Higgs searches at LHCb

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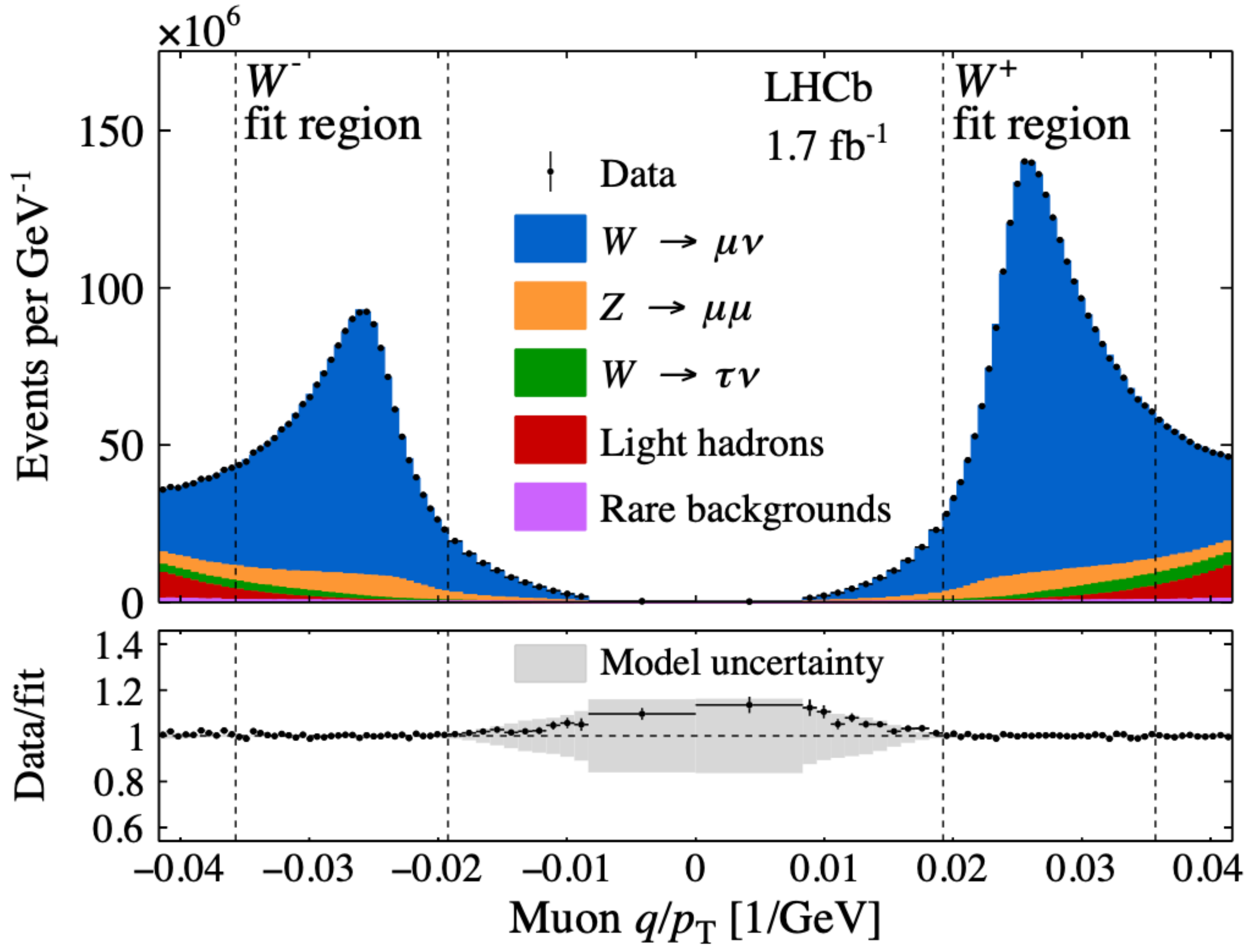
UK HEP Forum 2023: Completing the Higgs-saw puzzle - 21/11/2023

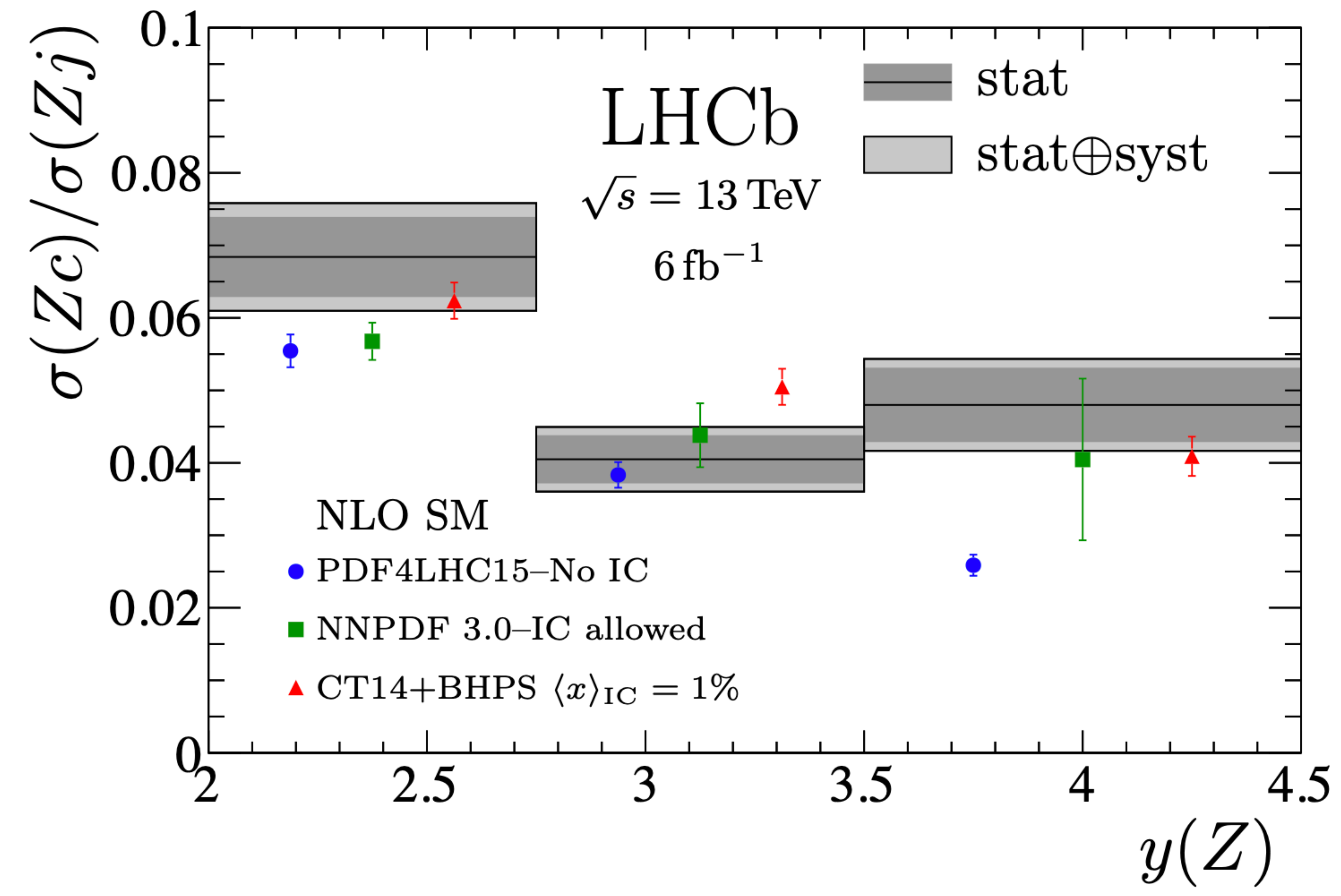
Not only flavour physics

- LHCb is well known for the excellent results on B physics
- But we have also many measurements on **electroweak and QCD physics**!
- **LHCb is now qualified as a general purpose detector in the forward region**
- The goal of this talk is showing you the **LHCb capabilities in Higgs physics**

W mass measurement JHEP 01 (2022) 036



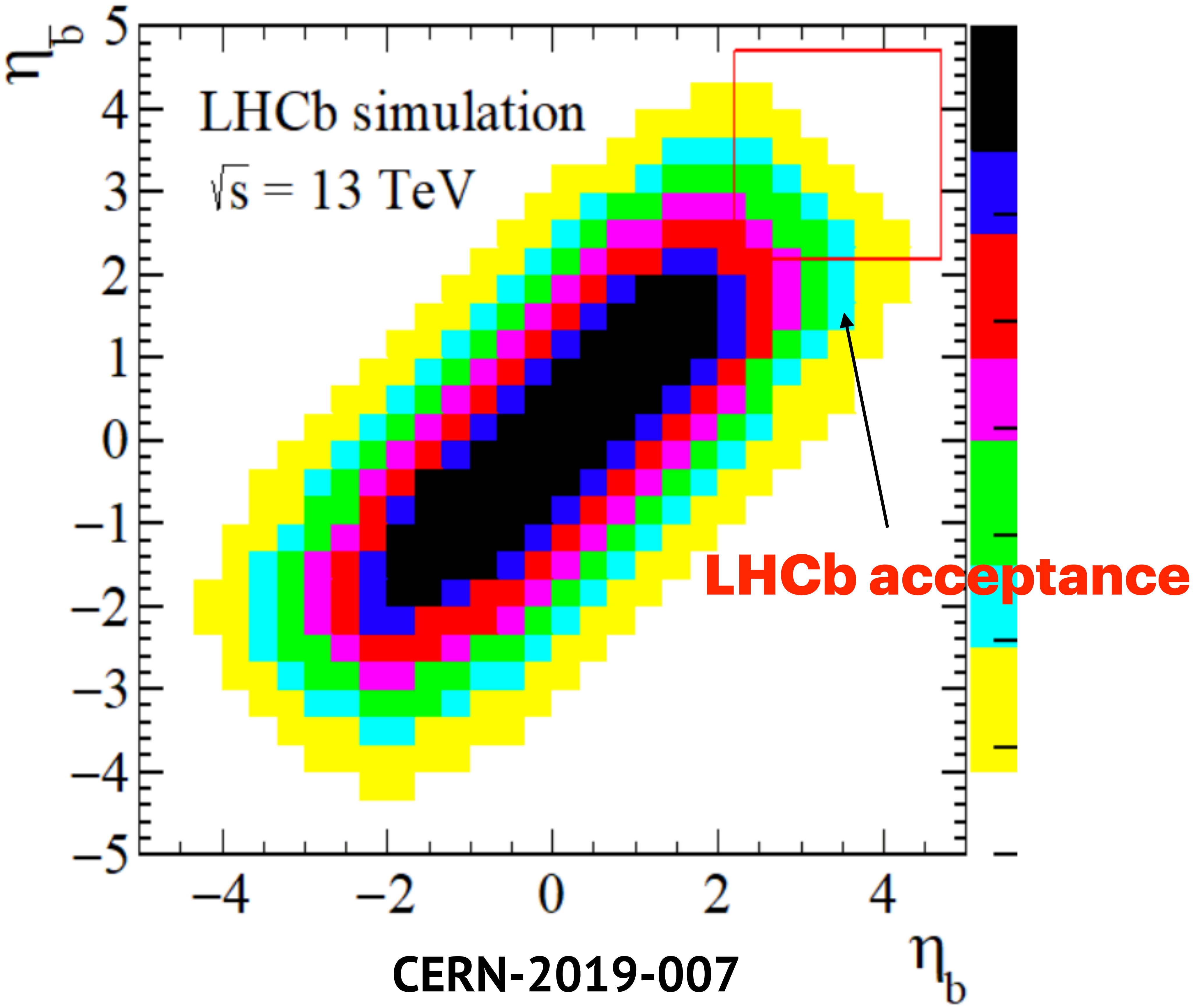
Z+c-jet measurement (intrinsic charm) Phys. Rev. Lett. 128 (2022) 082001



Why Higgs physics at LHCb?

- At first sight **LHCb** may not be seen as a detector for Higgs physics:
  - Reduced acceptance with respect to ATLAS and CMS
  - Lower luminosity due to leveling
- But there are also **strong points**:
  - **Lower pile-up** means cleaner events
  - **Low energy/momentum threshold** triggers
  - **Excellent secondary vertex reconstruction** performance is a plus for b- and c-jets tagging

$H \to b\bar{b}$ pseudorapidity distribution



CERN-2019-007

SM and BSM Higgs

Two main directions for Higgs research

Standard Model Higgs

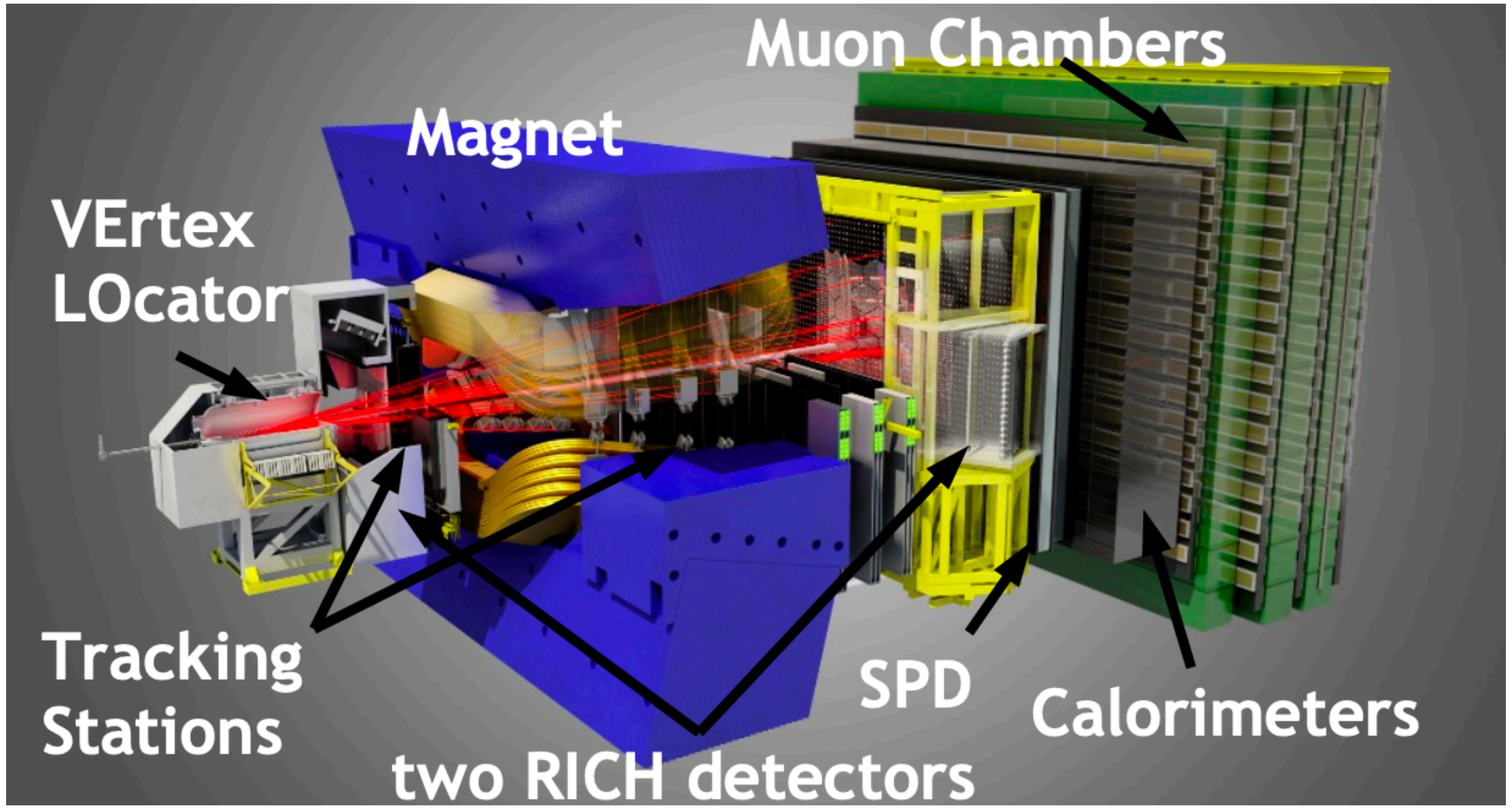
- **What is the LHCb sensitivity to the SM Higgs**?
- Which are the best production/decay channels?
- Which kind of detector and reconstruction improvements are necessary for the Higgs observation?
- **Could LHCb be the third experiment for measuring Higgs properties (and the first one in the forward region of p-p collisions)?**

Beyond Standard Model Higgs

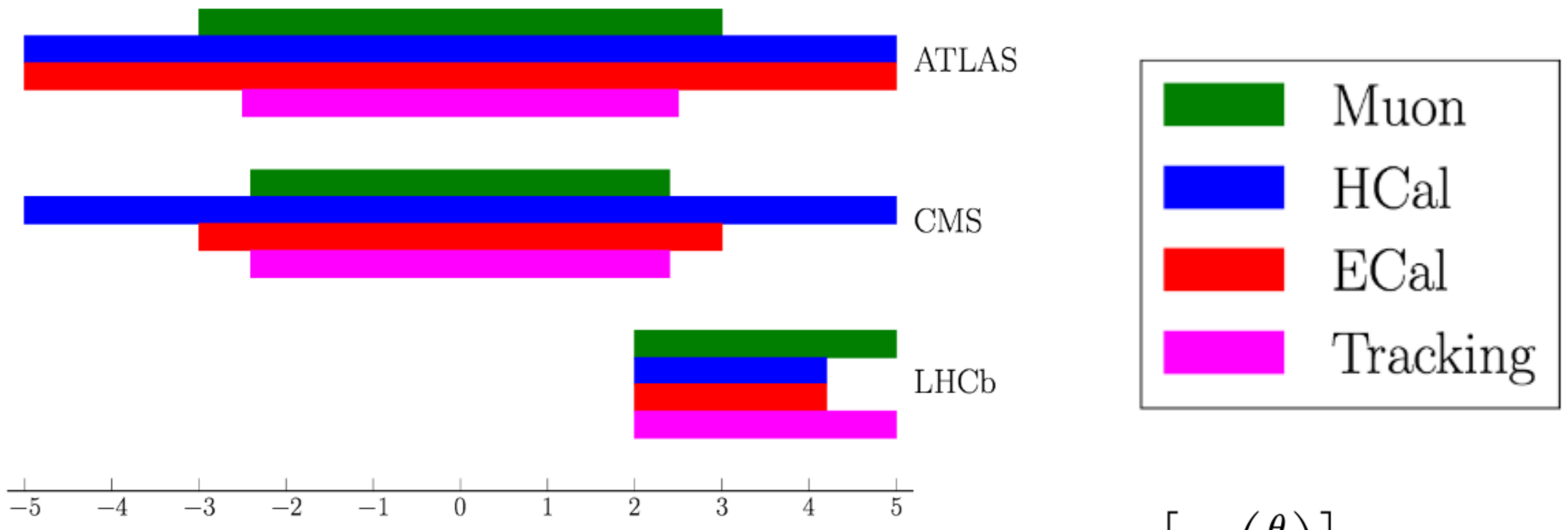
- **Could we take profit of the unique phase space?**
- Which kind of Exotic Higgs decays?
- What is the mass range where we can search for low mass Higgses?
- Indirect searches? Higgs as portal to new physics?

JINST 3 (2008) S08005

LHCb detector

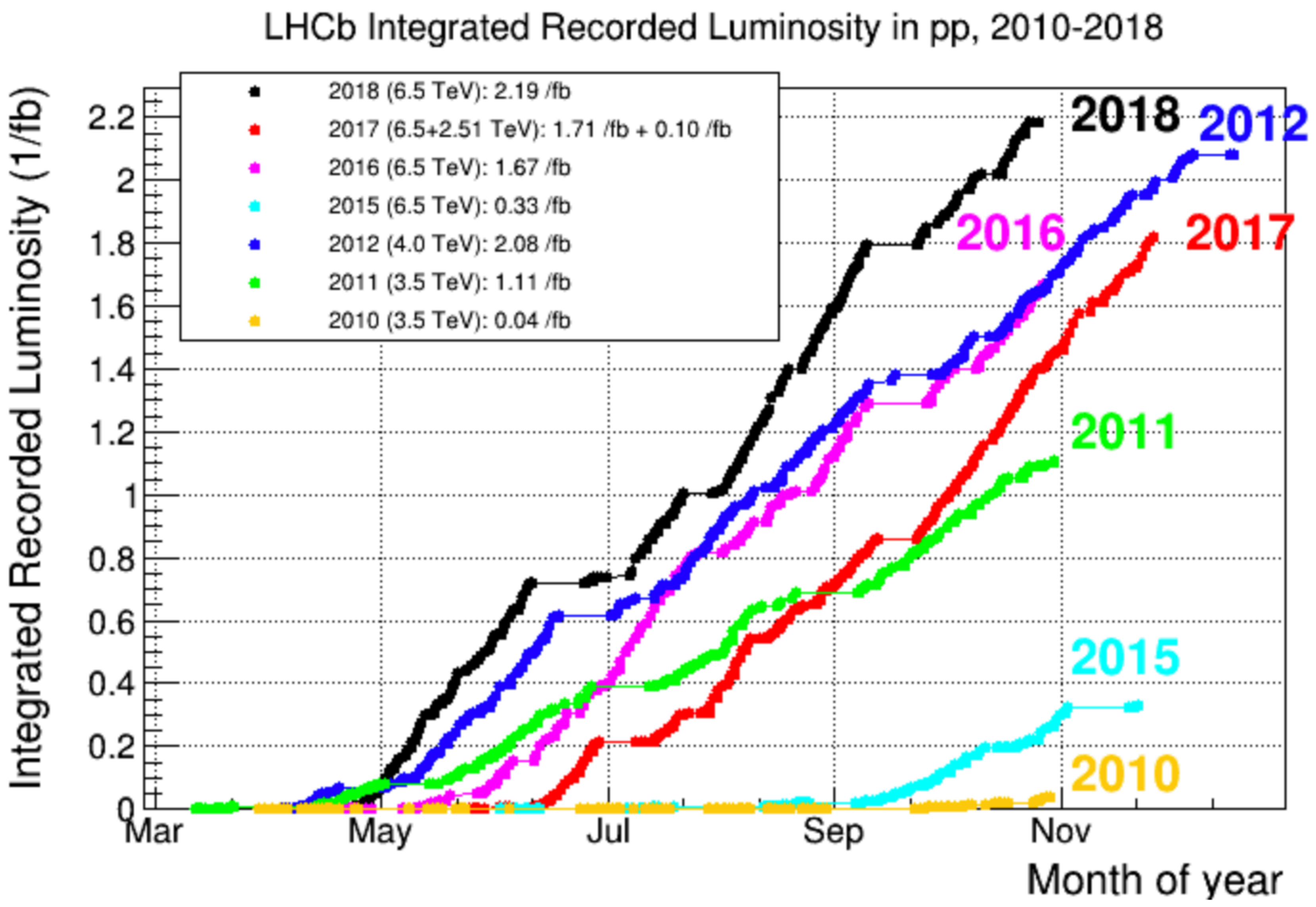


- LHCb is a spectrometer in the forward region
- Track momentum resolution: 0.4% at 5 GeV and 0.6% at 100 GeV
- **Excellent vertex reconstruction system**: impact parameter resolution of (15 + 29/p_T) μm, p_T in GeV
- Muon ID efficiency: 97% with 1-3% $\mu \to \pi$ mis-identification
- Electron reconstruction with bremsstrahlung recovery



2< η< 5

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

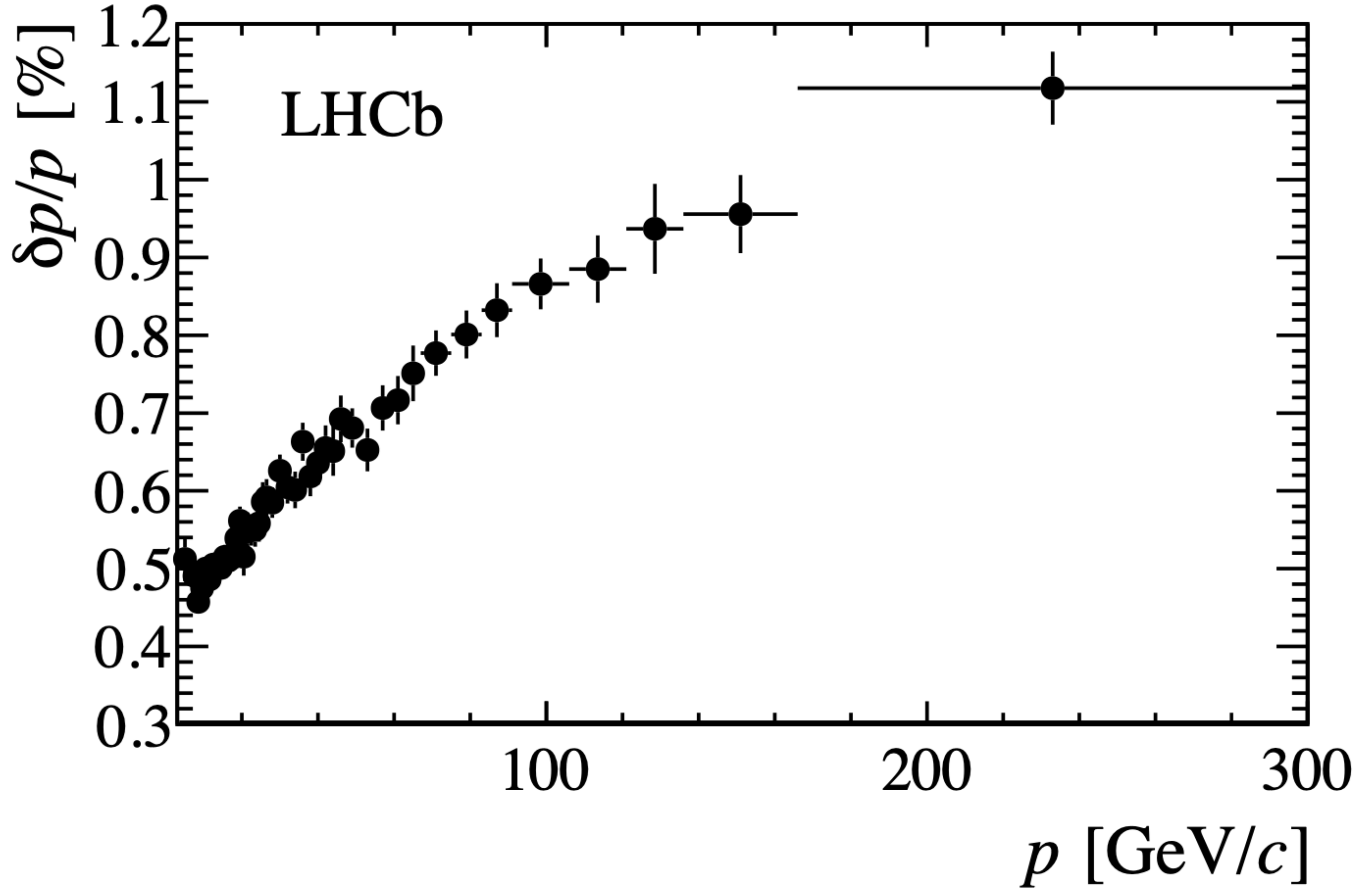


Run 1-2 data fully available for Higgs studies

Run 3 data on their way

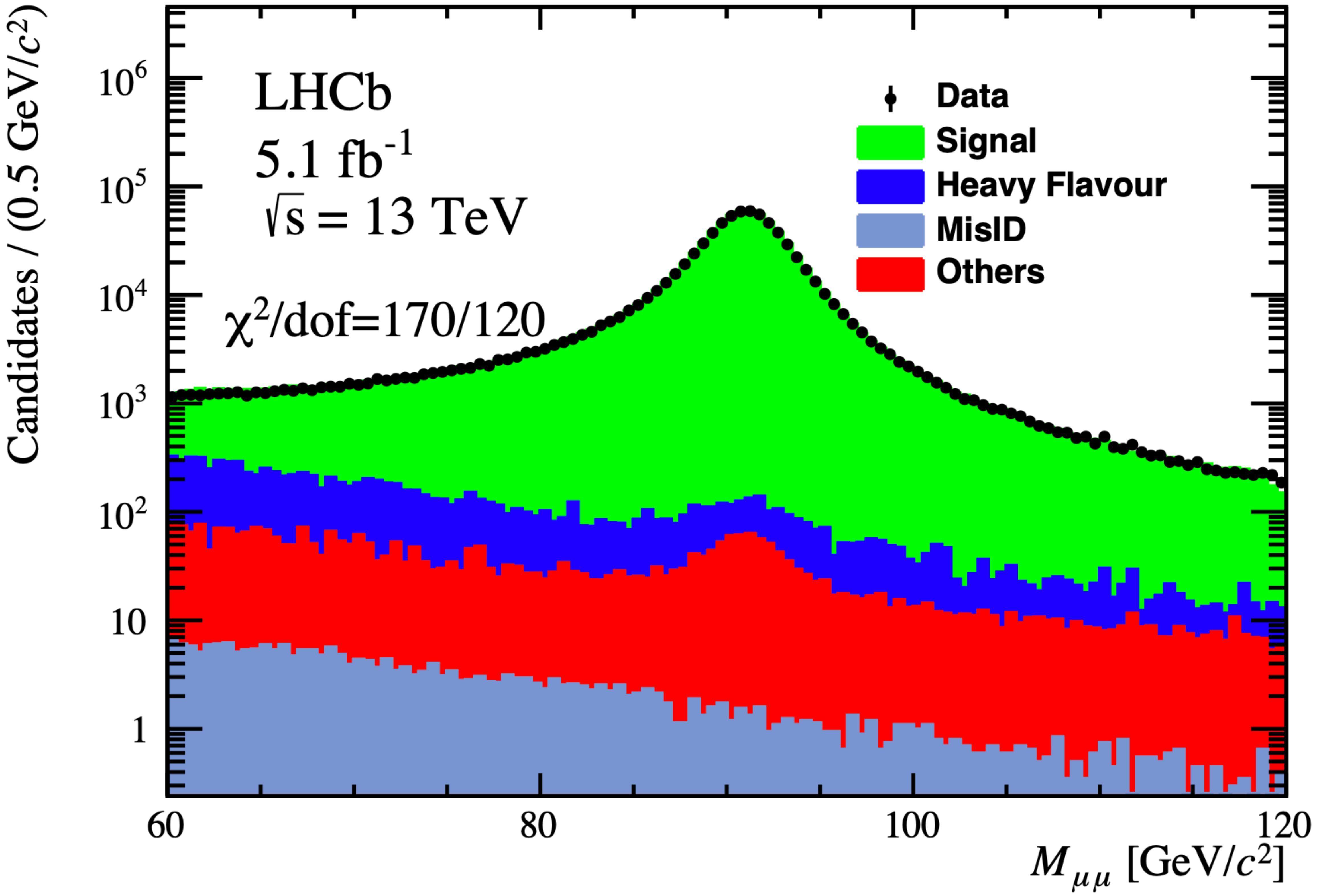
Muons at LHCb

Int. J. Mod. Phys. A 30, 1530022 (2015)



Relative momentum resolution versus momentum for long tracks in data obtained using $J/\psi \to \mu\mu$ decays

JHEP 07 (2022) 26



$Z \to \mu\mu$ invariant mass peak

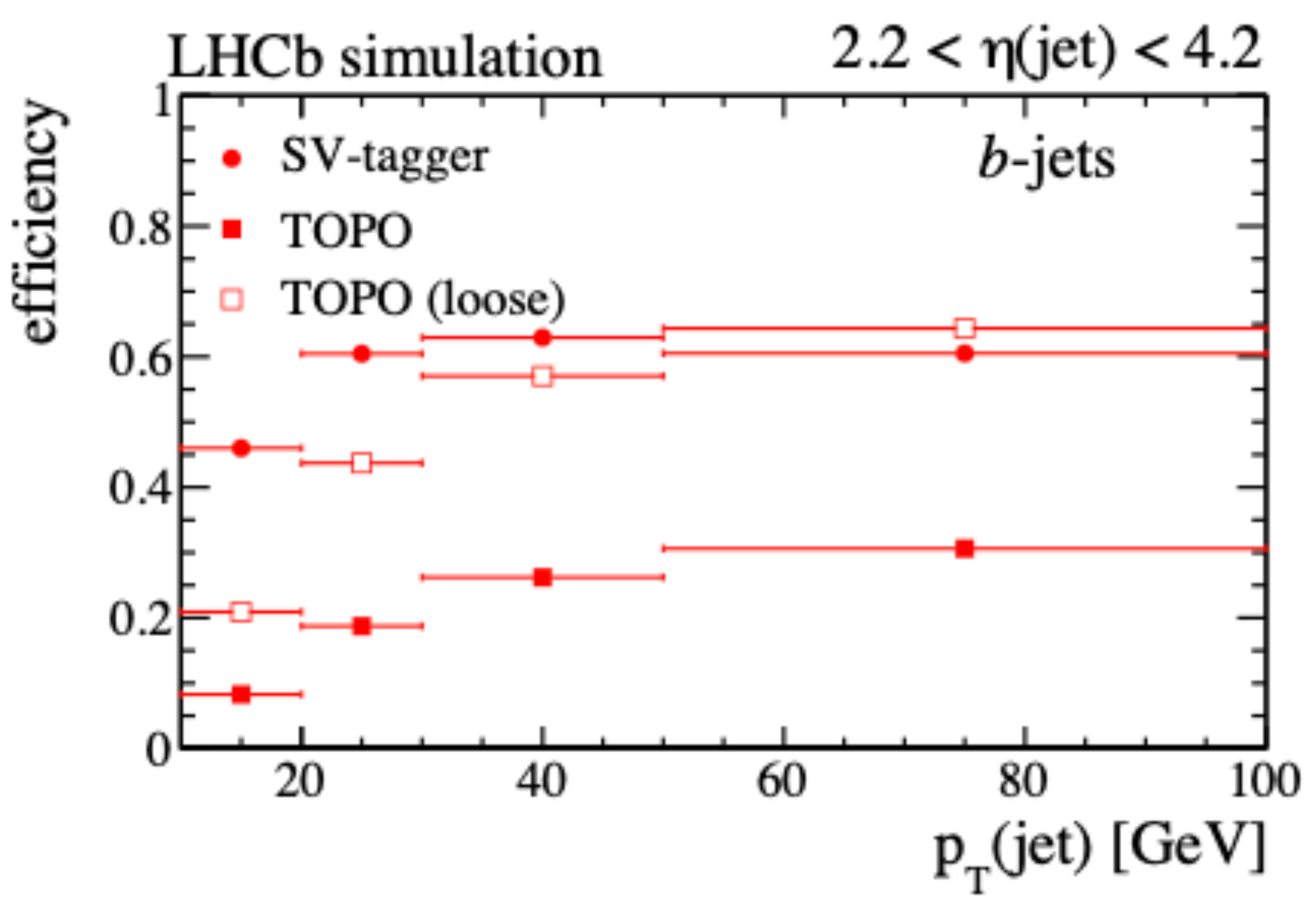
Excellent muon performance from low to high momentum

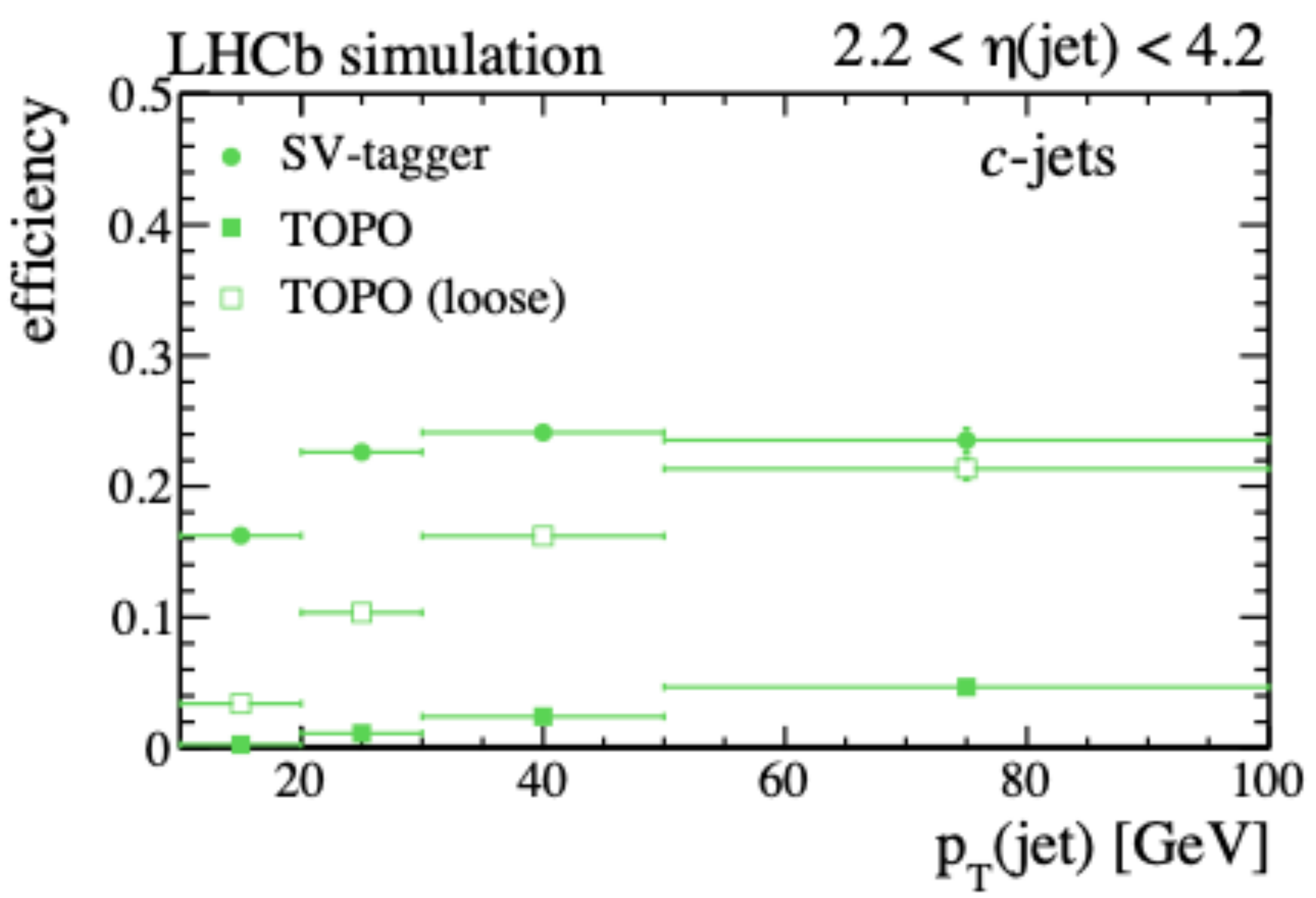
Jet tagging at LHCb

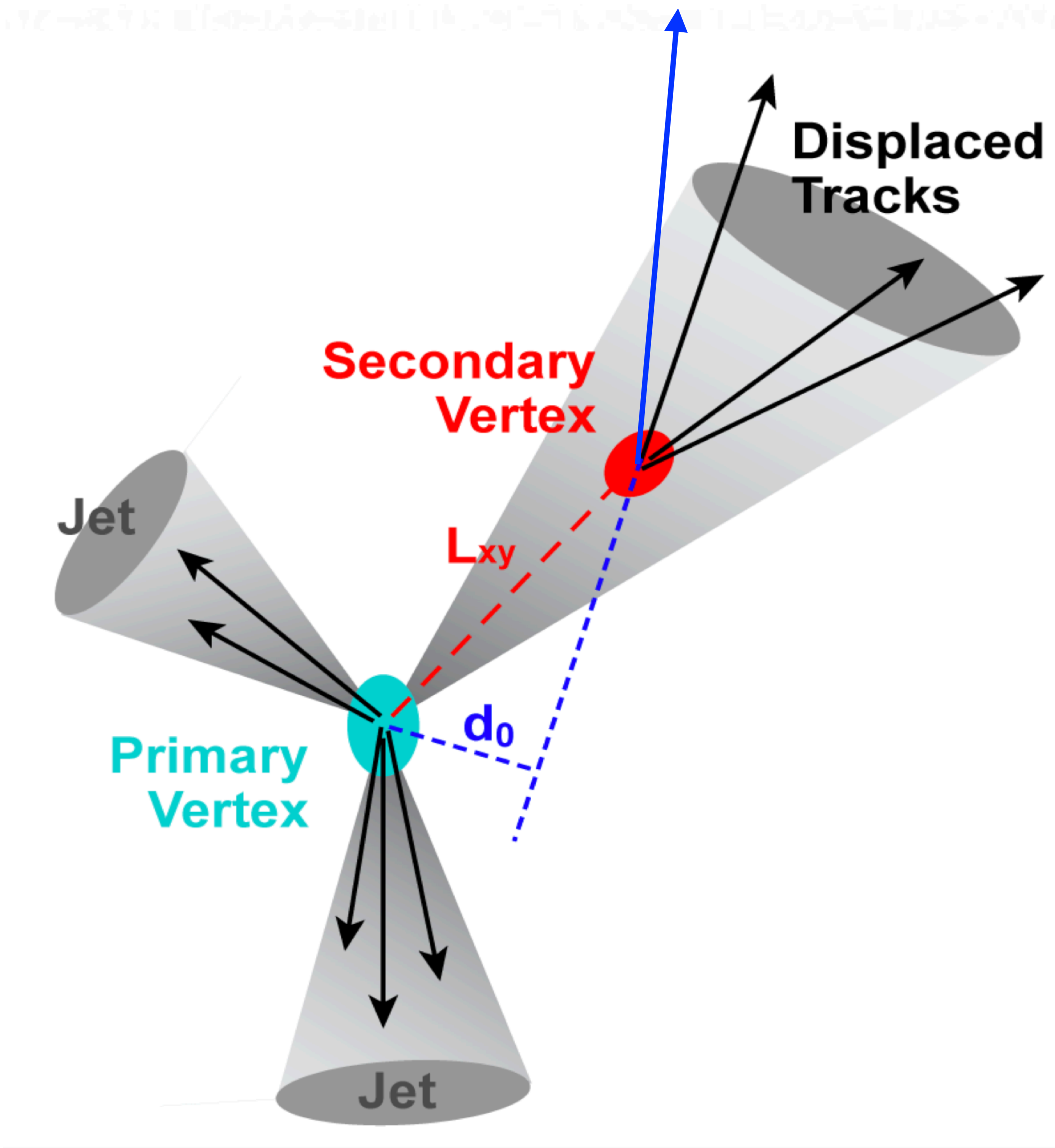
- The jet tagging system takes advantage of LHCb features → **precise vertex reconstruction**

- **Secondary vertices (SV)** are reconstructed **by using all the tracks in the events, not only those that belong to the jet**

- In Run 1/2 t**he efficiency for tagging a b-(c-) jets is of about 60% (25%), with a light jet misidentification below 0.1%**







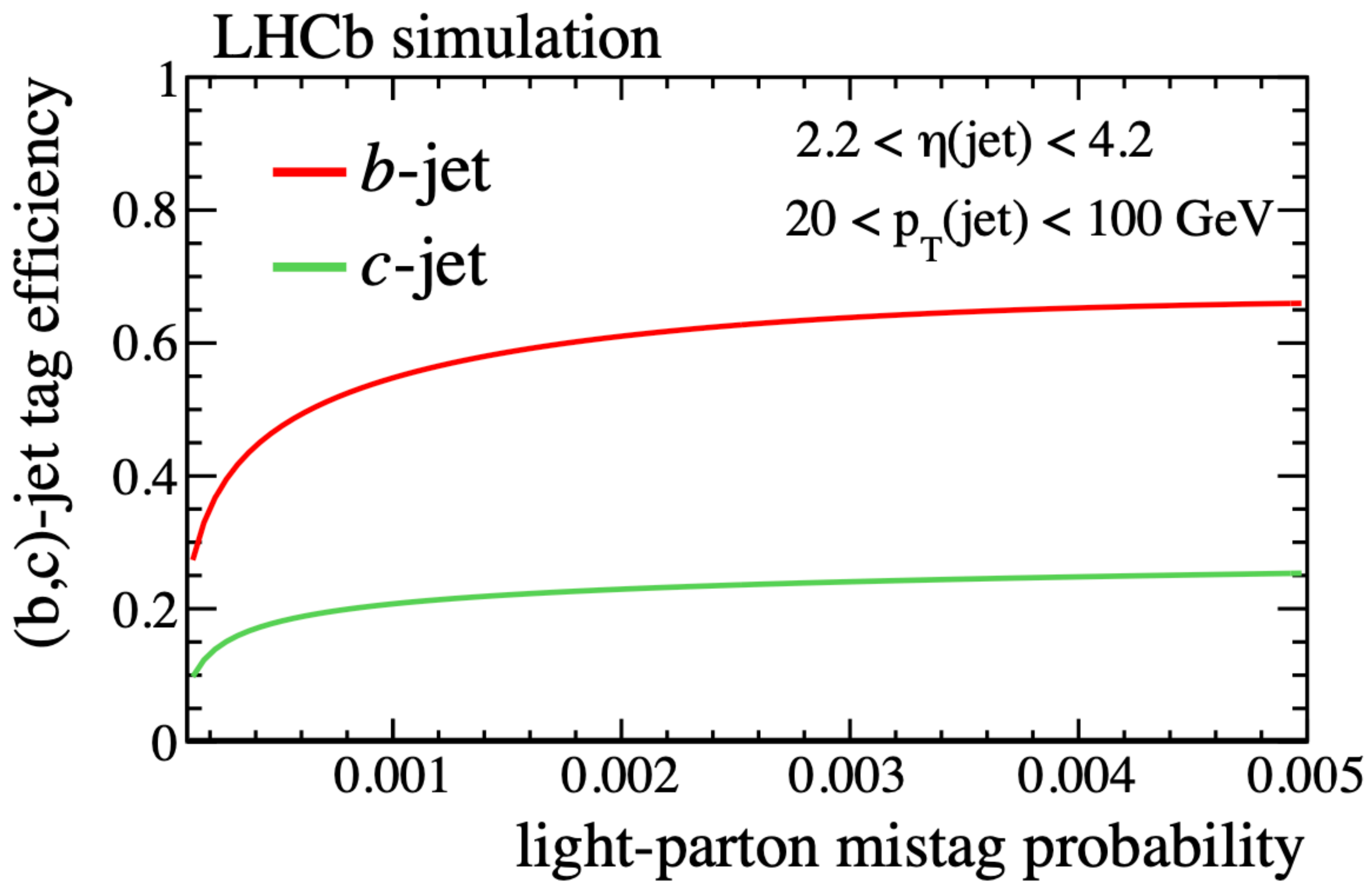
JINST 10 (2015) P06013

Jet tagging at LHCb

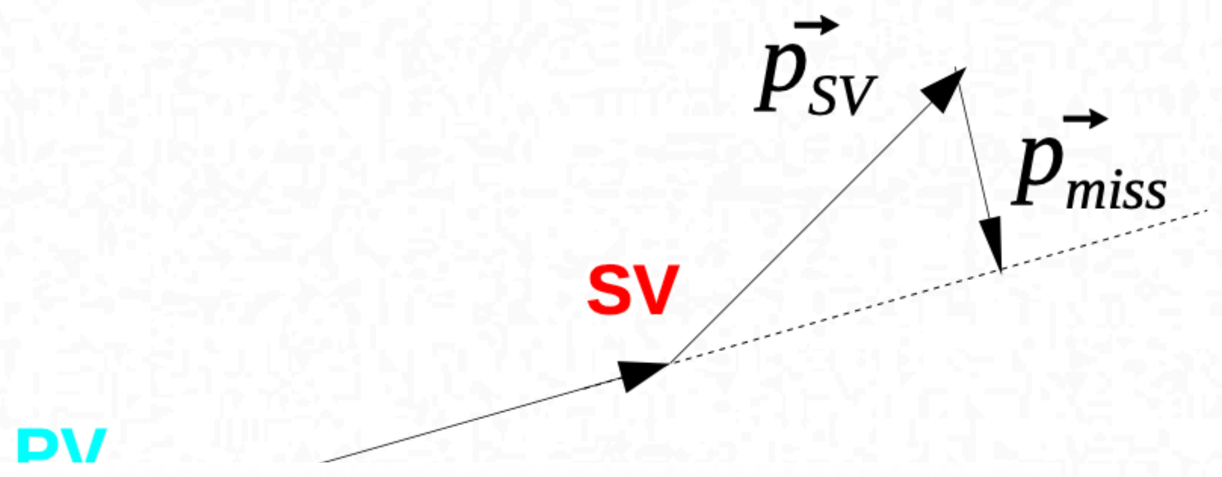
- Two **Boosted Decision Trees** (BDT) are used to identify b and c jets.

BDT(bc|udsg)
To separate **heavy flavour** jets from **light** jets

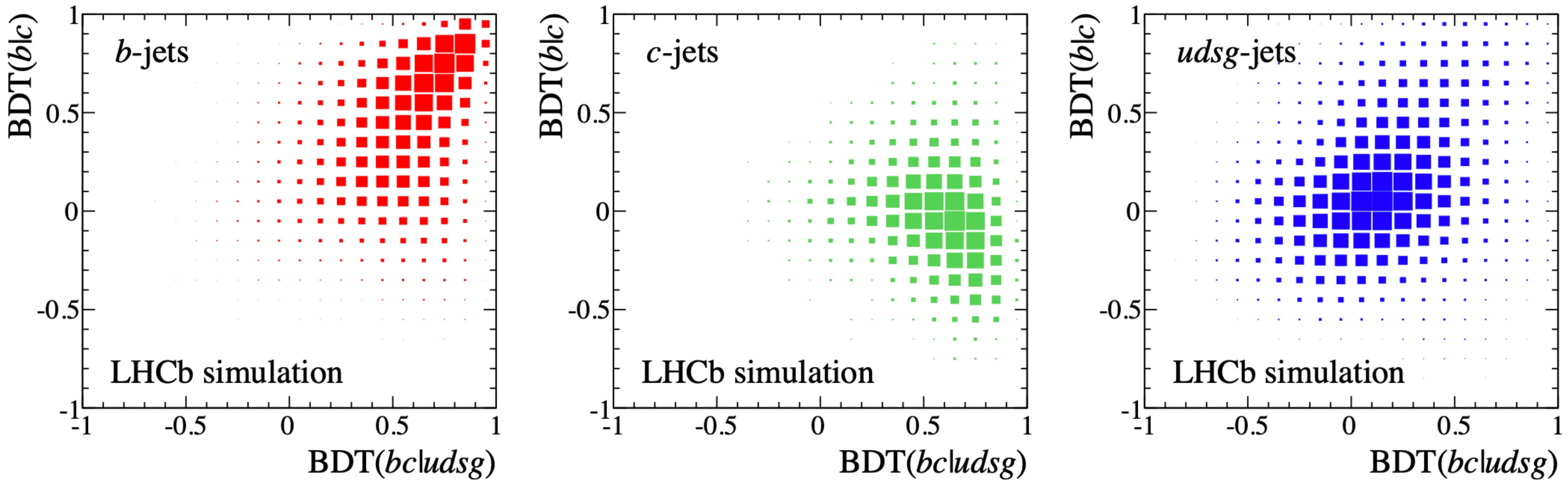
BDT(b|c)
To separate **b-jets** from **c-jets**



- **Some observables in input to the BDTs:**
  - **SV mass**
  - **Fraction of jet p_T taken by the SV**
  - **Flight distance χ^2**
  - **SV corrected mass**



$$M_{corr} = \sqrt{M_{SV}^2 + p_{miss}^2} + p_{miss}$$



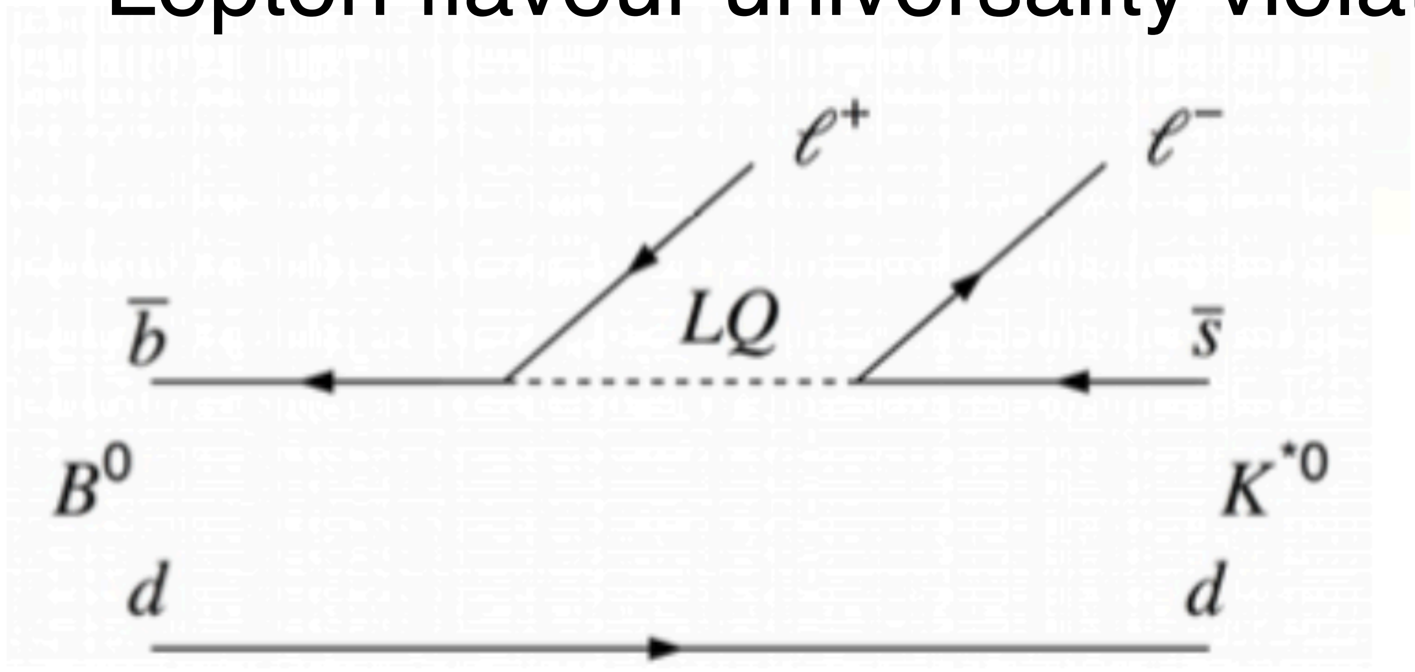
Beyond Standard Model Higgs

Search for new physics

Quest for New Physics

Indirect searches

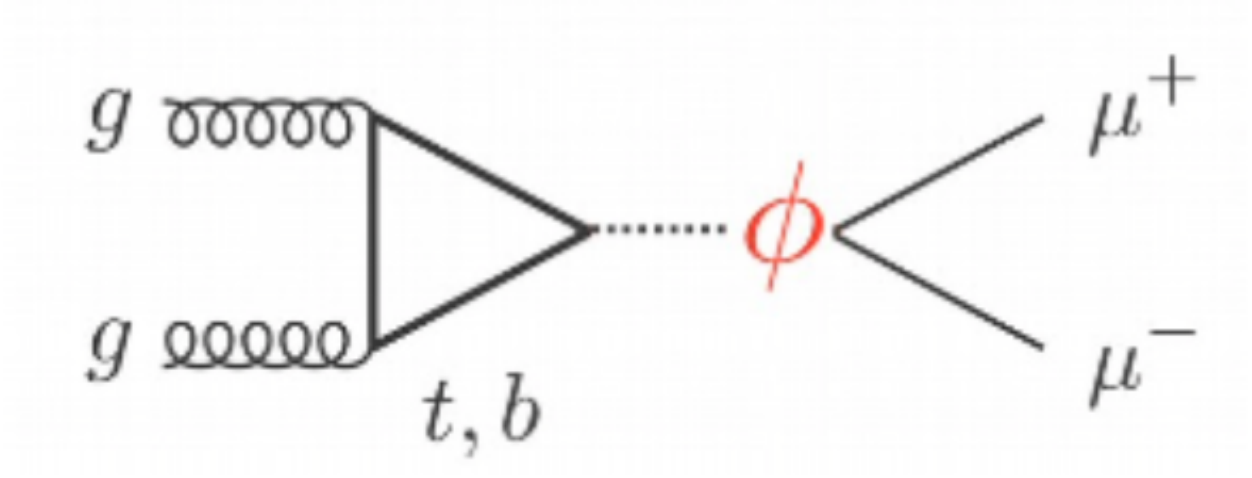
- Hints of flavour anomalies
- b→s transitions
- Lepton flavour universality violation



Both approaches followed at LHCb

Direct searches

- Higgs-like resonances
- Dark photons
- Exotic Higgs decays



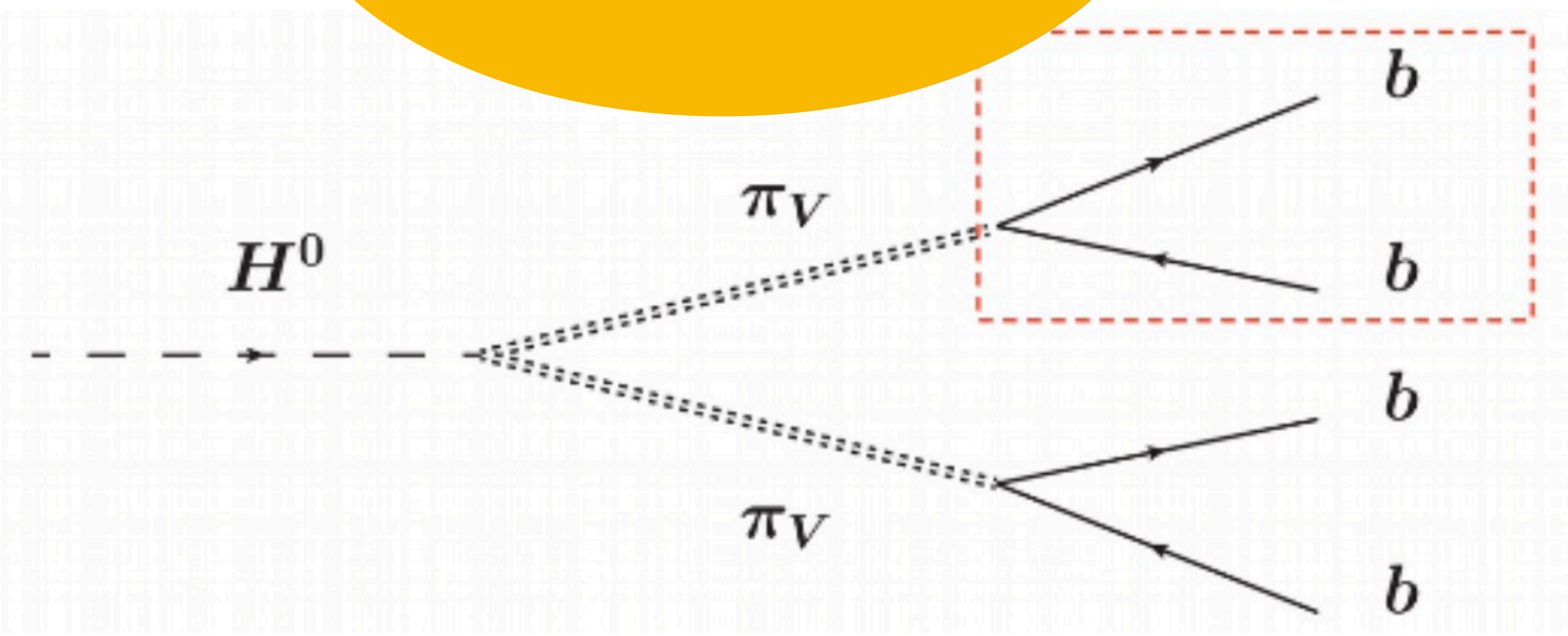
Direct searches: Exotic Higgs decays

Higgs decay to Long Lived Particles

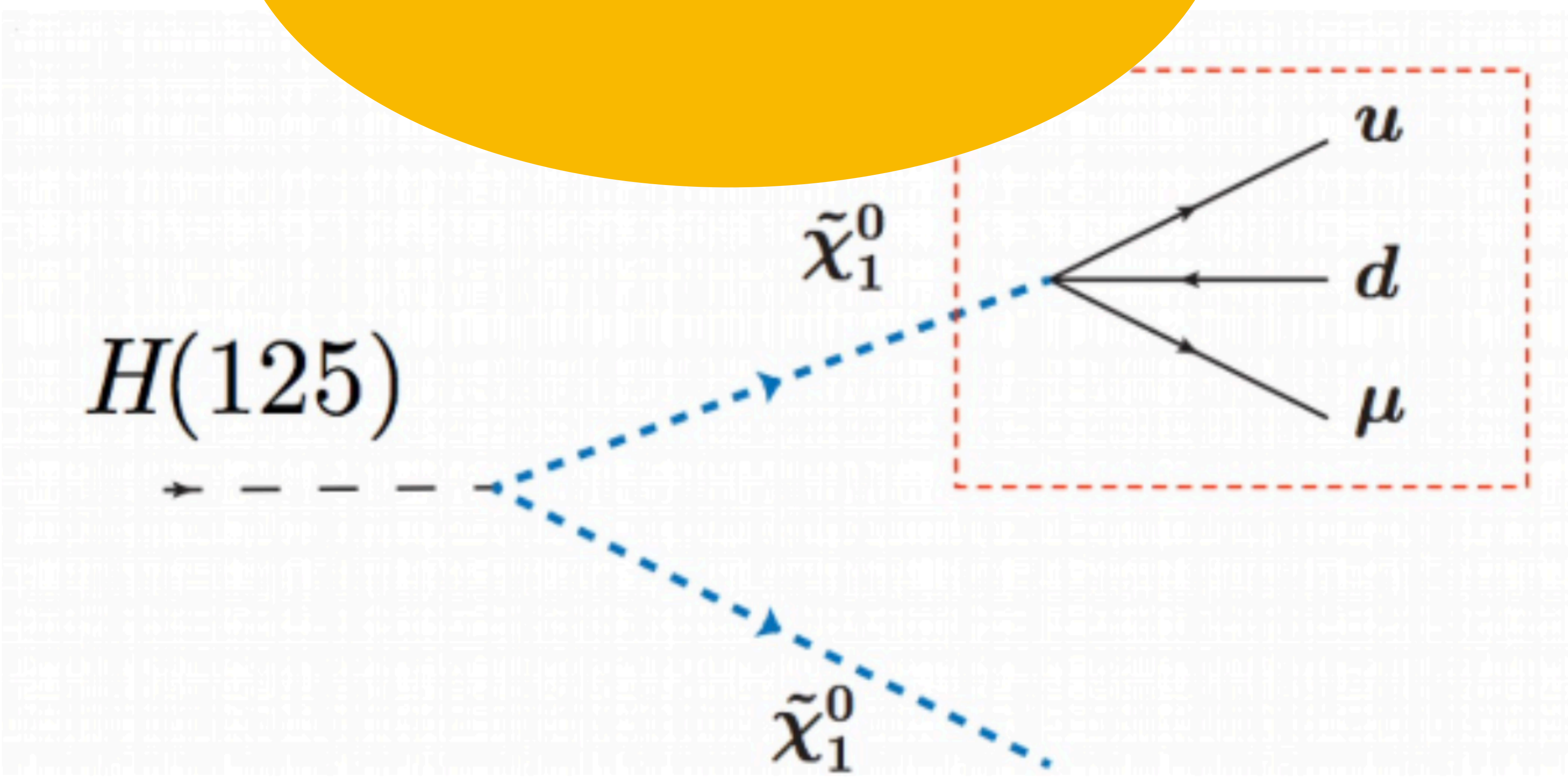
Search for particles with long life-time, coming from the decay of the SM Higgs

Exploit the LHCb vertex reconstruction

Hidden valley pions



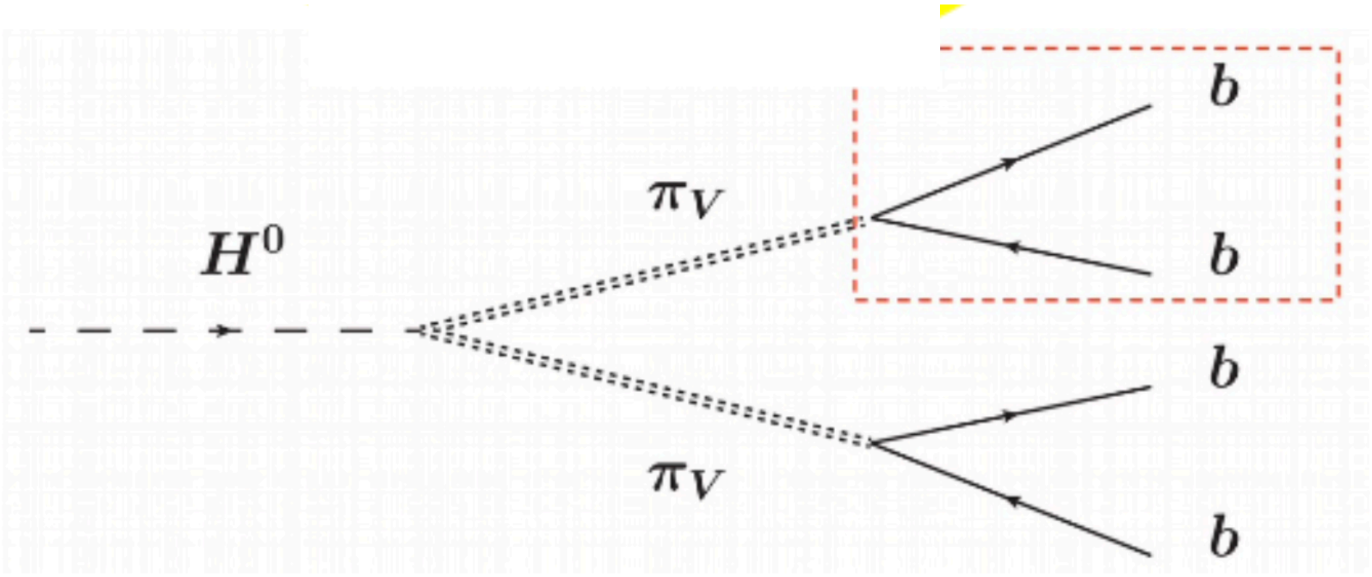
R-parity violating neutralinos (mSUGRA)

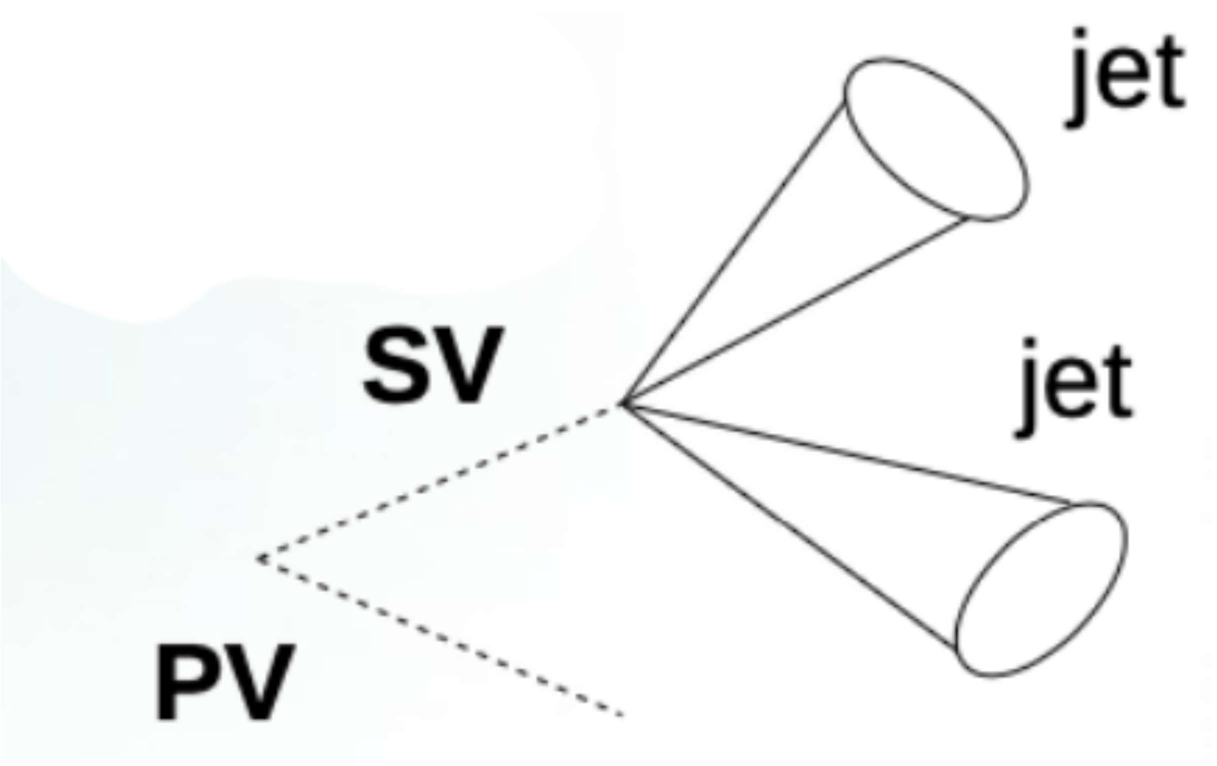


At LHCb we have mainly considered two benchmark models for LLP
But results are available for re-interpretation

LLP decaying to jets

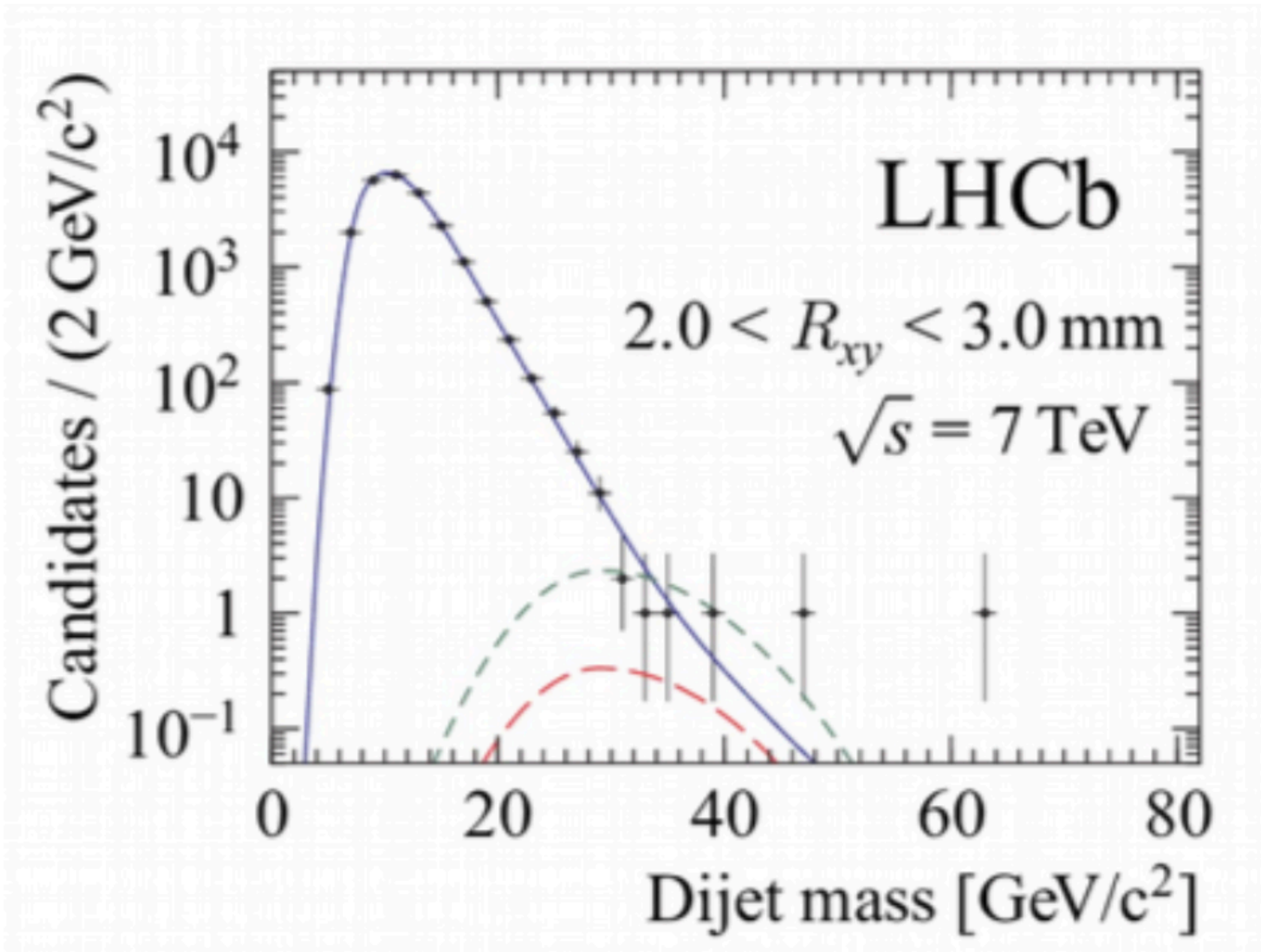
Eur. Phys. J. C77 (2017) 812





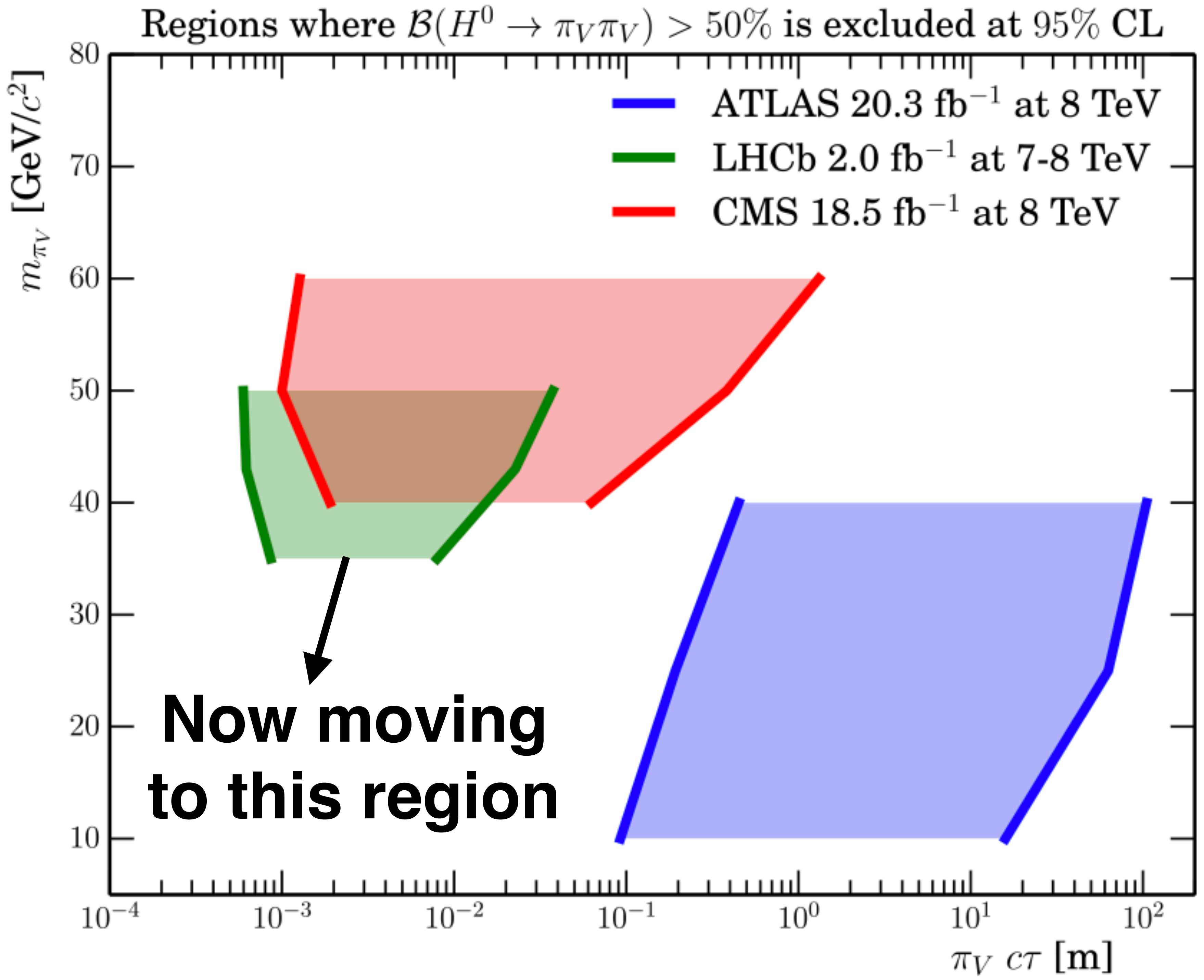
Signature: **two b-jets associated to a displaced SV**

Fit to the dijet invariant mass, in different intervals of displacement



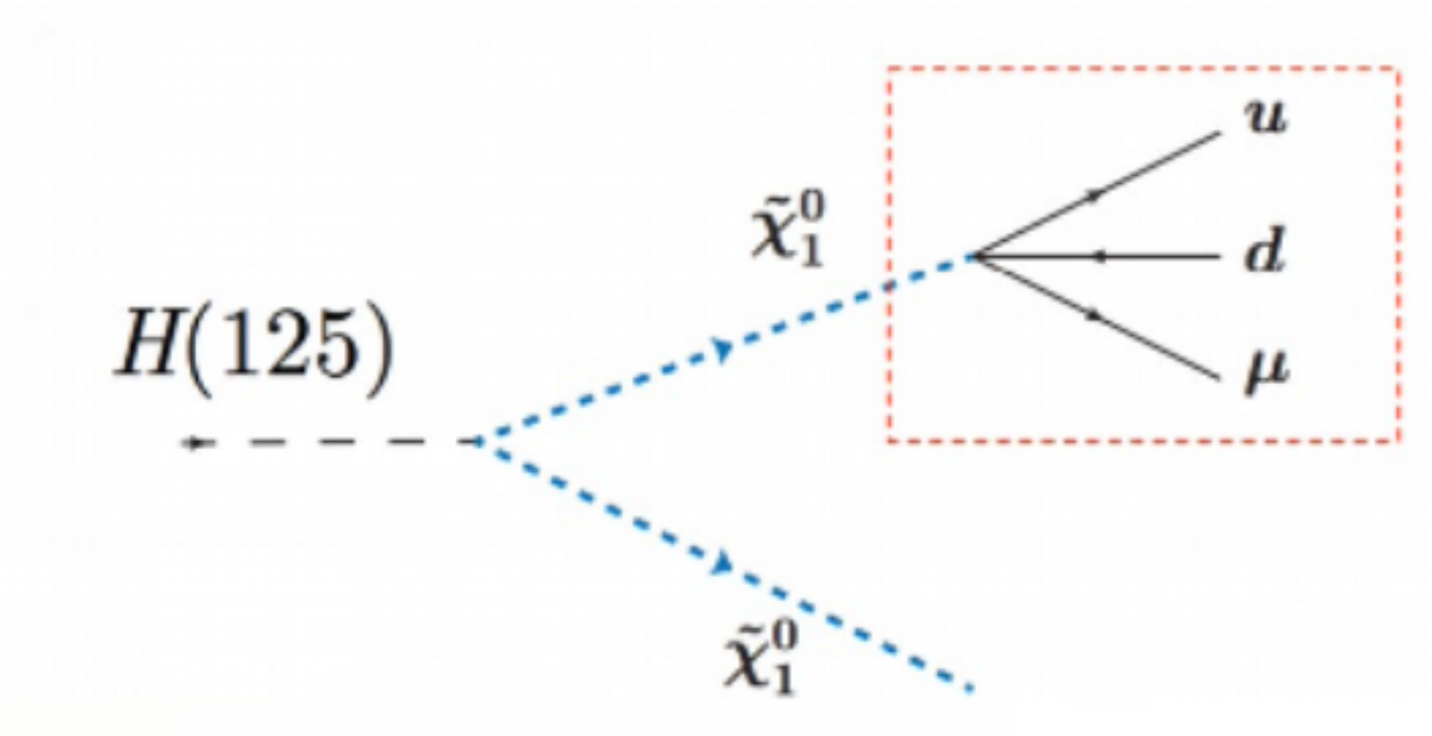
Upper limit to

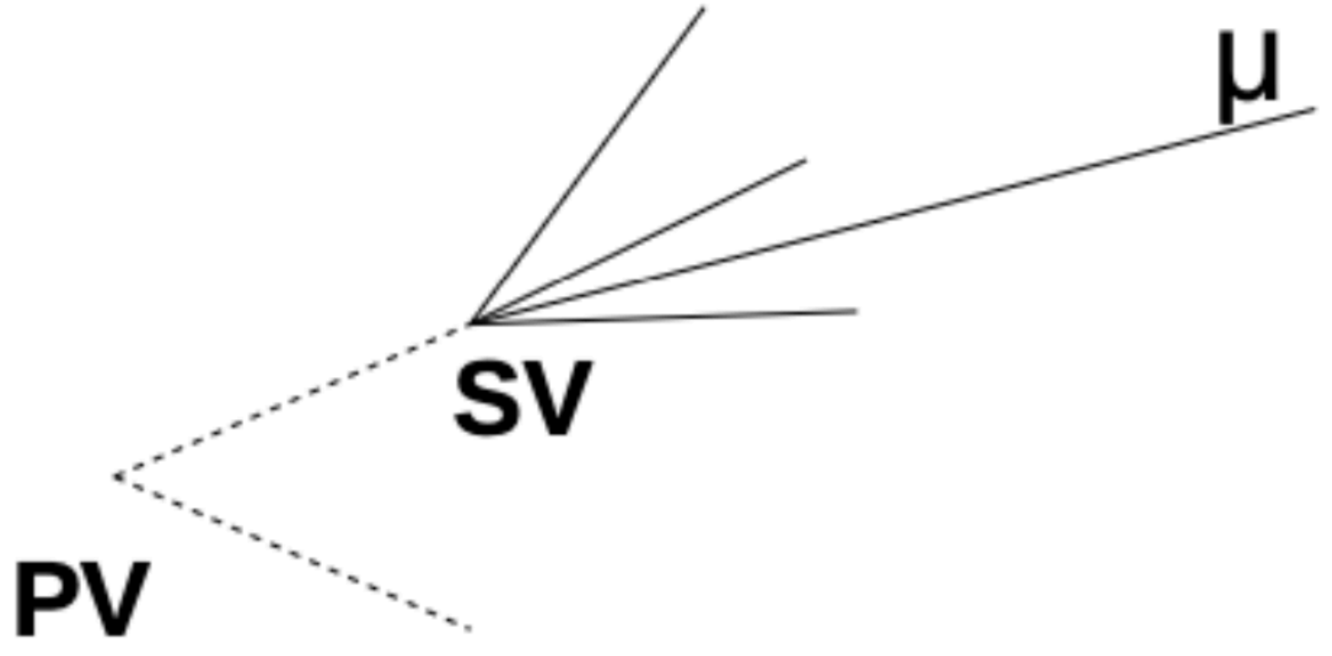
$$\frac{\sigma(gg \to H)}{\sigma_{SM}(gg \to H)} \cdot BR(H \to \pi_v \pi_v)$$



ATLAS and CMS limits not up-to-date

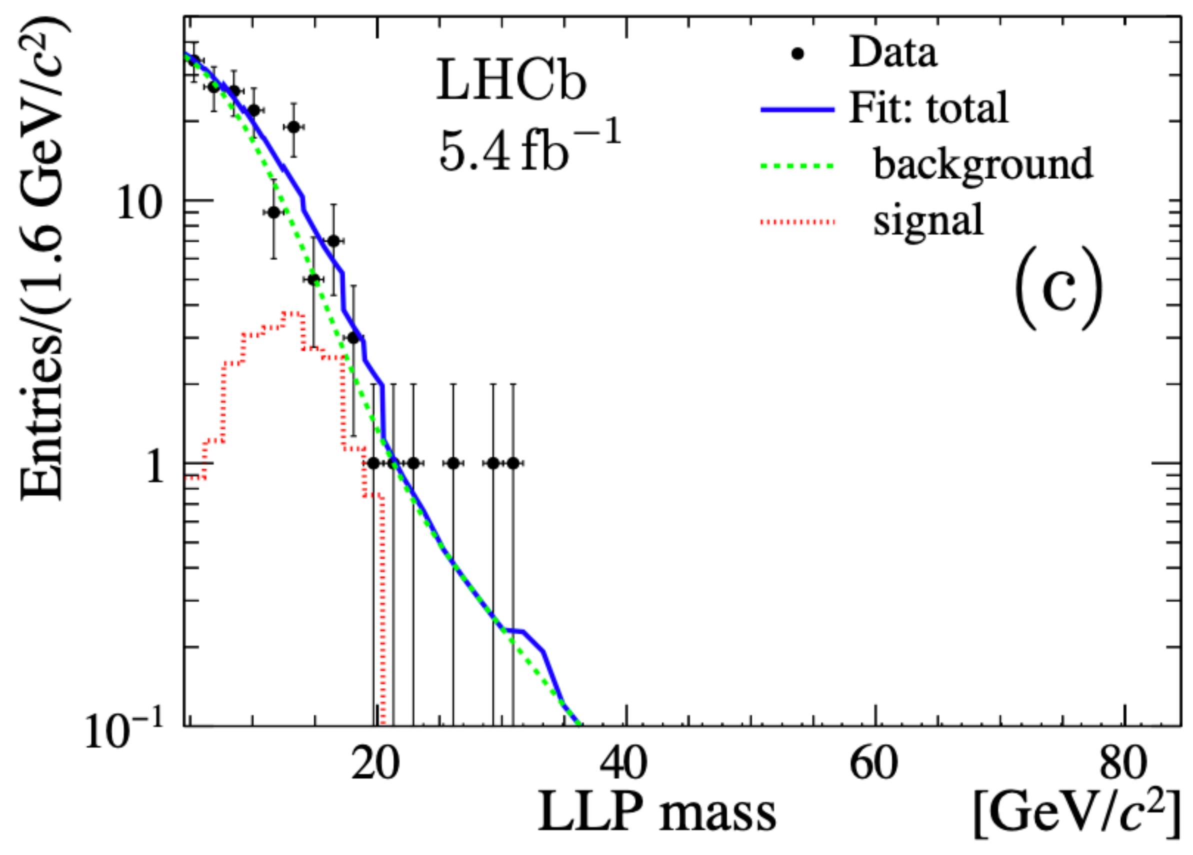
LLP decaying semileptonically





- 4 tracks SV
- muon with pT > 12 GeV
- mass(SV)> 4.5 GeV

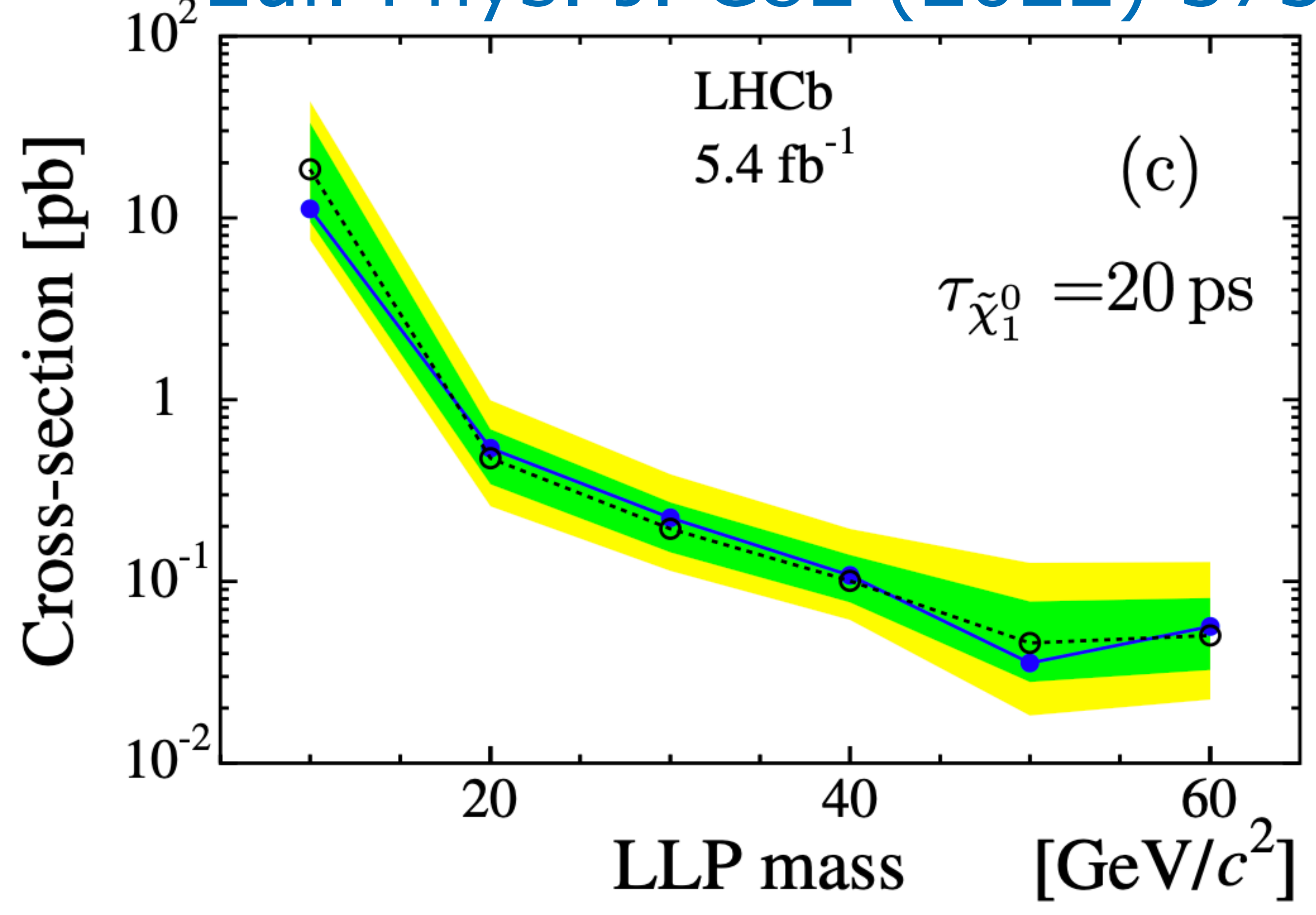
Fit to the neutralino mass
Background from bb events

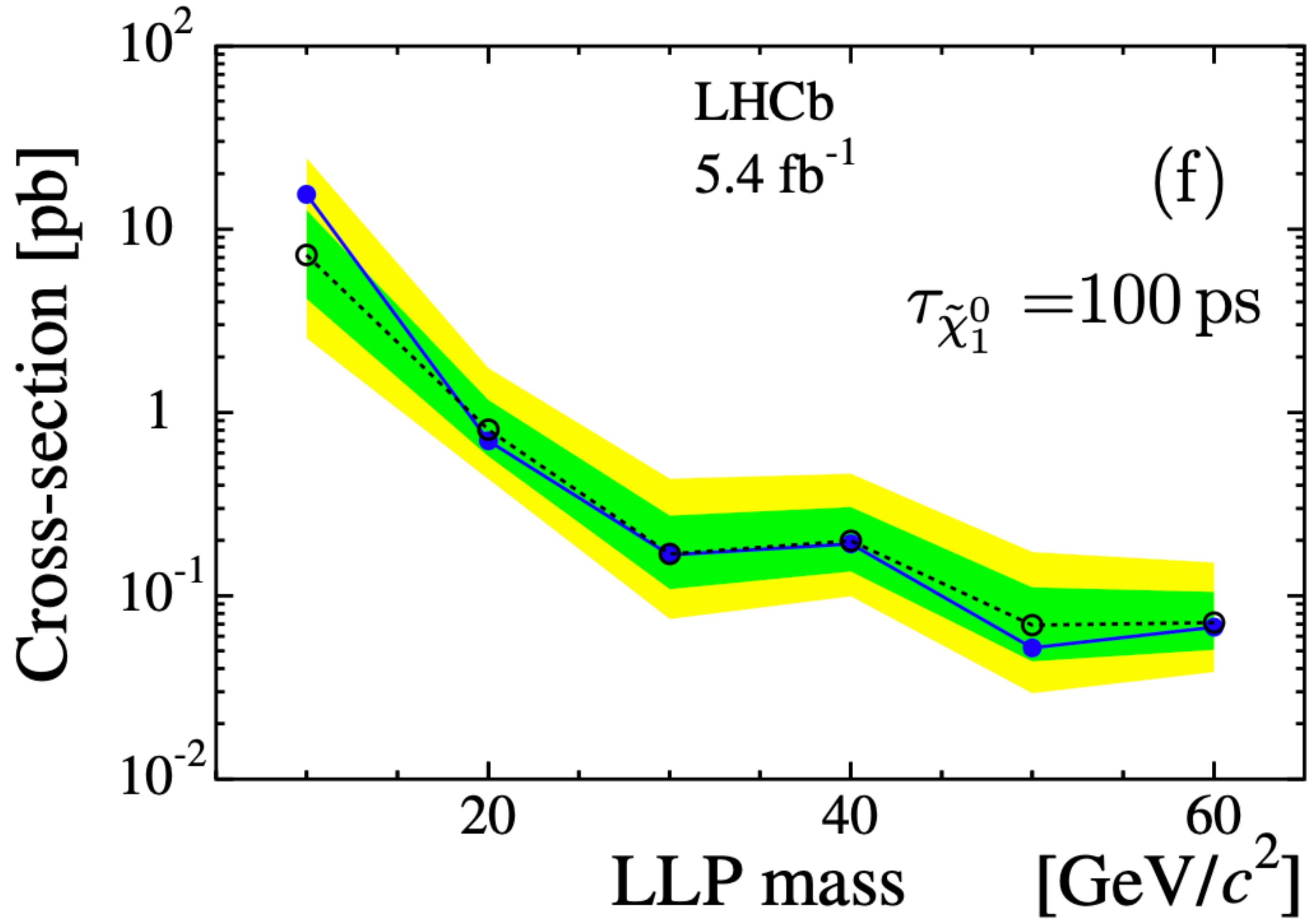


Tested lifetimes from 20 ps to 200 ps

Mass from 5 to 60 GeV

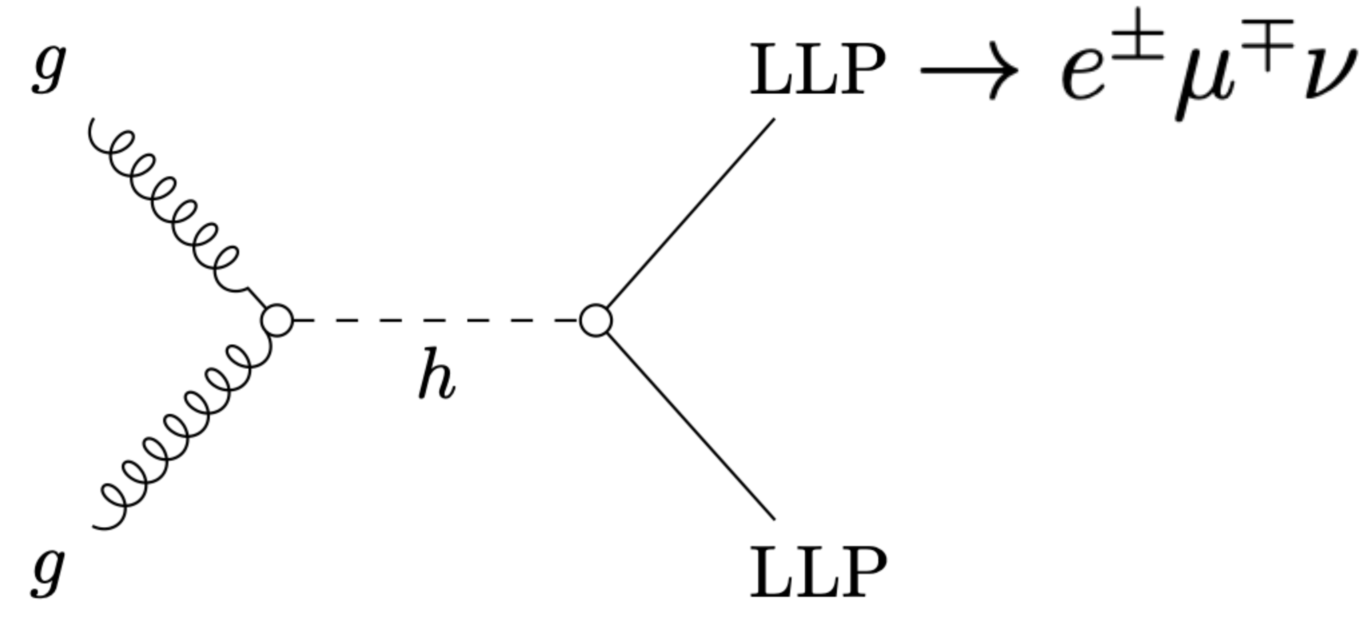
Eur. Phys. J. C82 (2022) 373





95% CL upper limits

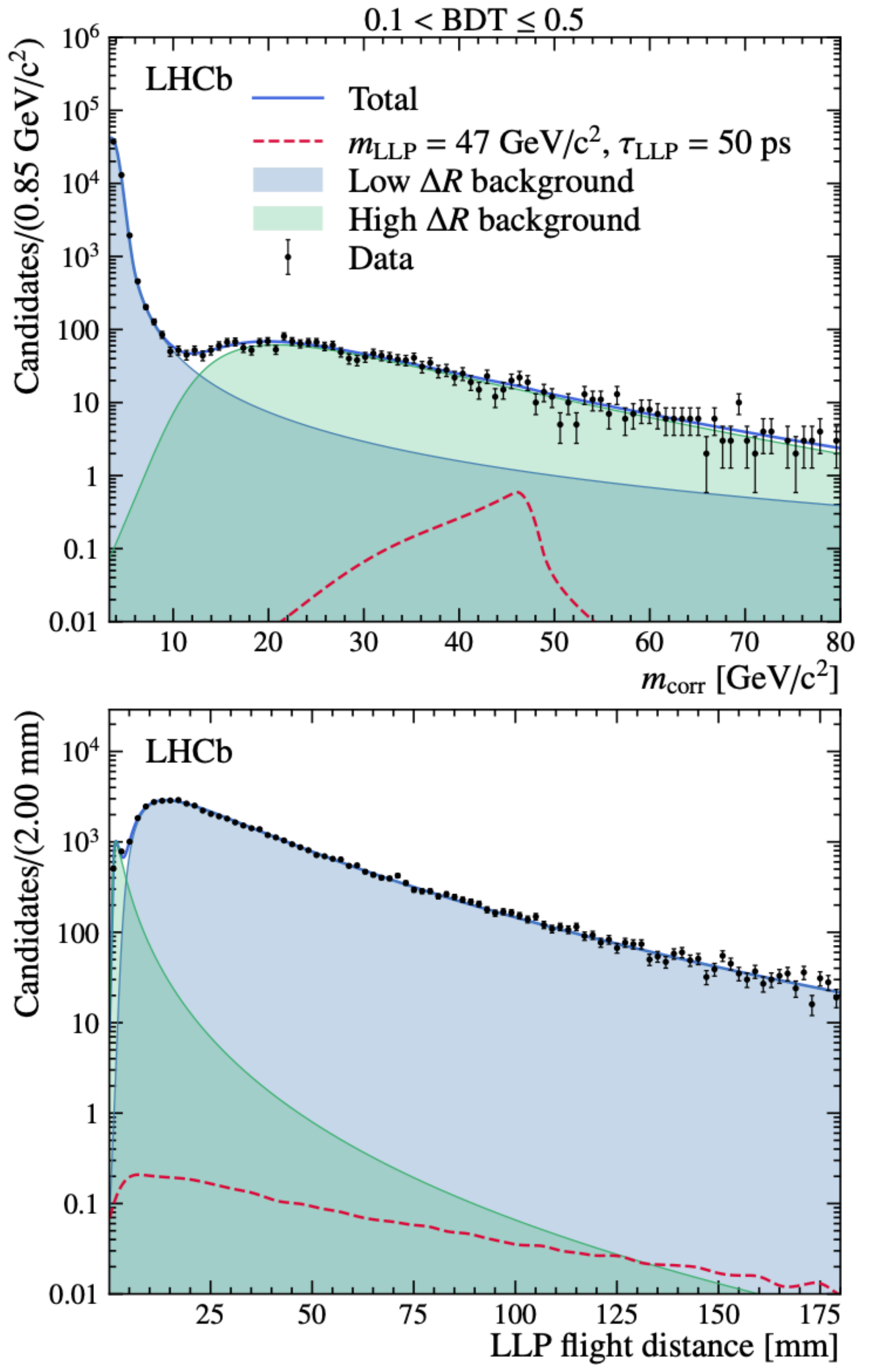
LLP decaying semileptonically



Lepton flavour violating LLP decay

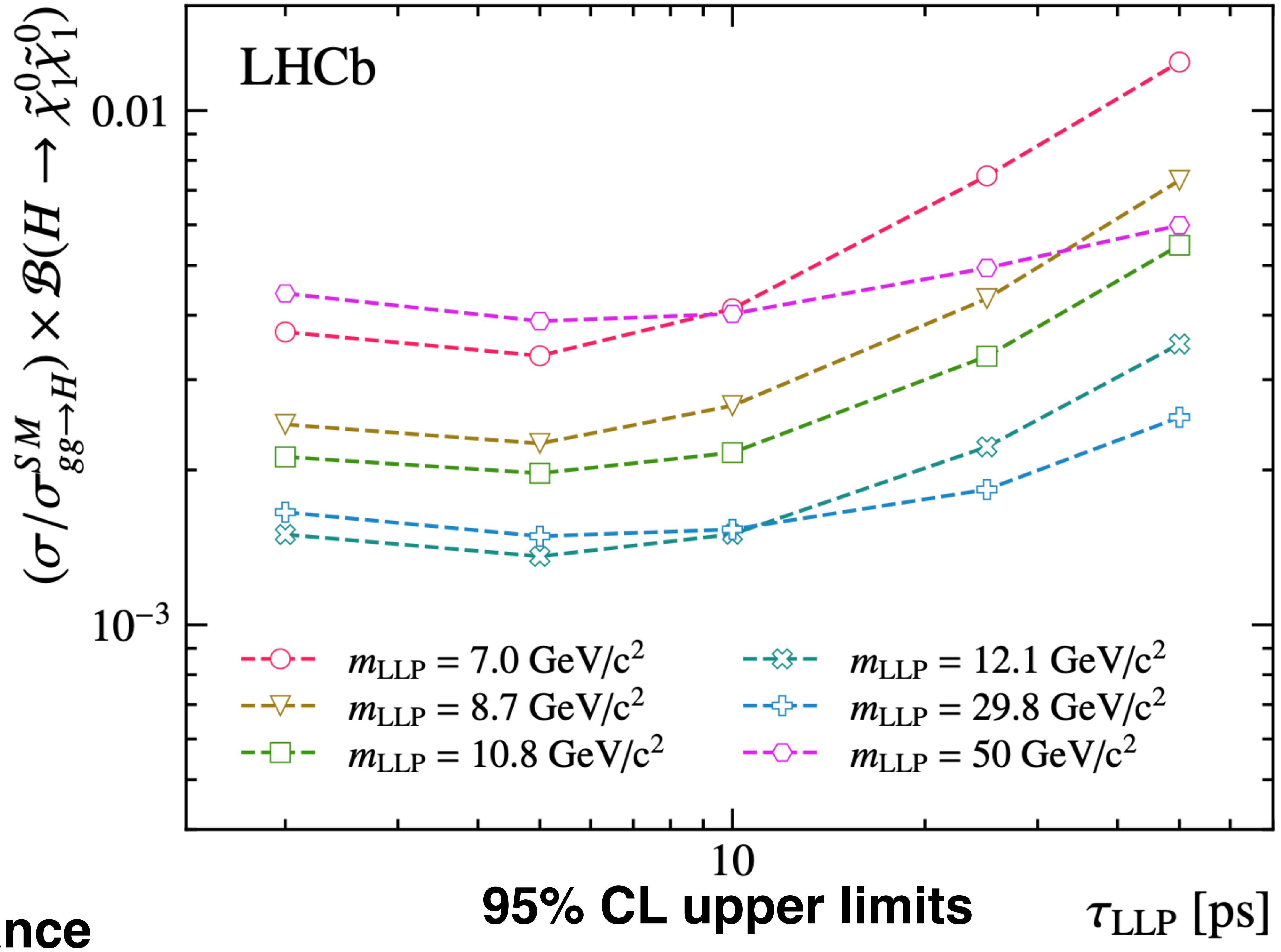
Signature: electron-muon pair

Eur. Phys. J. C81 (2021) 261



Fit to LLP mass and flight distance

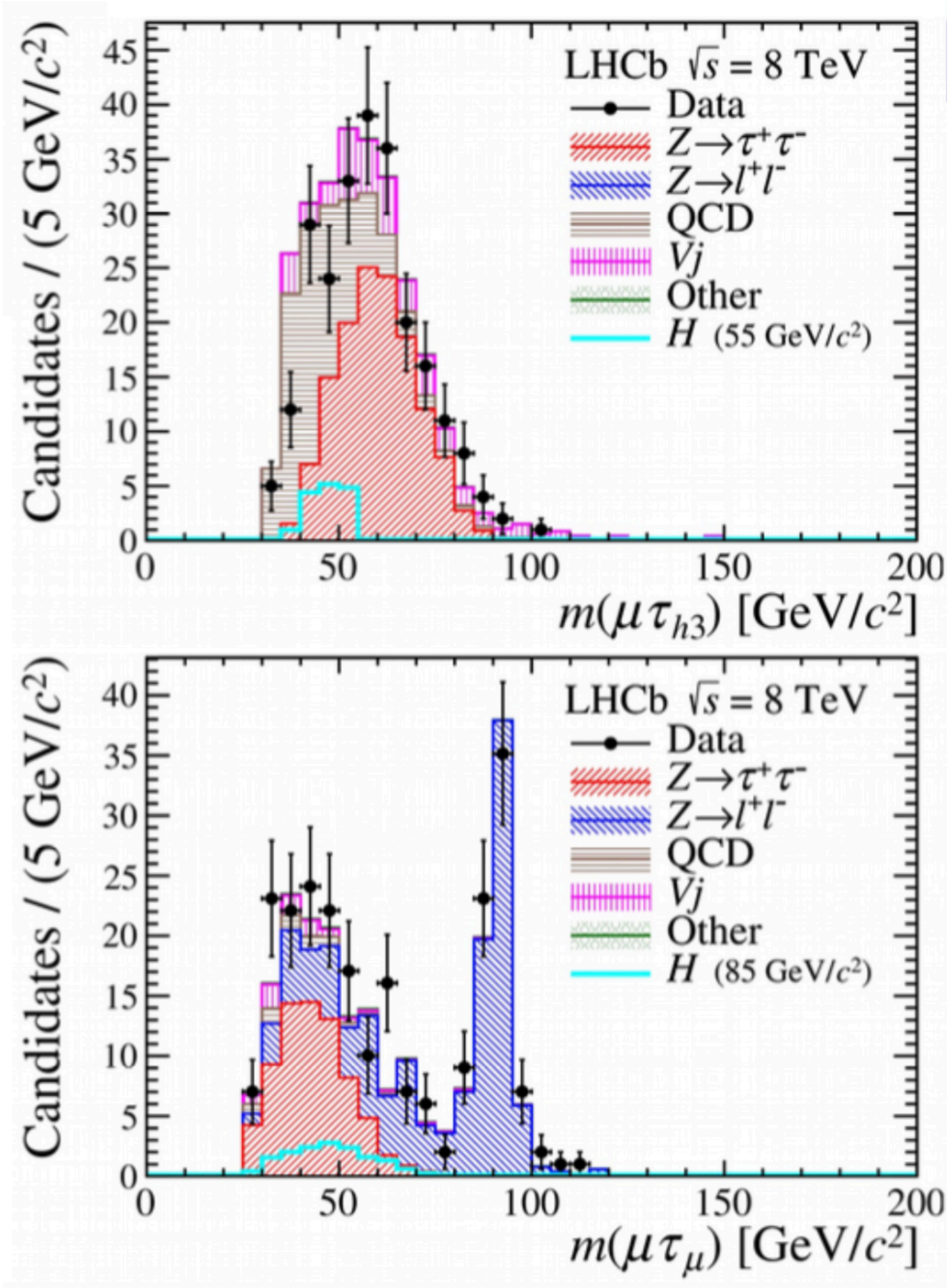
Mass from 7 to 50 GeV



95% CL upper limits

Lepton flavour violating Higgs decays

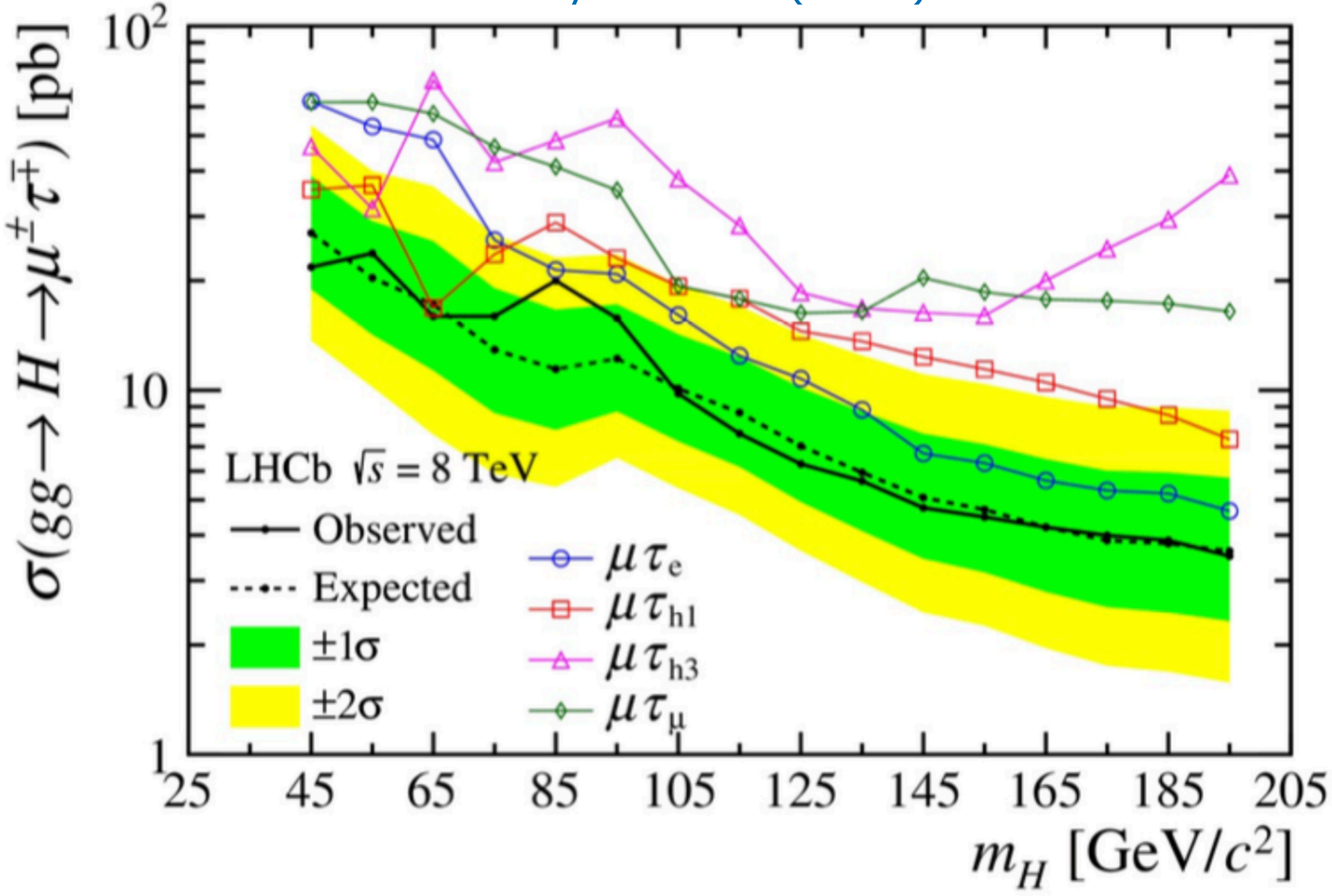
Search for H→μτ



Tau reconstructed in different channels:

- muon
- electron
- hadron
- 3-hadron

Eur. Phys. J. C78 (2018) 1008



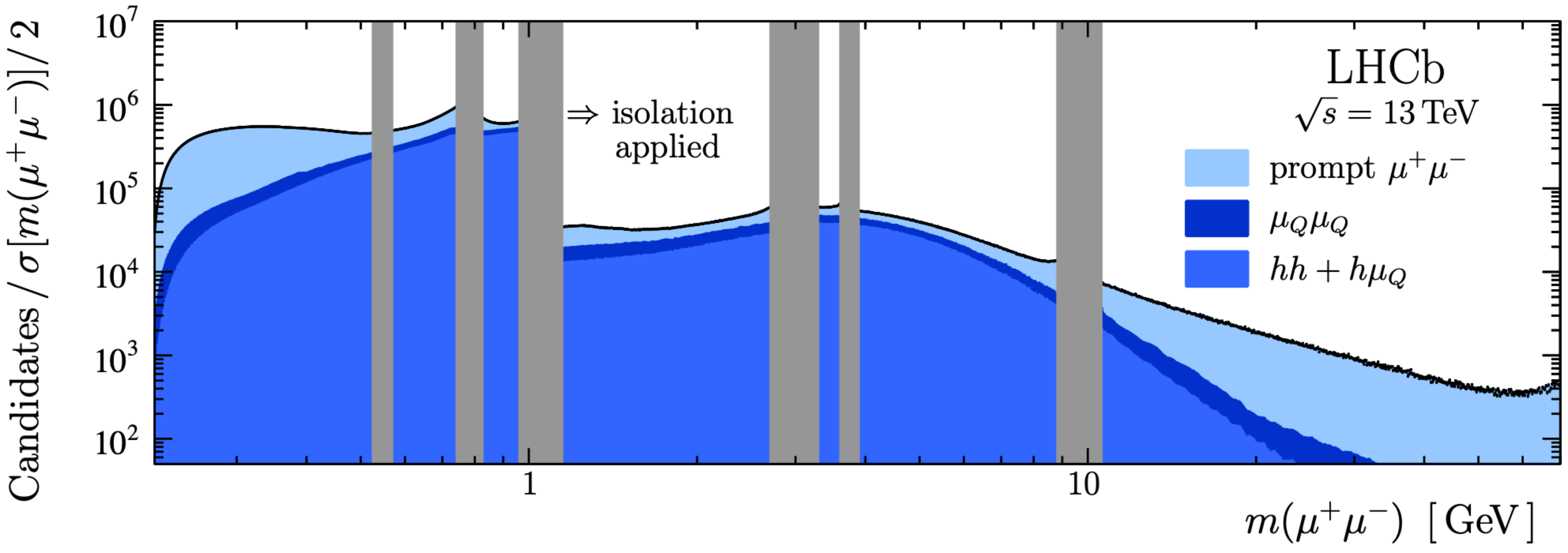
Not competitive with ATLAS/CMS for the SM Higgs, but a wide range of masses has been studied

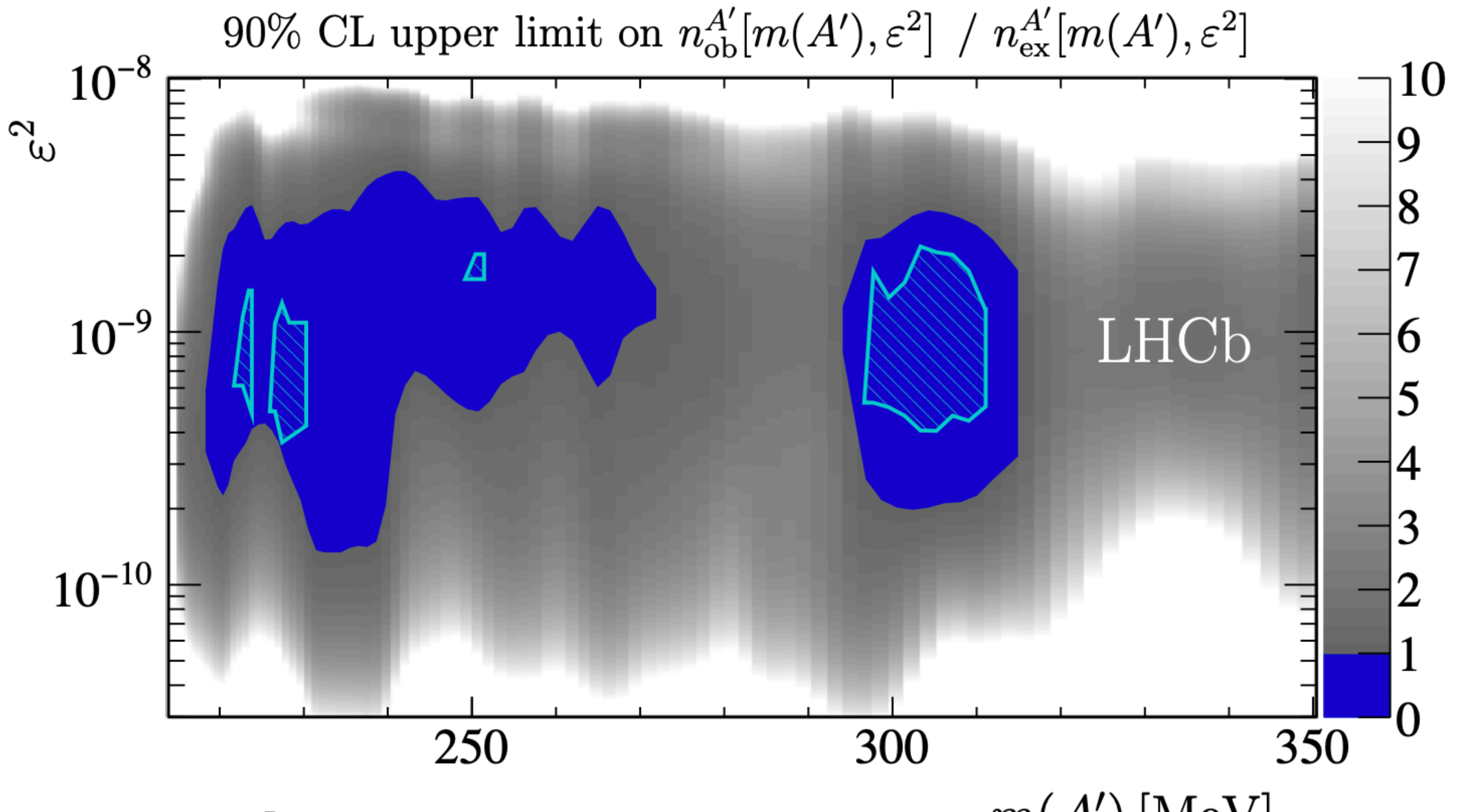
Light Higgs bosons

Dimuon searches

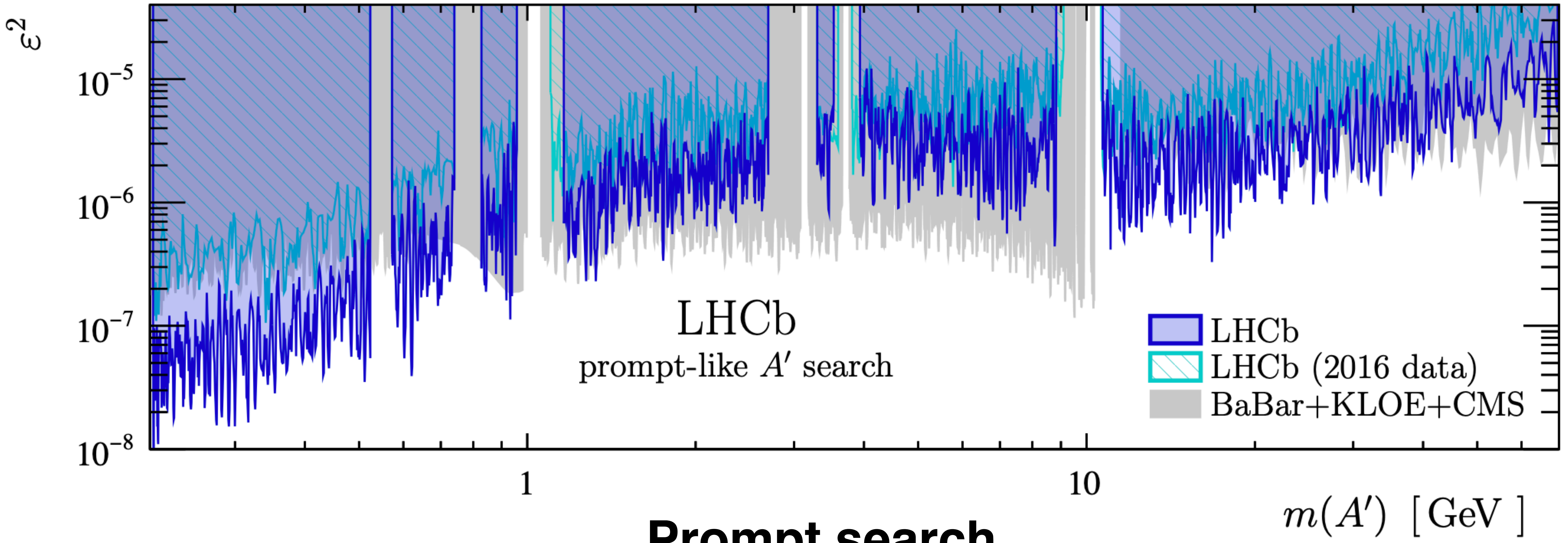
- **Since Run 2 we have dedicated trigger lines for dimuon searches**
- We have used them to put the most stringent constraints on dark photons in the mass range [214, 740] MeV and [10.6, 30] GeV

PHYS. REV. LETT. 124 (2020) 041801





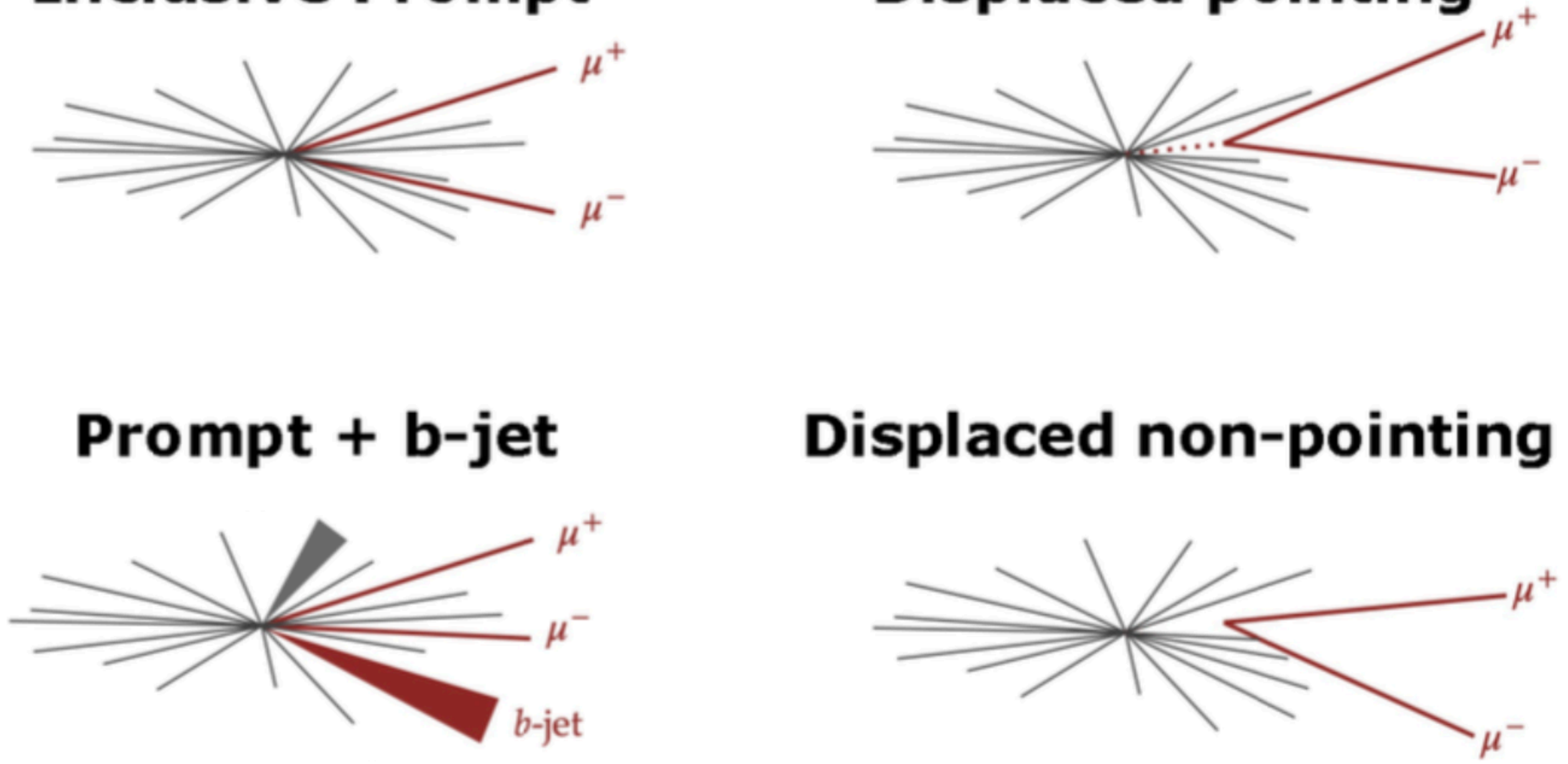
Displaced search



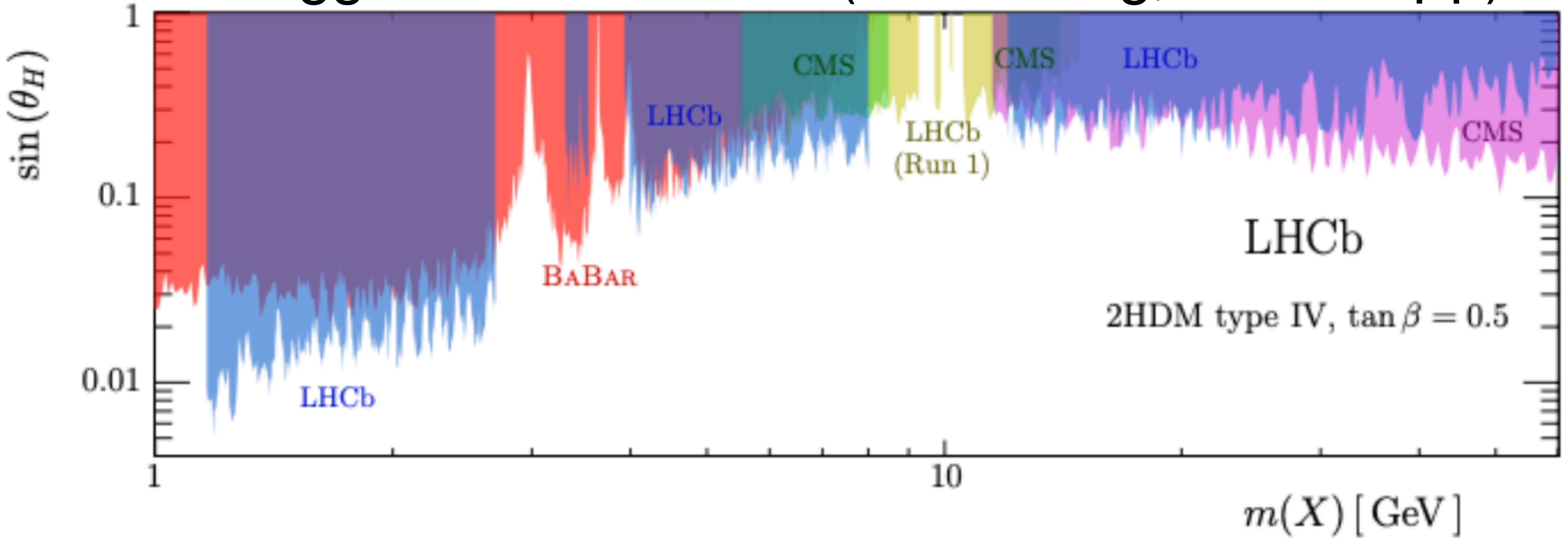
Prompt search

Higgs to dimuons

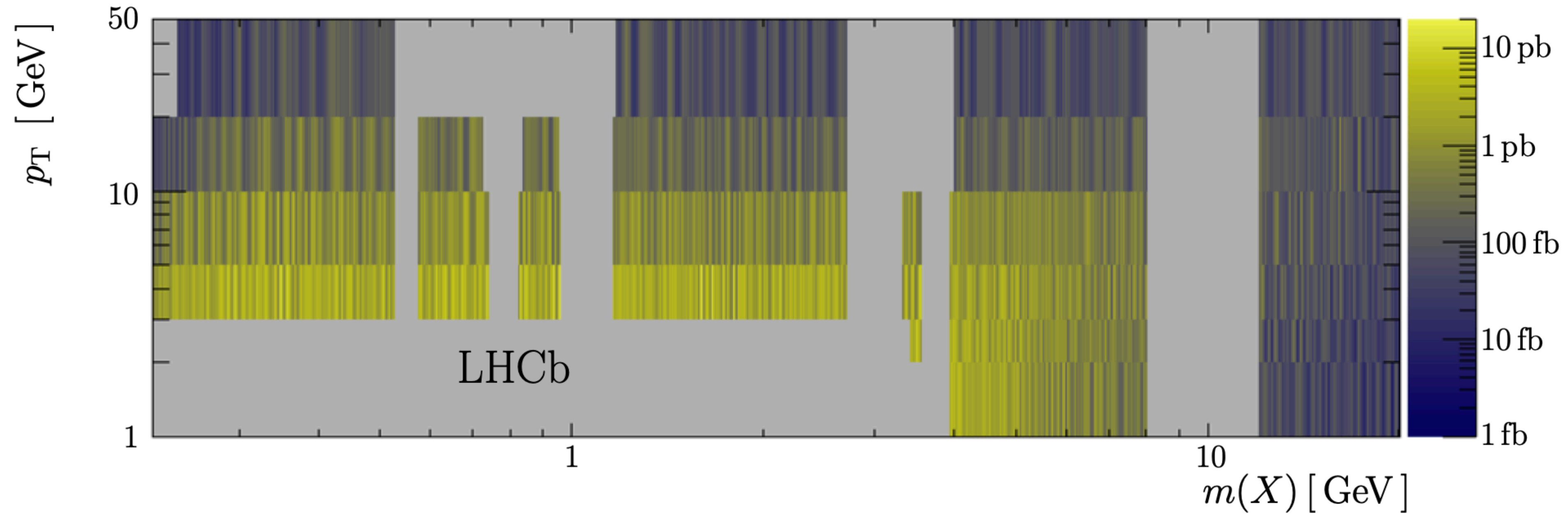
JHEP 10 (2020) 156

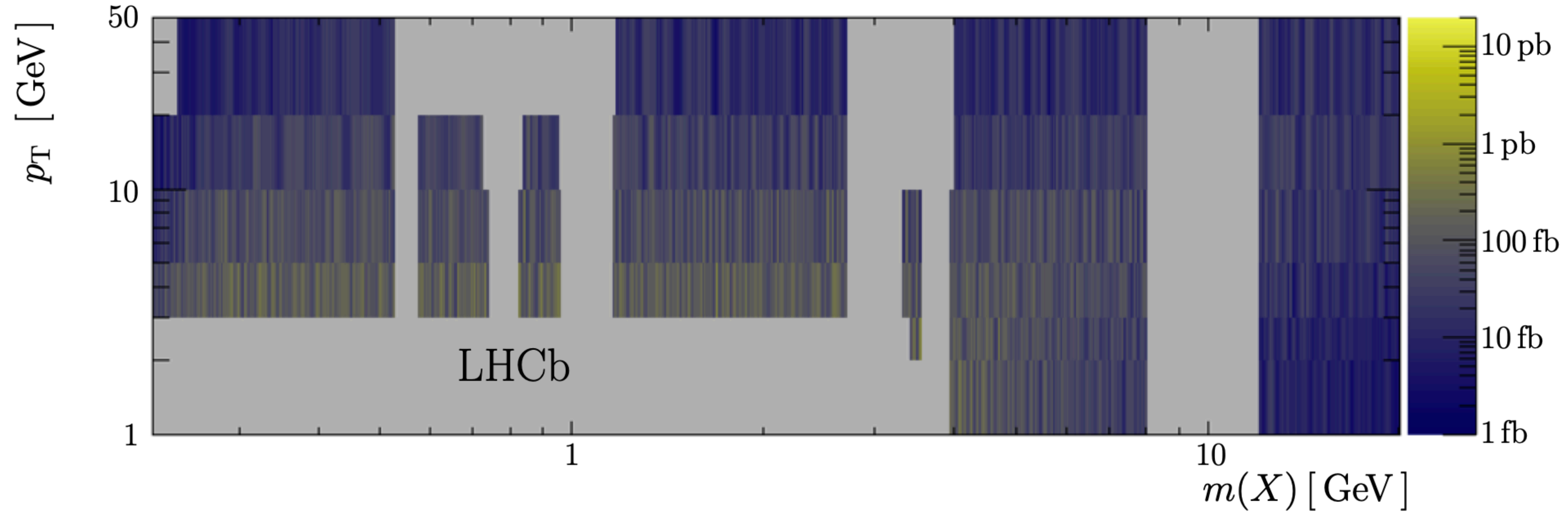


2 Higgs Doublet Model (H-X mixing, with X→μμ)



Inclusive prompt 90% CL upper limits

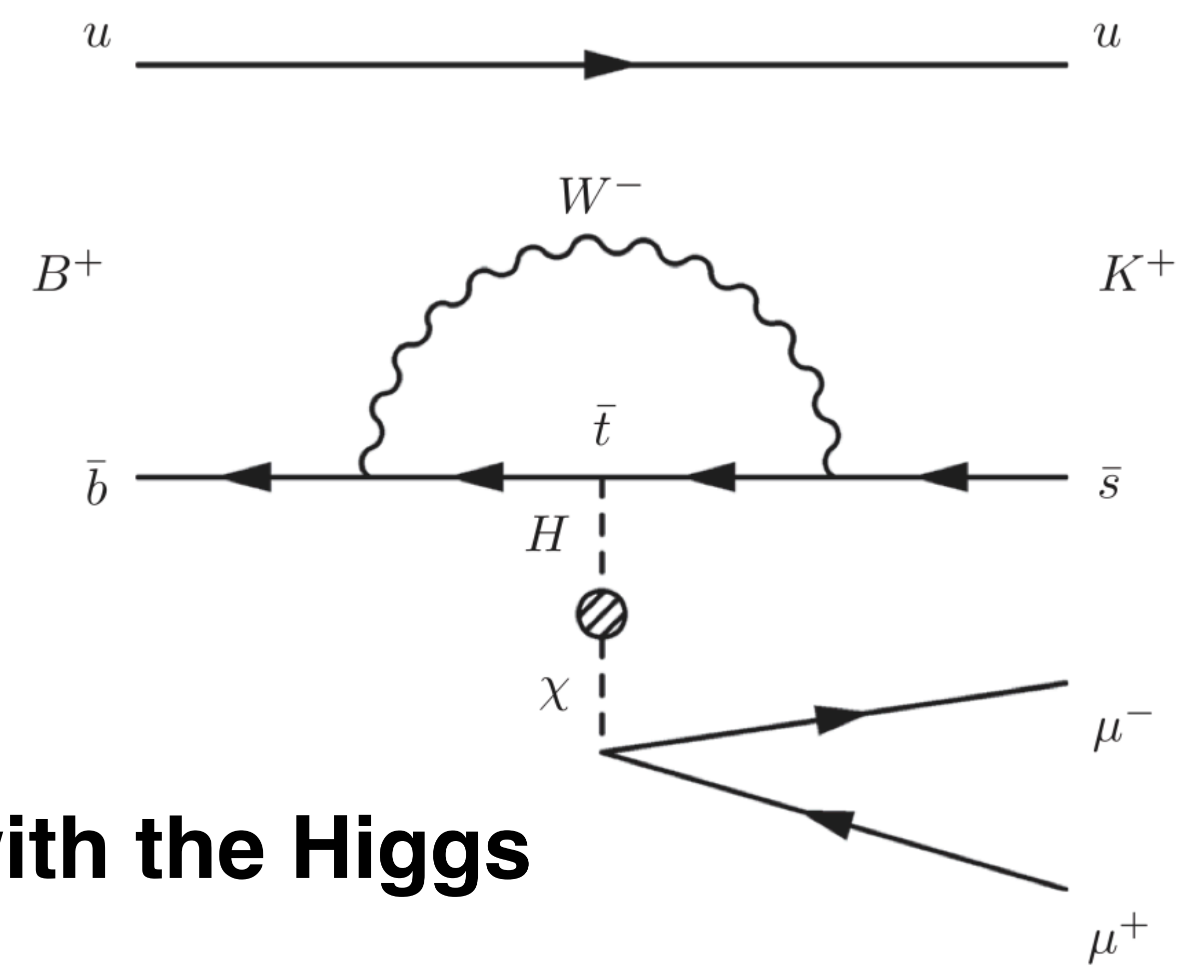




Prompt + b-jet 90% CL upper limits

Searches with B decays

Hidden sector bosons

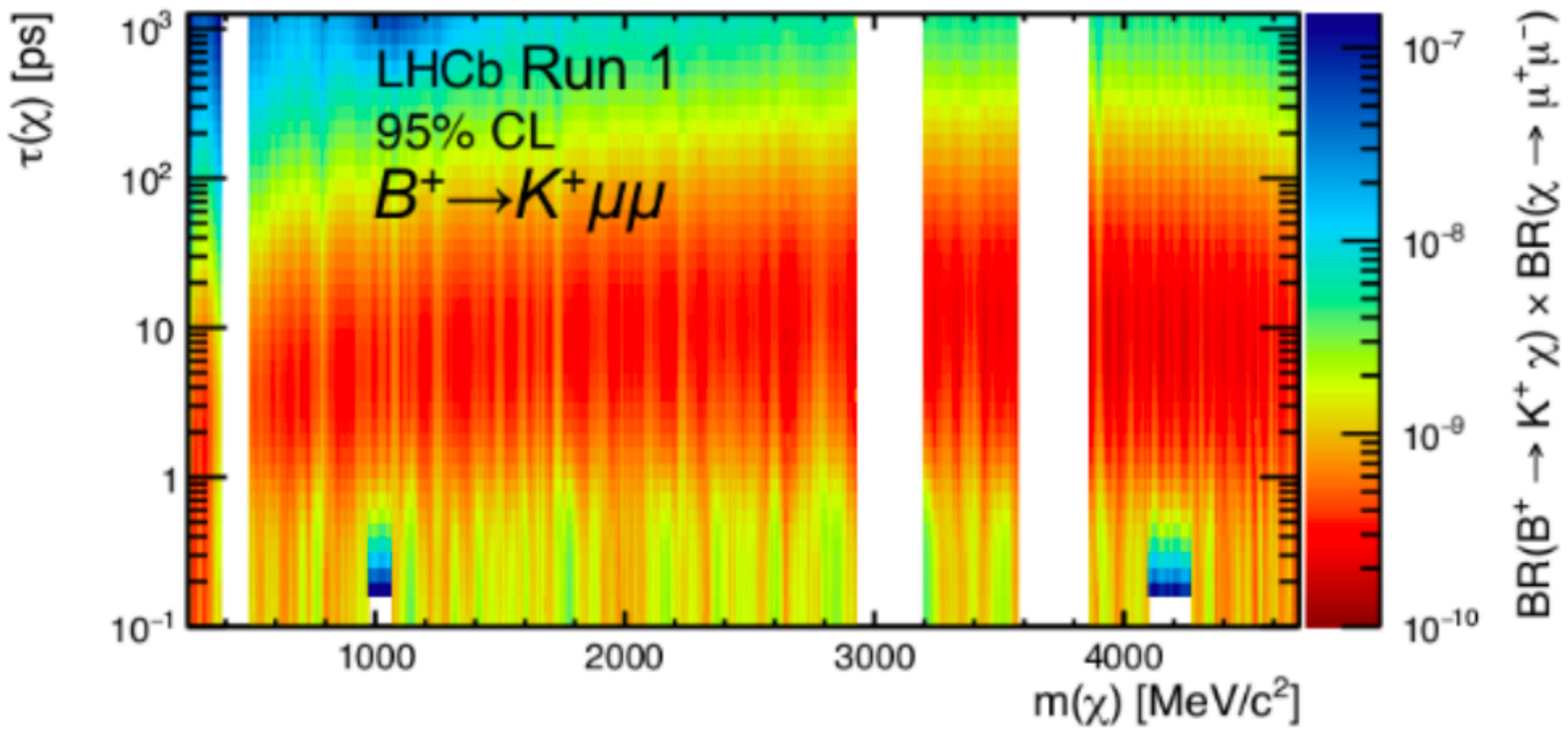


Mixing with the Higgs

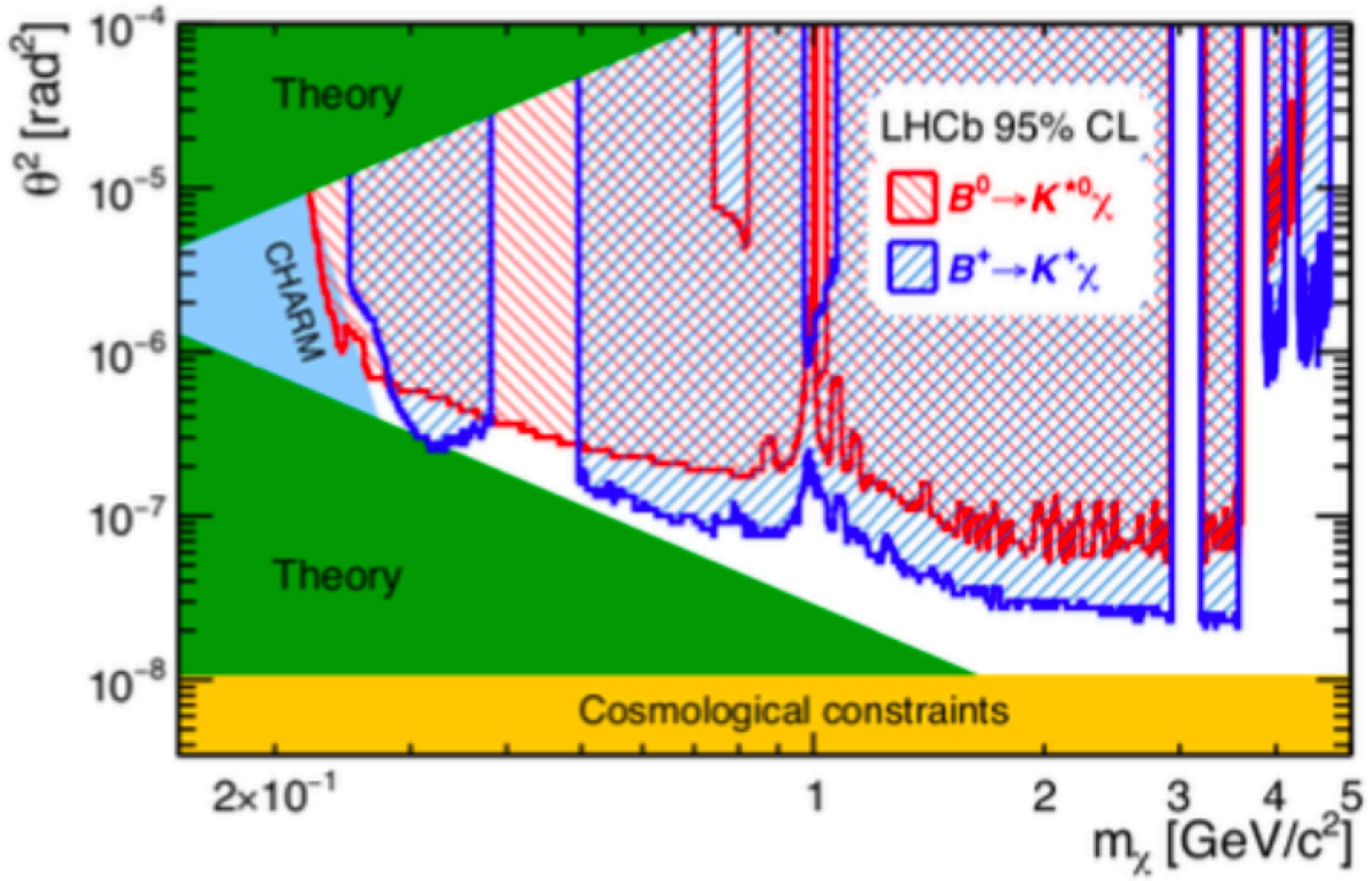
$$B^+ \to K^+\chi(\mu^+\mu^-)$$

LHCb can search for new particles from B decays: Higgs portal to new physics

Phys. Rev. D **95**, 071101



Inflaton model

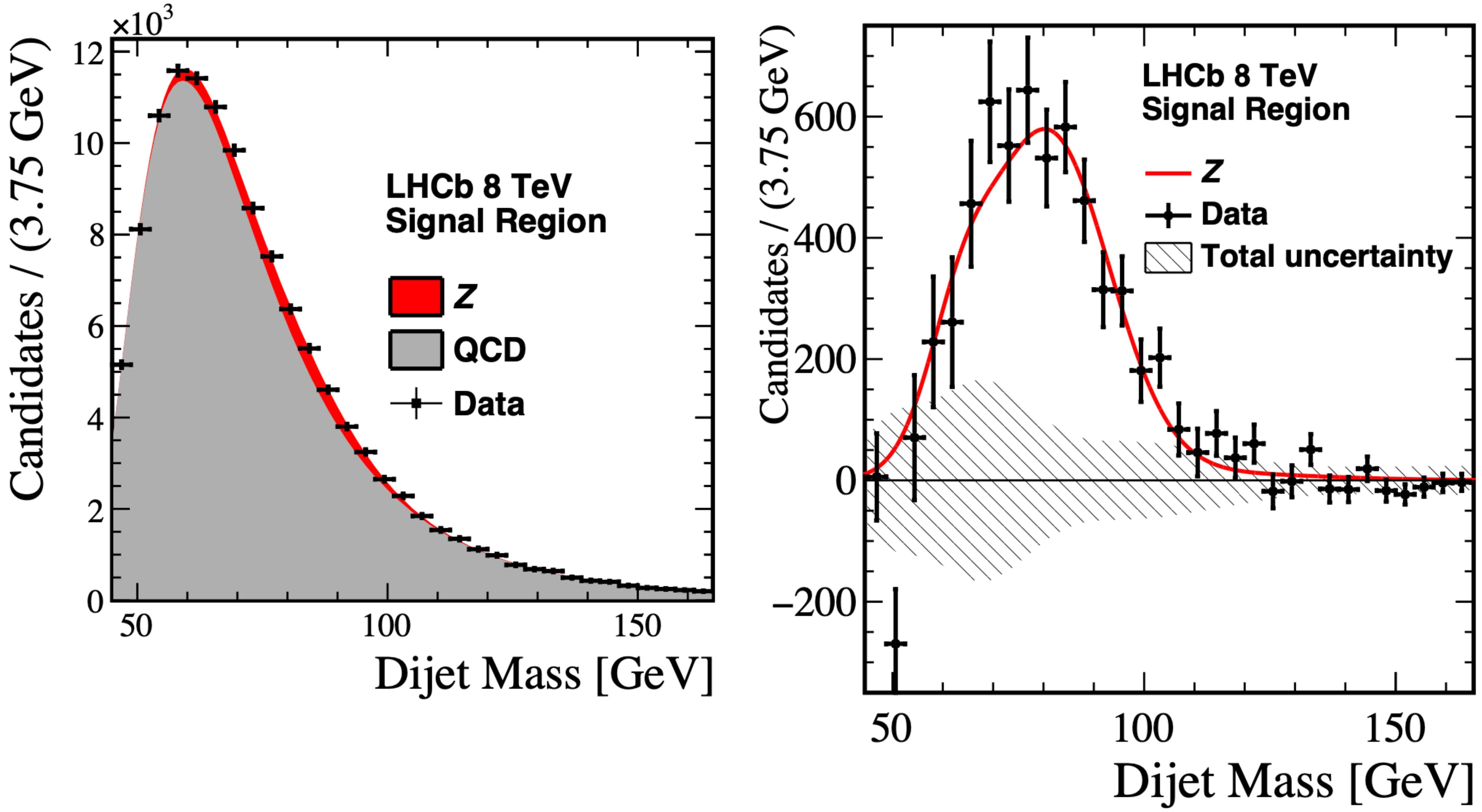


Standard Model Higgs

Dijet resonances

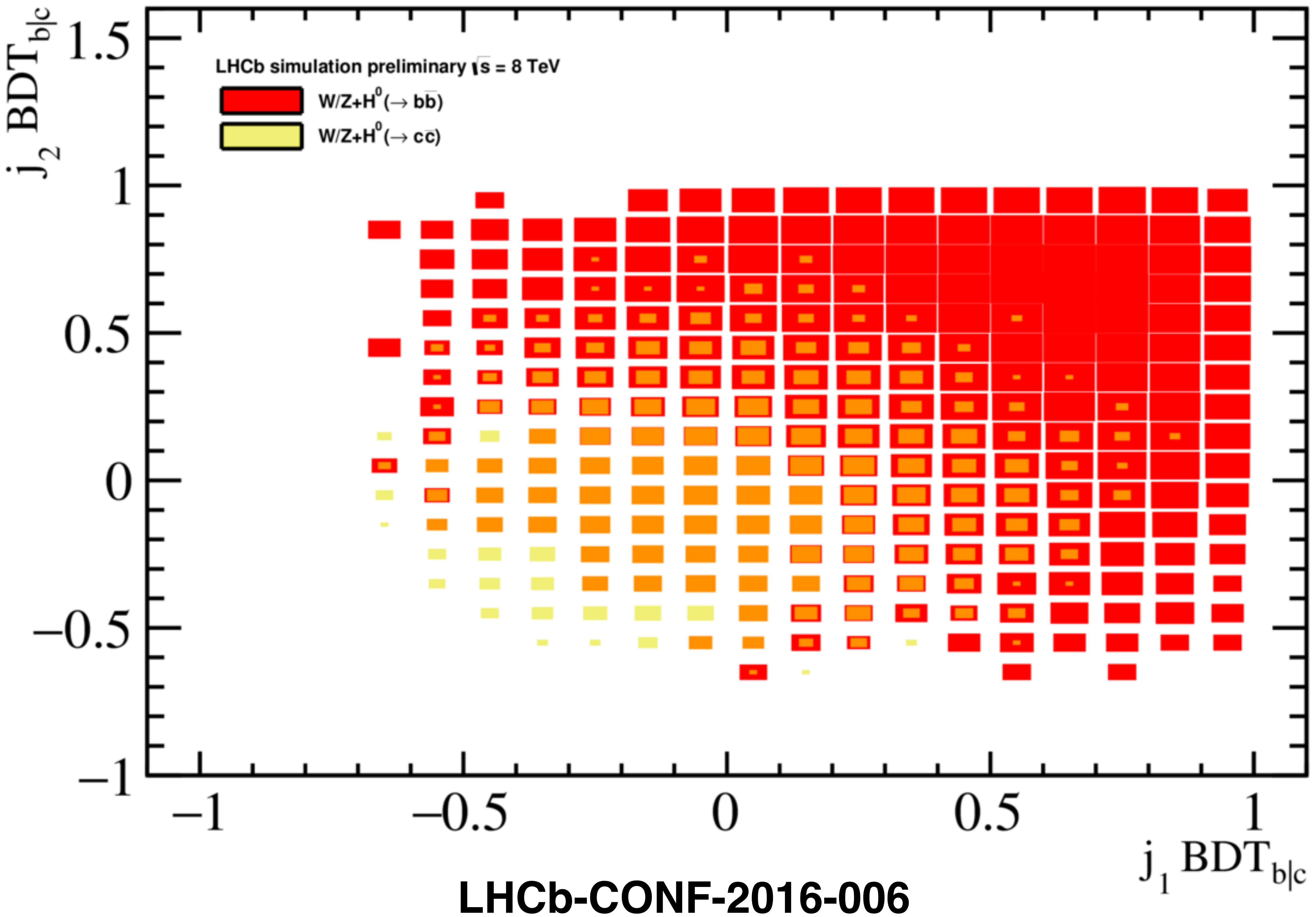
- **LHCb has the potential to look for the decay of the Higgs to $b\bar{b}$ and $c\bar{c}$ quarks**:
  - Excellent jet reconstruction
  - Excellent SV reconstruction
  - Low p_T thresholds triggers (selecting SV-tagged jets with p_T>17 GeV)
  - Separation between b and c quarks
- The **measurement of the $Z \to b\bar{b}$ process** is a a proof of LHCb capabilities

Phys. Lett. B776 (2018) 430



W/Z+H production

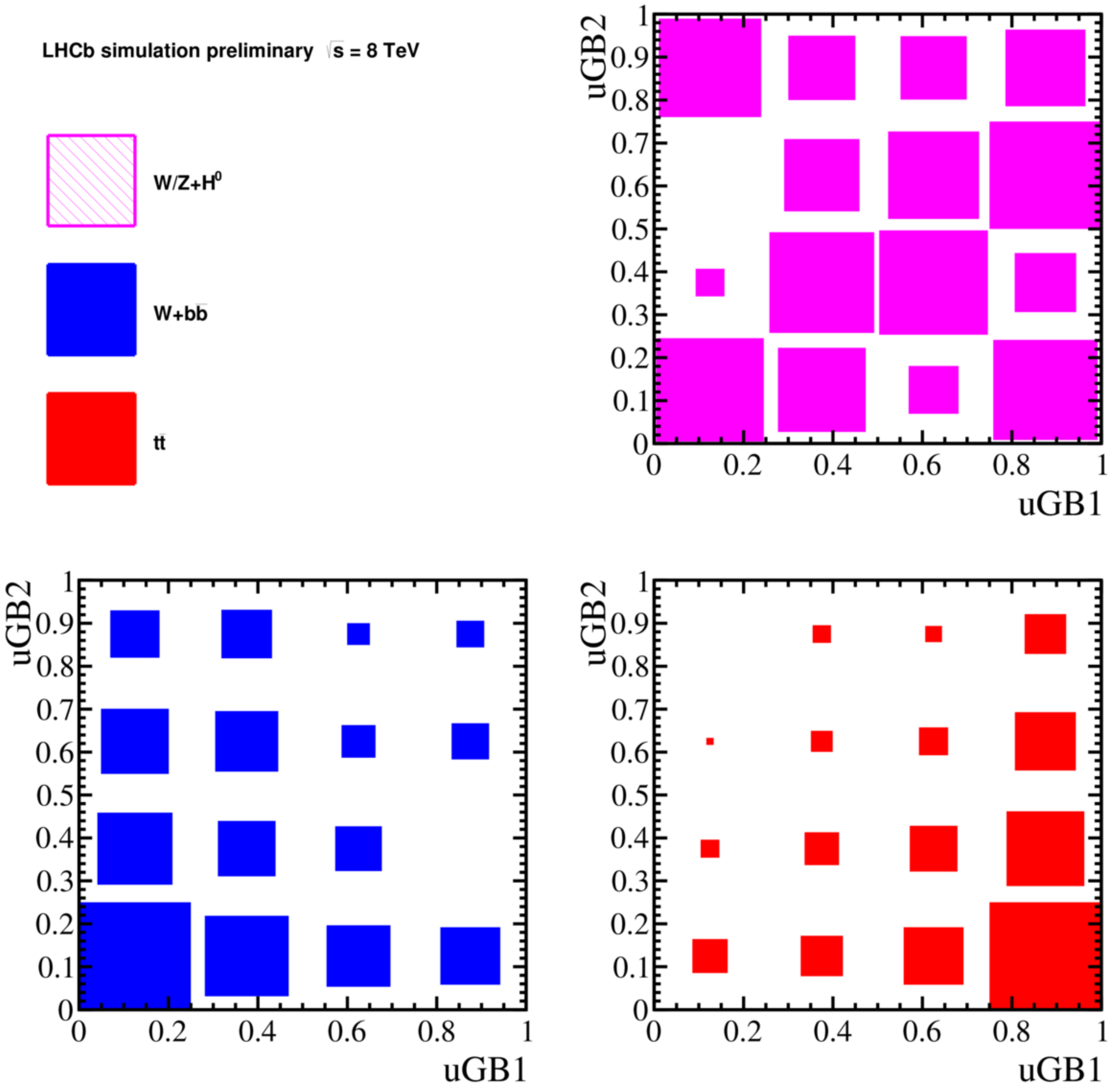
- LHCb searched for **W/Z + H** in Run 1 data (**2 fb^{-1} at 8 TeV**), by looking at the **dijet+lepton (muon or electron) final state**
- The two jets are required to have p_T>20 GeV and SV-tagged
- One of the key aspects is that **$H\to b\bar{b}$ is an irreducible background for $H\to c\bar{c}$**.
- We can use the **BDT(b vs c)** to separate the two Higgs contributions
- The optimal cut on BDT(b vs c) on both jets **removes 90% of $H\to b\bar{b}$ while keeping 62% of $H\to c\bar{c}$.**



LHCb-CONF-2016-006

W/Z+H production

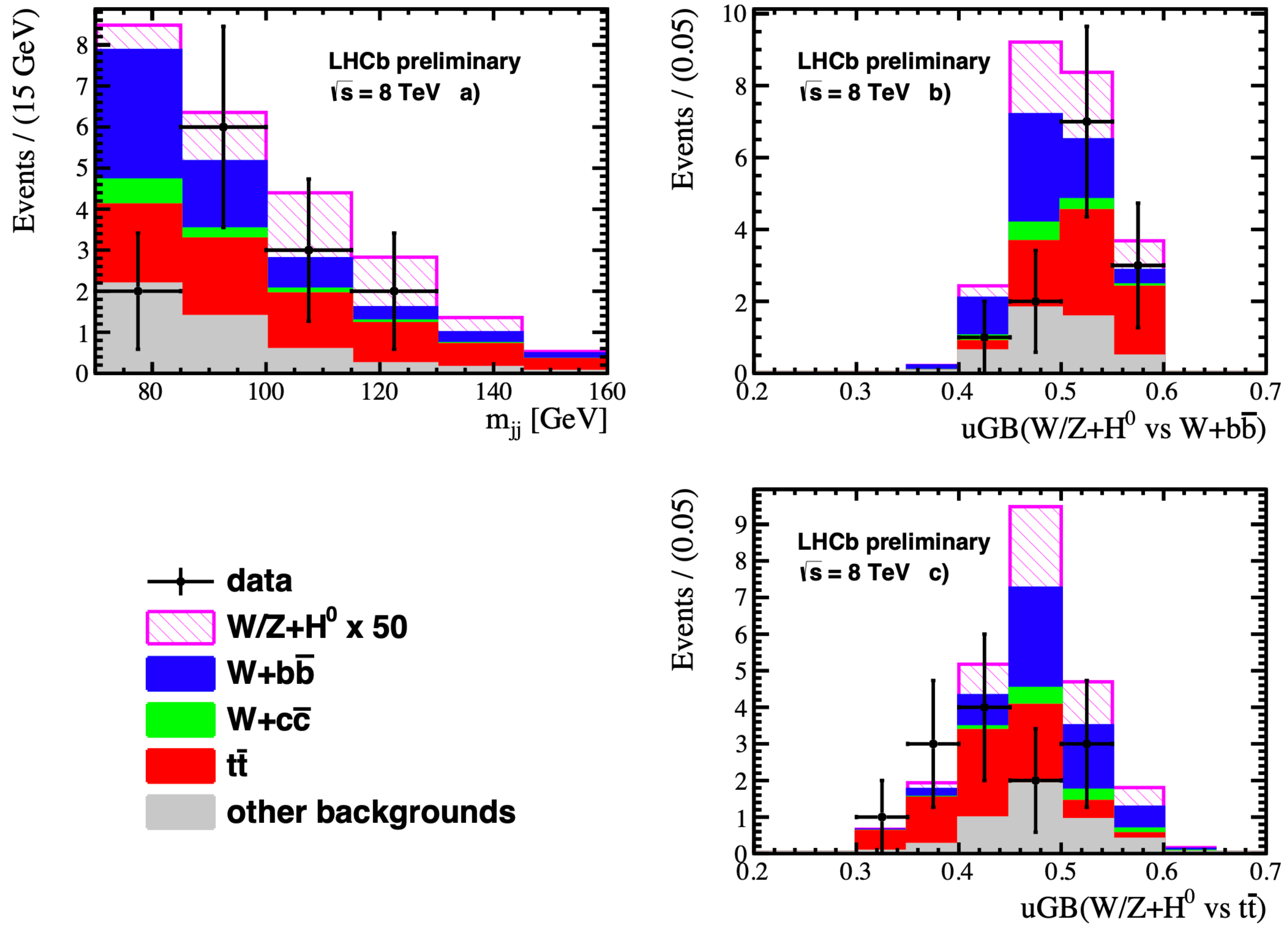
- The other backgrounds are **W+b$\bar{b}$/c$\bar{c}$ and top**
- A multivariate method (**uniform gradient boost, uGB**) has been used to separate the backgrounds from the signal
- Inputs are 12 kinematic variables of jets and leptons
- **Two uGBs are trained in order to be uncorrelated with the dijet invariant mass**
- A transformation is applied in order to make the distribution flat for the Higgs
- The upper limit is set by using the dijet invariant mass and the two uGBs distributions



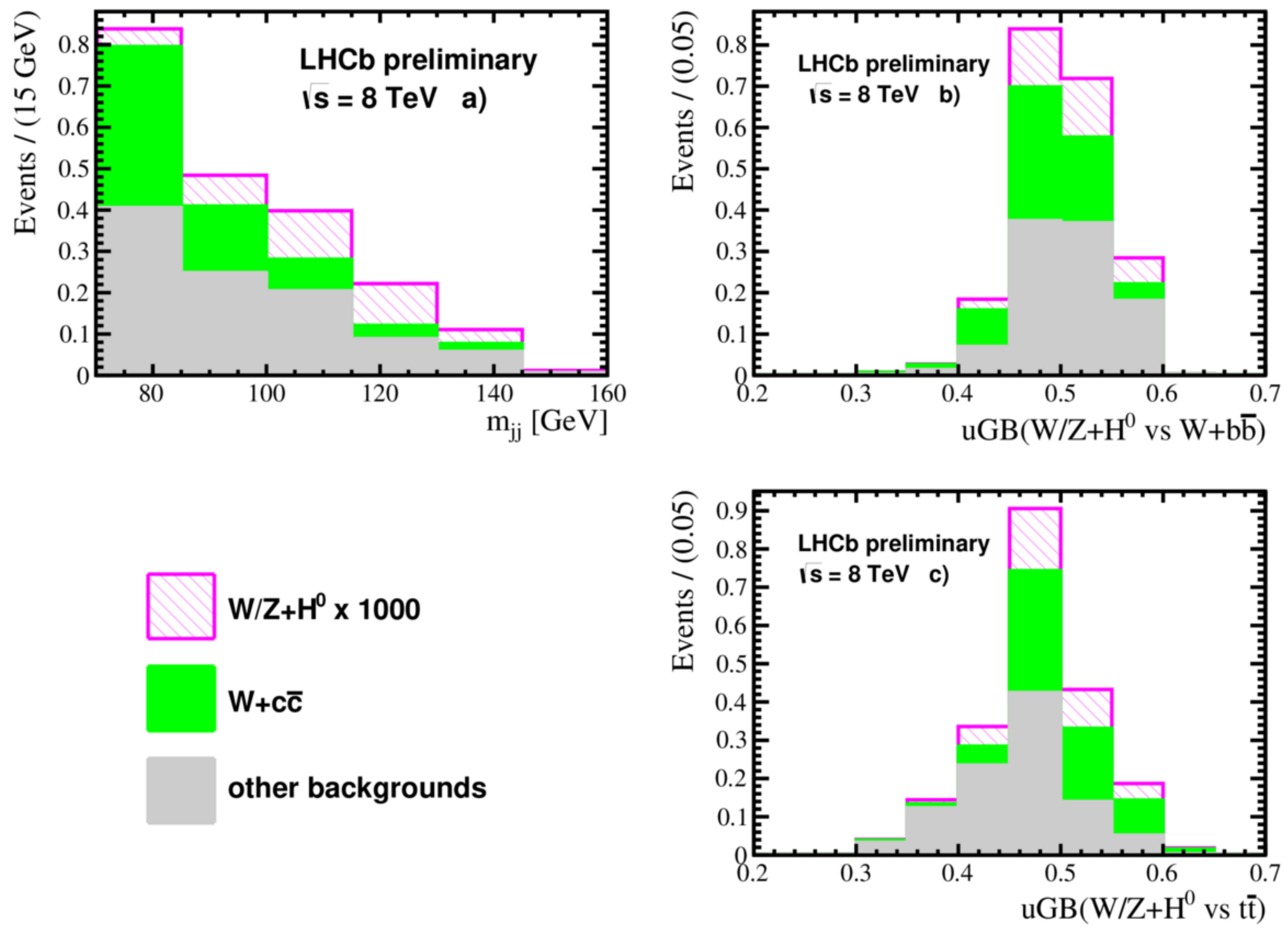
LHCb-CONF-2016-006

W/Z+H production

W/Z+H→$b\bar{b}$



W/Z+H→$c\bar{c}$



LHCb-CONF-2016-006

- **27.3 events expected → 20 observed.**
- **σ x BR(H→$b\bar{b}$) < 50 times the SM** expectation at 95% CL

- **2.6 events expected → 0 observed.**
- **σ x BR(H→$c\bar{c}$) < 6400** times the SM expectation at 95% CL

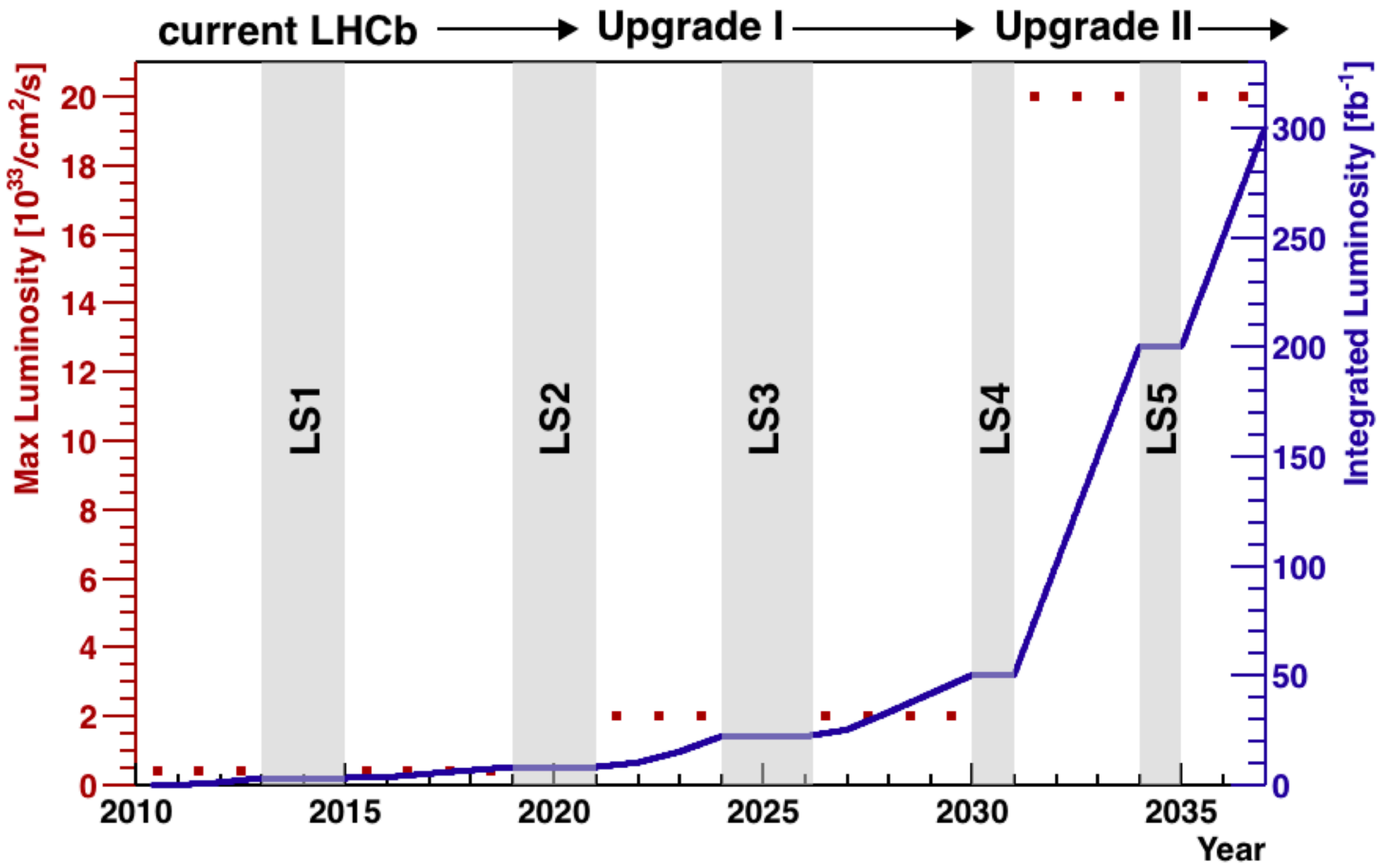
The upper limit on the charm Yukawa coupling is $y^c < 80\ y^c_{SM}$

Cannot appear so good, but it is the starting point for our extrapolation

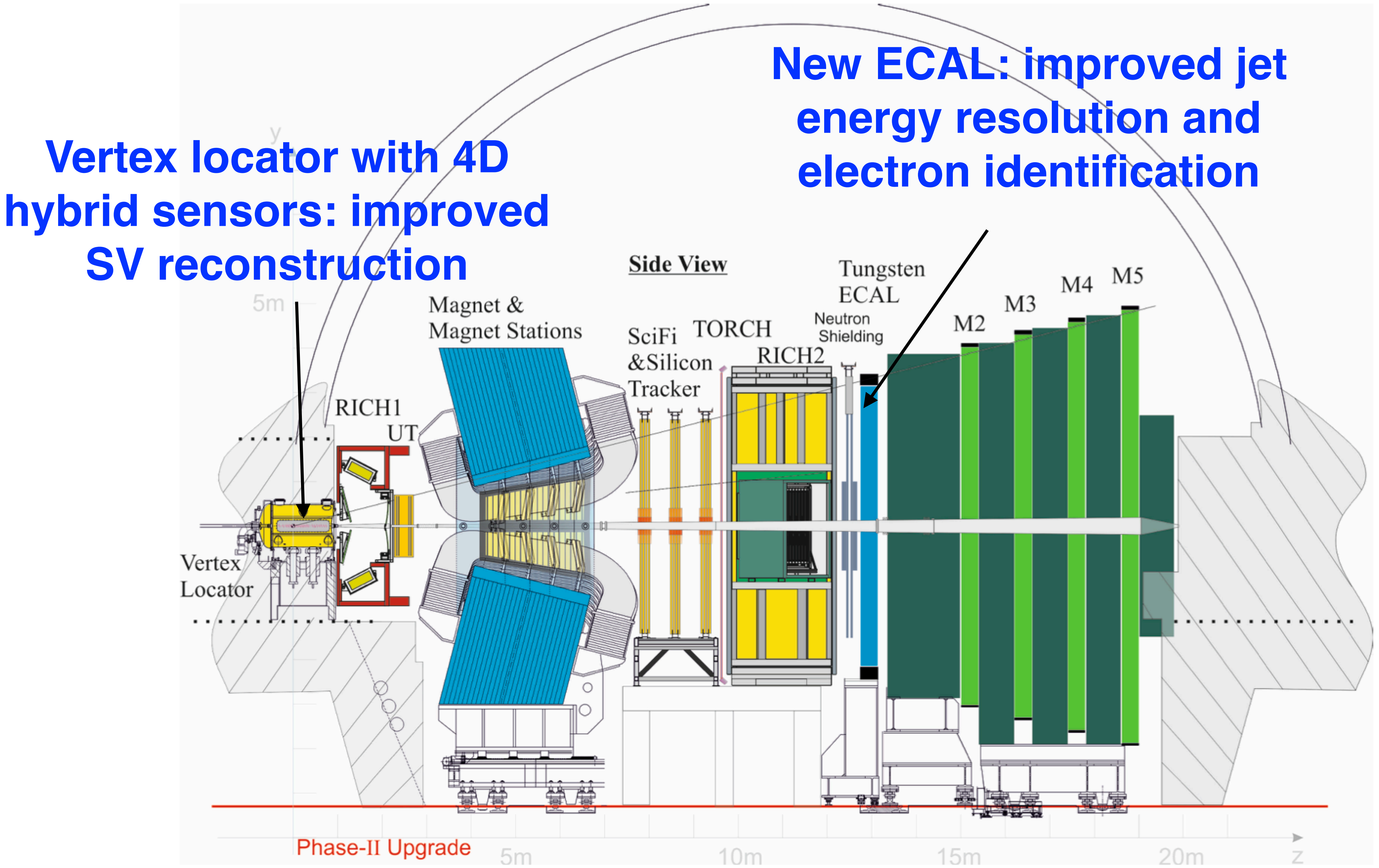
INFN Istituto Nazionale di Fisica Nucleare

LHCb at HL-LHC

- **The LHCb Collaboration has proposed an upgrade for the HL-LHC era**
- The goal is to collect **300 fb^{-1}** of integrated luminosity with an **improved detector**

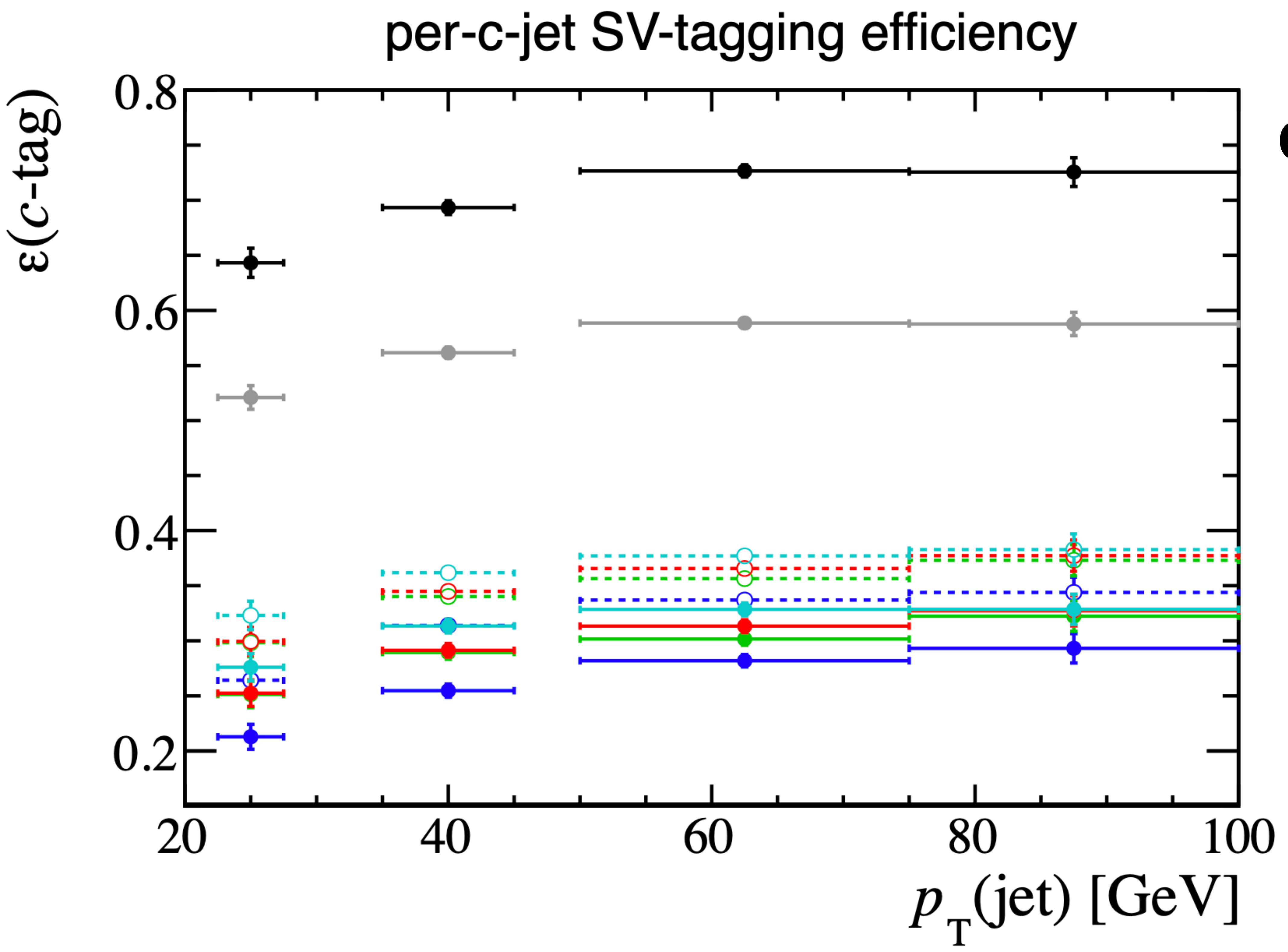


CERN-LHCC-2018-027



Prospects on $H \rightarrow c\bar{c}$ search at HL-LHC

- With the **new Vertex Locator** the impact parameter resolution is expected to improve.
- An optimized selection for SV from c-hadron decays can be applied.
- **In our estimation the c-jet SV-tagging efficiency improves roughly from 25% to 35%**.



CERN-2019-007

Perfect detector, i.e. has true SV in kinematic fiducial region.

Perfect IP resolution, but including RECO efficiency (assumed to be same as Run 1, which may not be true), etc.

Phase-II Scenario 2
Phase-II Scenario 1
Run 3
Run1
Solid: IP $X^2 > 16$ (as in Run 1)
Dashed: IP $X^2 > 9$

$H \rightarrow c\bar{c}$ search with 300 fb^{-1}

- The **starting point** is the upper limit on the cross section set with **8 TeV data (2 fb^{-1})**: **6400 x SM**.
- Step-by-step we have the following improvements:
  - **higher cross section and acceptance at 14 TeV and 300 fb^{-1} → 50 x SM**;
  - **improved SV-tagging efficiency → 13x SM**;
  - **improved electron reconstruction → 9 x SM**;
  - **improved background removal → 6 x SM**.

CERN-2019-007

- A **toy study with simulation** leaded to a similar result **→ 5-10 x SM**.
- This translates to an upper limit of **$y^c < 2\text{-}3\ y^c_{SM}$** on the Hcc coupling: **we may be the same game of the General Purpose Detectors**!

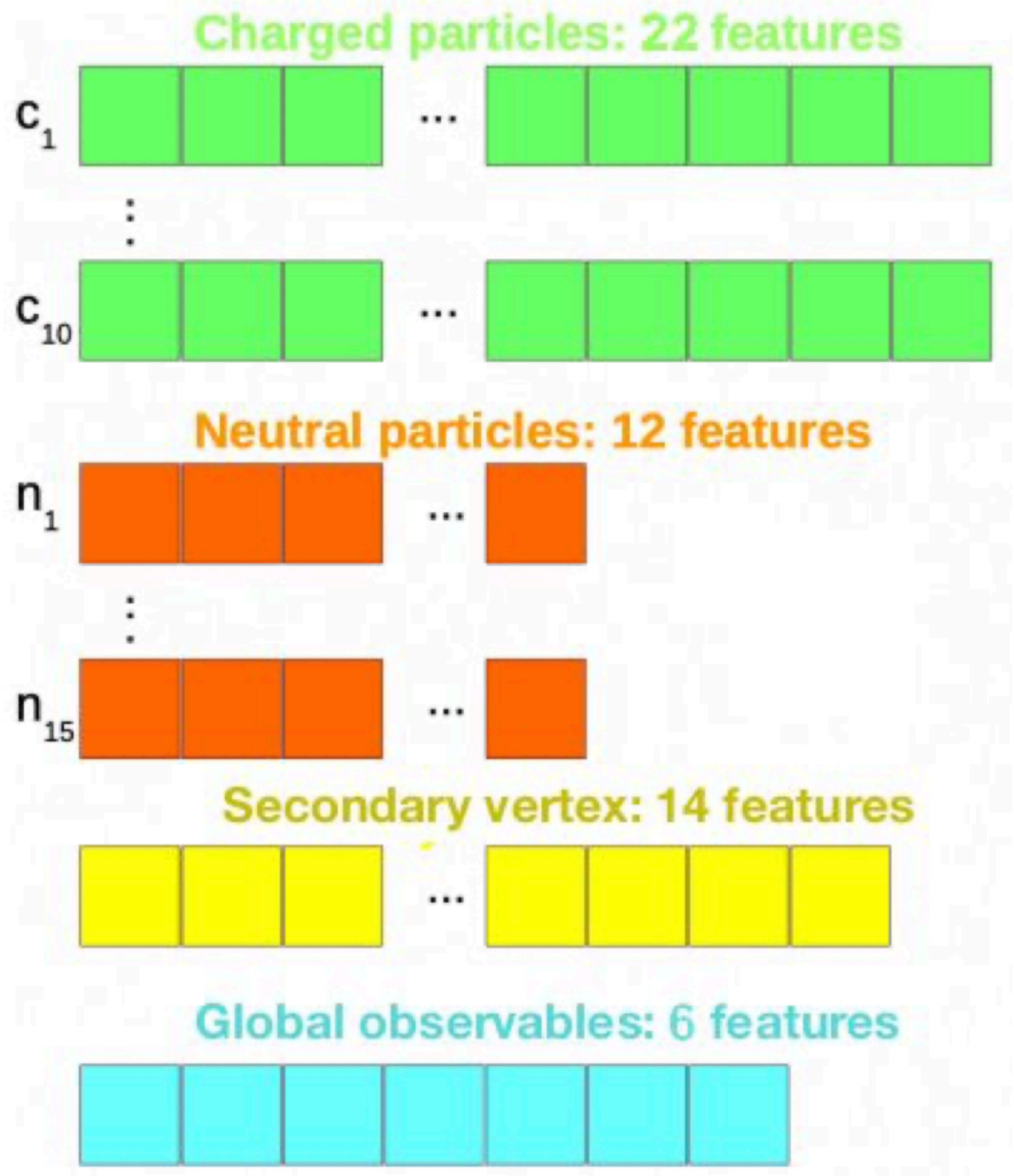
What about $H \to b\bar{b}$ with 300 fb^{-1}?

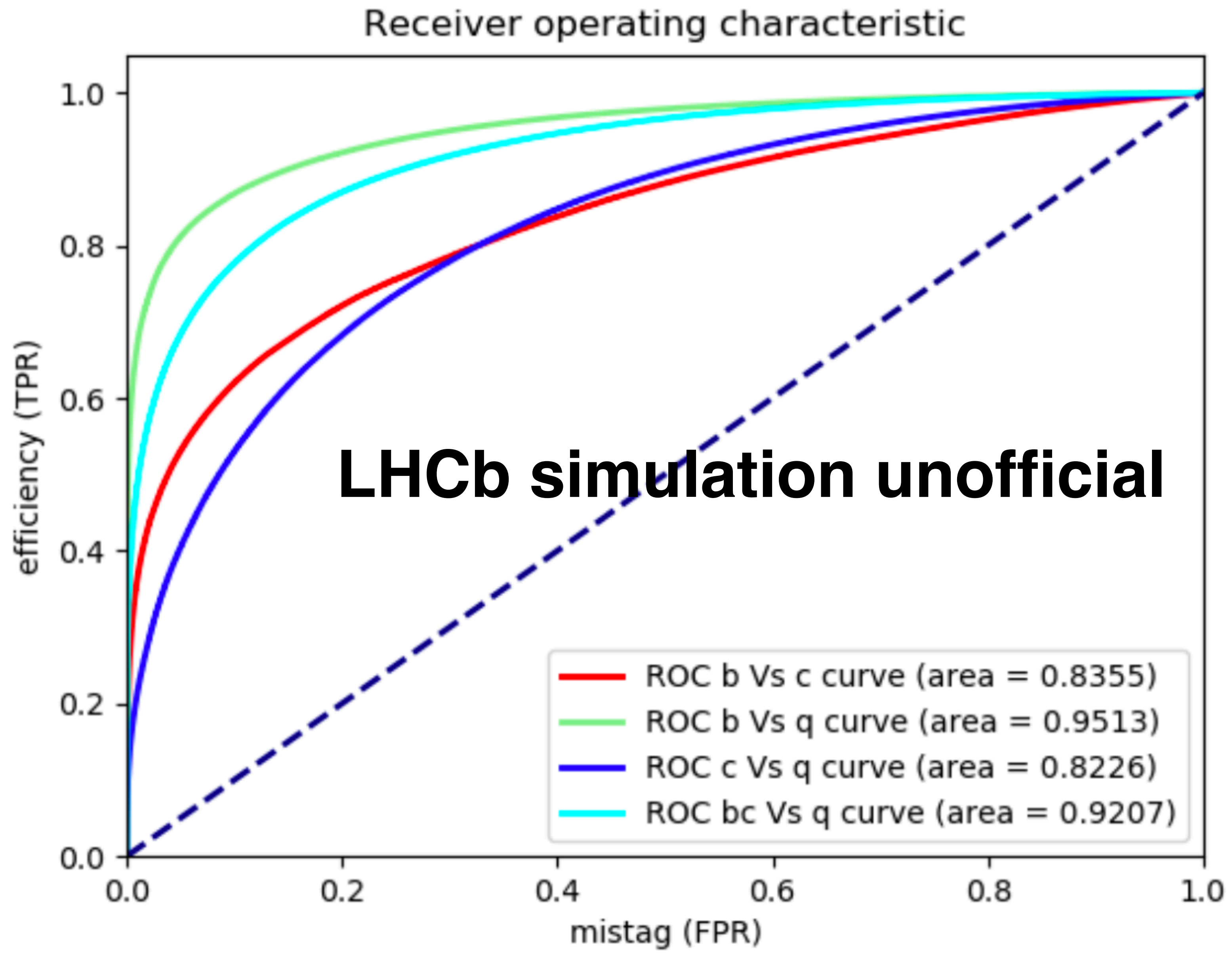
- Let's start again from the $H \to b\bar{b}$ limit set with **8 TeV data (2 fb^{-1})**: **50 x SM**
- With just the statistical improvement:
  - **higher cross section and acceptance at 14 TeV and 300 fb^{-1} → 1.5 x SM**

- It does not include detector and reconstruction developments, and considers just VH
- **We may seriously try to measure the properties of $H \to b\bar{b}$ in the forward region!**

Further improvements: jet substructure

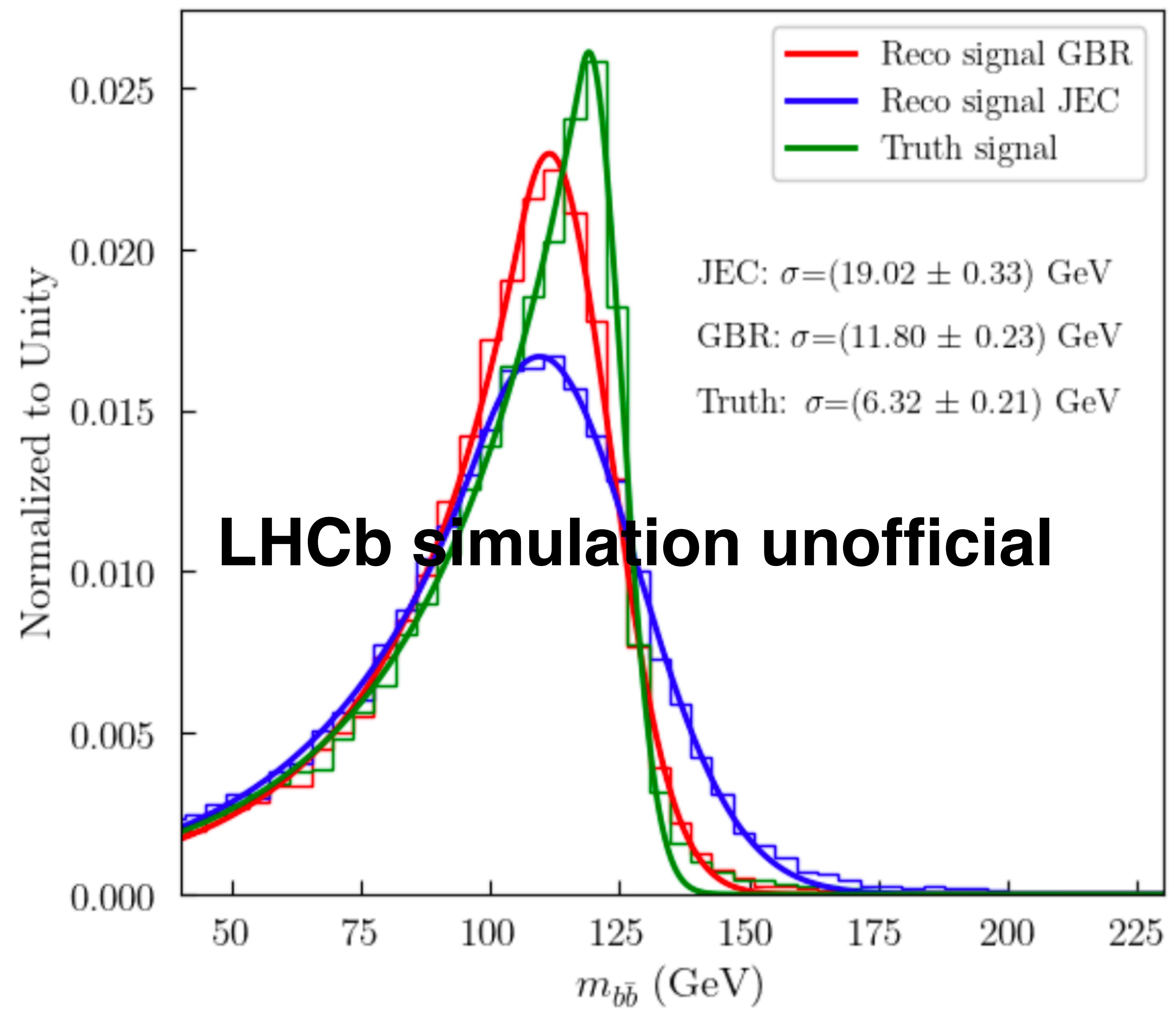
Input features to the DNN





Exploiting the jet substructure: Deep Neural Network for jet flavour identification

Regression technique for improving the Higgs mass reconstruction



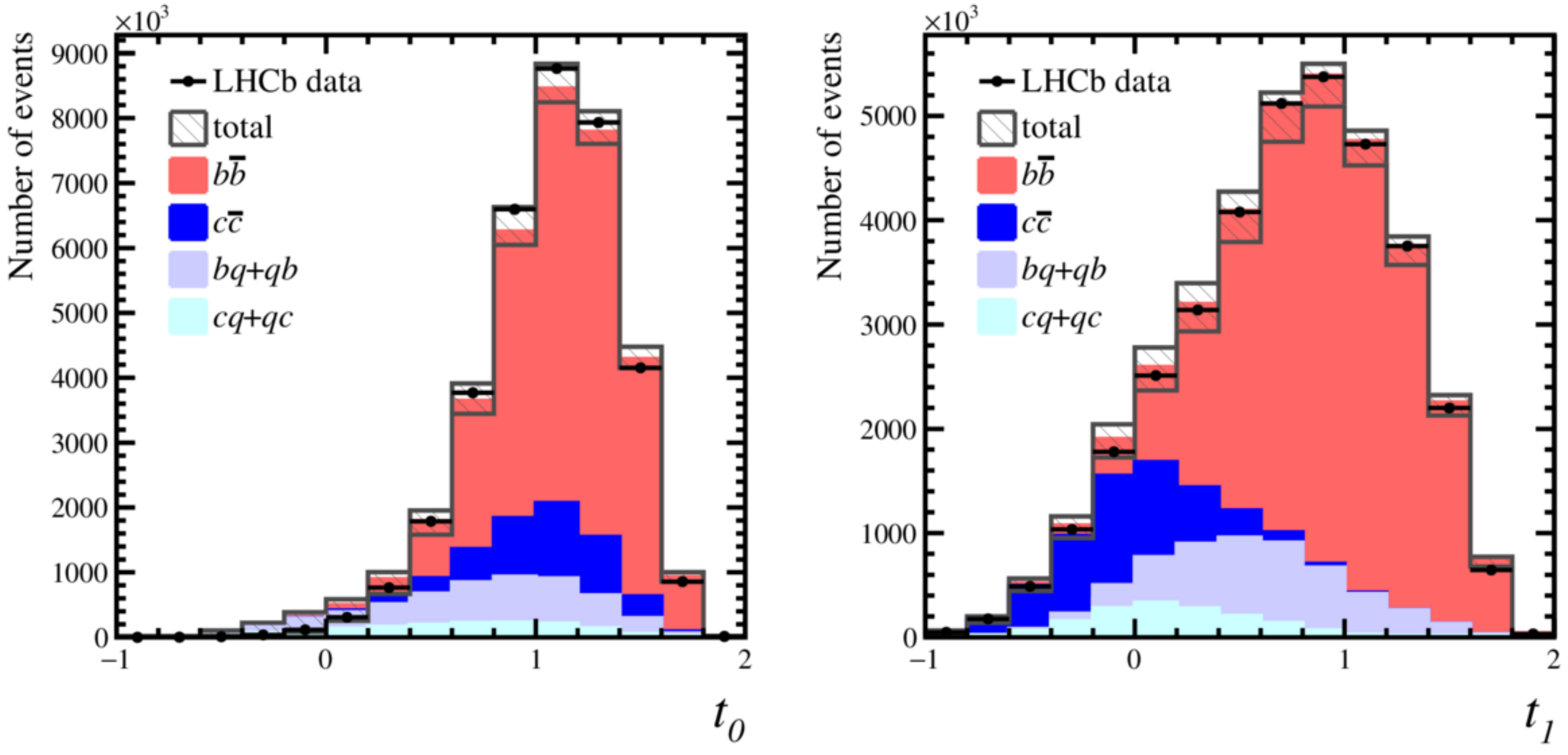
We are checking biases and systematics

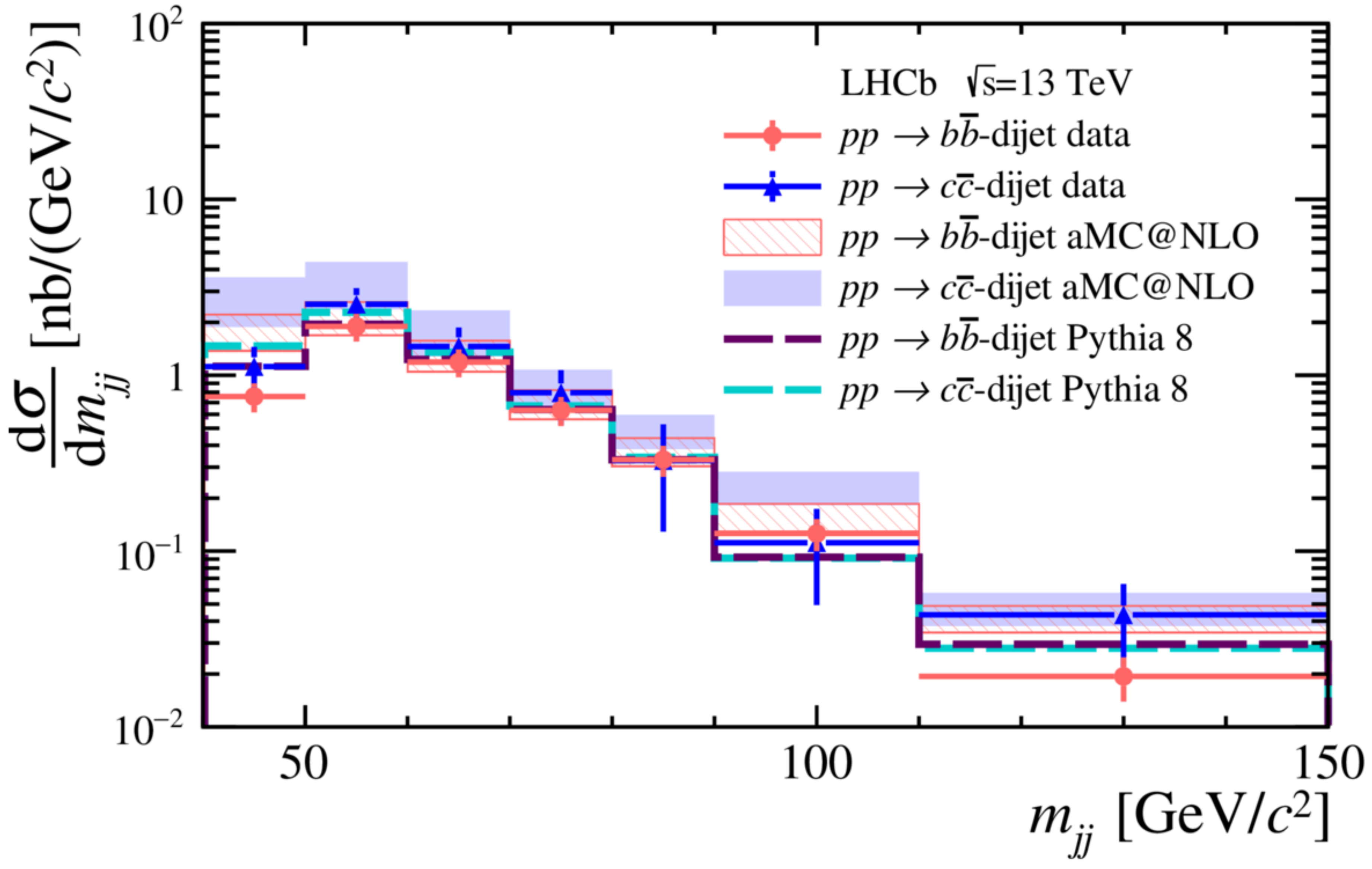
Inclusive H→$b\bar{b}$/H→ $c\bar{c}$ search

- The **inclusive dataset with two SV-tagged jets (1.6 fb^{-1} at 13 TeV)** has been analyzed to measure the **differential $b\bar{b}$ and $c\bar{c}$ cross section**.
- The technique for disentangle the **$b\bar{b}$** and **$c\bar{c}$** processes has been demonstrated, and the the measured cross sections are compatible with the expectations.
- This is an important step for the **search for inclusive H→$b\bar{b}$ and H→$c\bar{c}$ (so mainly produced by gg fusion)**: **the analysis is on-going**!

$$t_0 = \mathrm{BDT}_{bc|q}(j_0) + \mathrm{BDT}_{bc|q}(j_1),$$
$$t_1 = \mathrm{BDT}_{b|c}(j_0) + \mathrm{BDT}_{b|c}(j_1).$$

JHEP 02 (2021) 023





Conclusions

- **Higgs physics at LHCb is possible!**
- LHCb can search for **BSM Higgs** in a phase space complementary to other experiments
- Exotic Higgs decays, light mass Higgses and indirect searches are on the table
- **With the LHCb Upgrade 2, LHCb could measure the SM Higgs in the forward region of pp collisions**
- **Excellent prospects on $H \to c\bar{c}$**
- **Many other improvements are expected!**

Thanks for your attention!