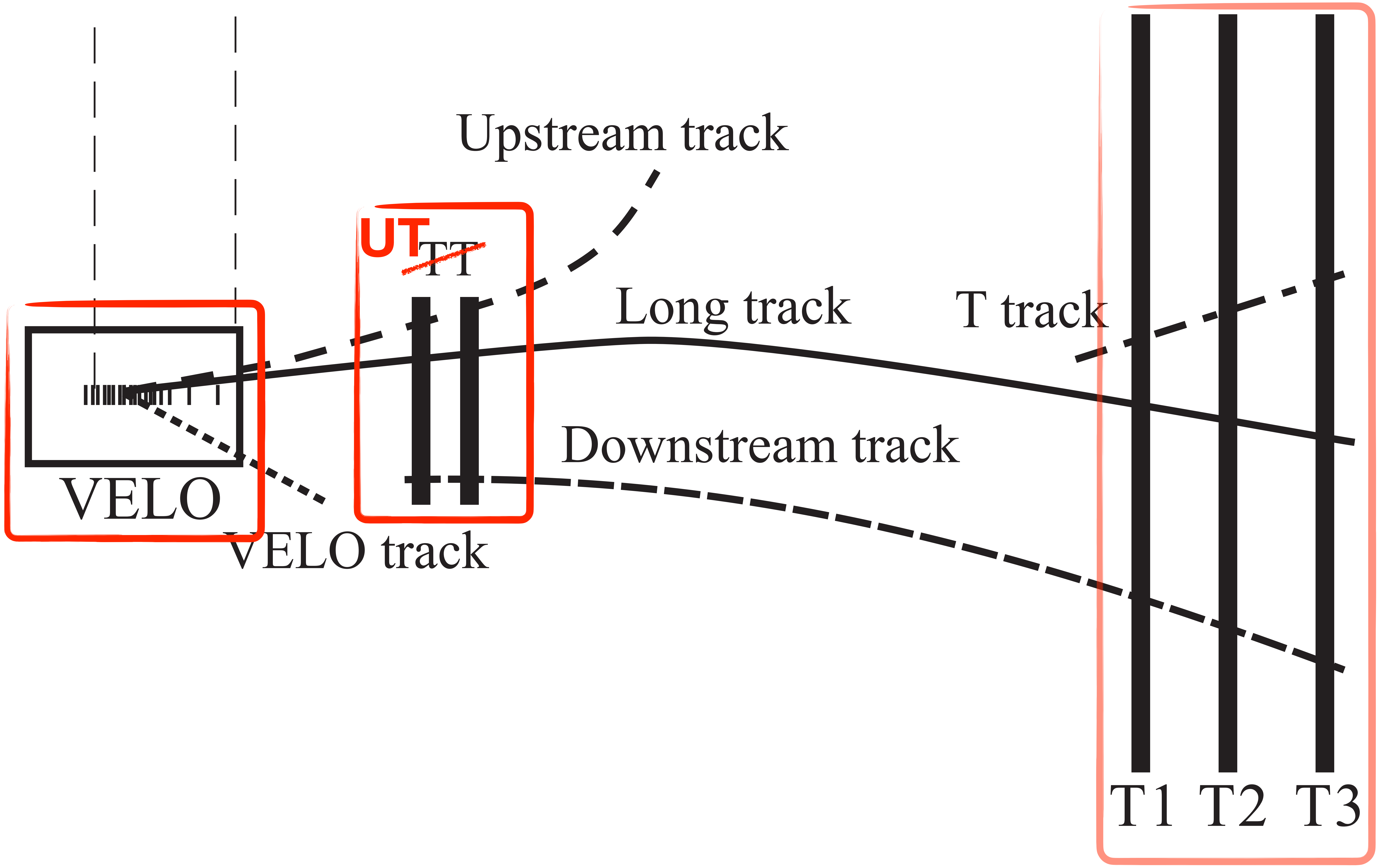
Present trigger



LHCb Upgrade Trigger Diagram



LHCb track types



LHCb data

- 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

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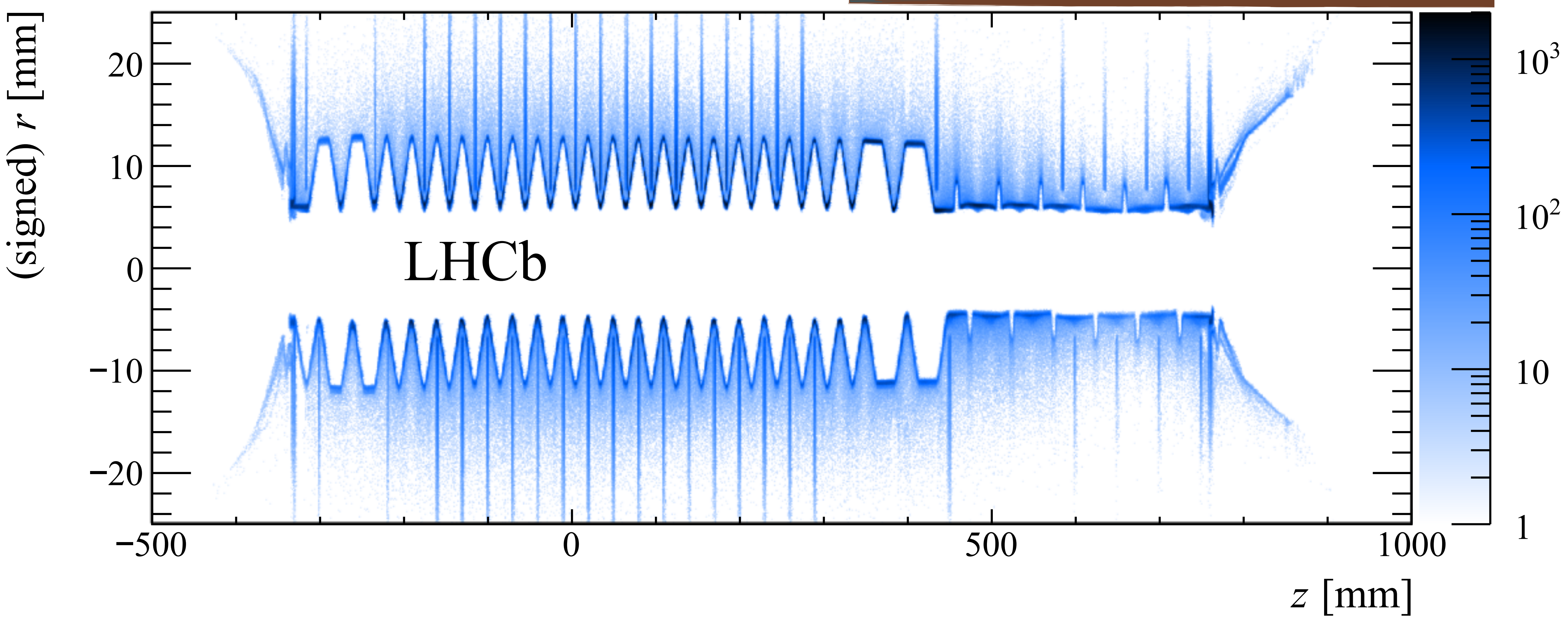

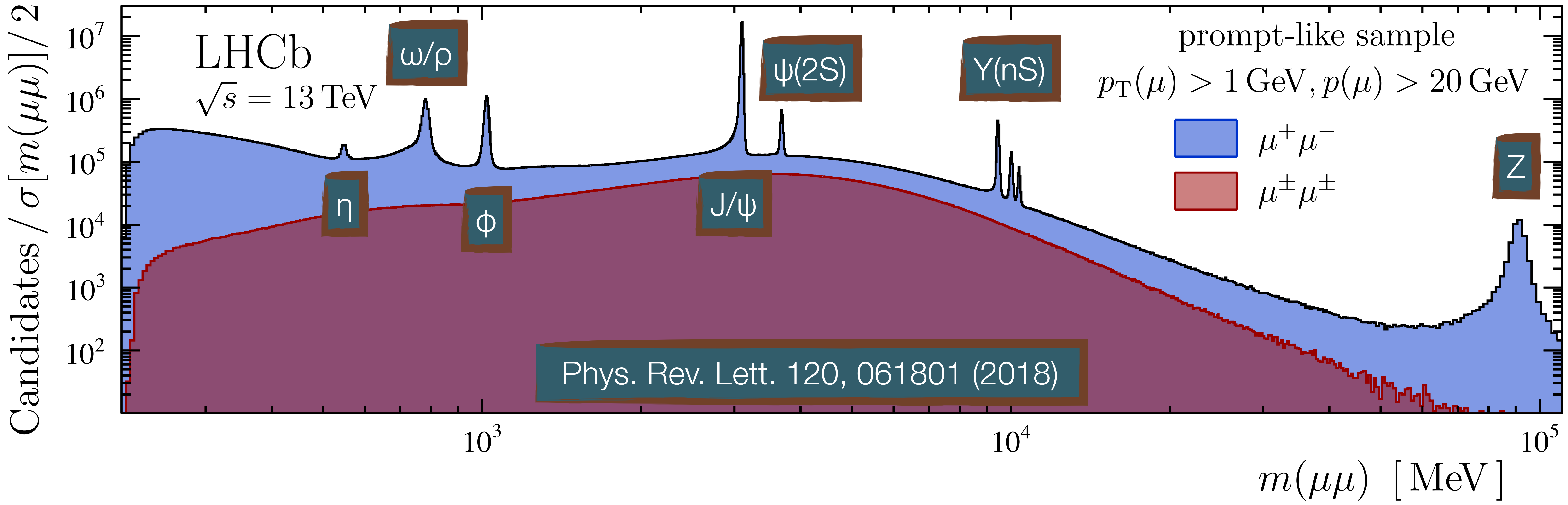

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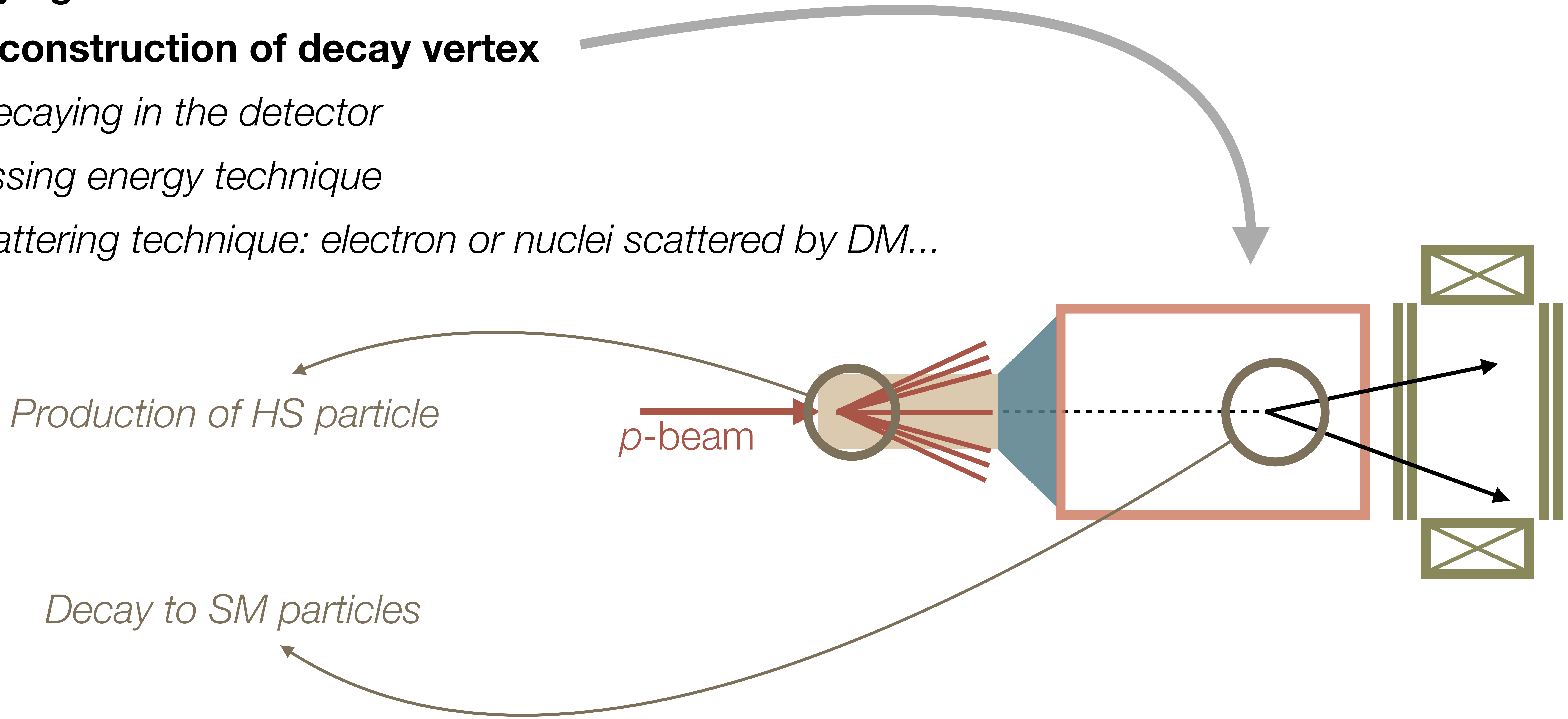
Exploring the dark sector / 2

- **Decaying in the detector**
  - **Reconstruction of decay vertex**
- *Not decaying in the detector*
  - *Missing energy technique*
  - *Scattering technique: electron or nuclei scattered by DM...*



Exploring the dark sector / 3

- *Decaying in the detector*
  - *Reconstruction of decay vertex*
- **Not decaying in the detector**
  - **Missing energy technique**
  - **Scattering technique: electron or nuclei scattered by DM**