Probing the Higgs Sector at LHCb: Techniques, Measurements, and Future Prospects

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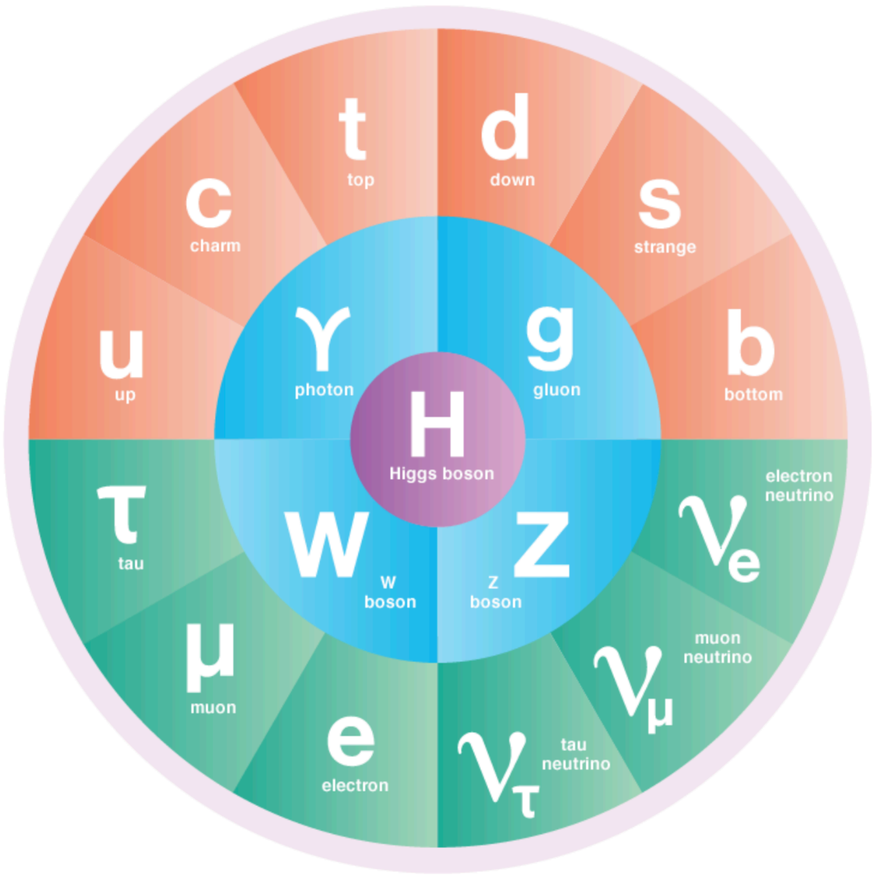
Wuhan - 30 September 2025

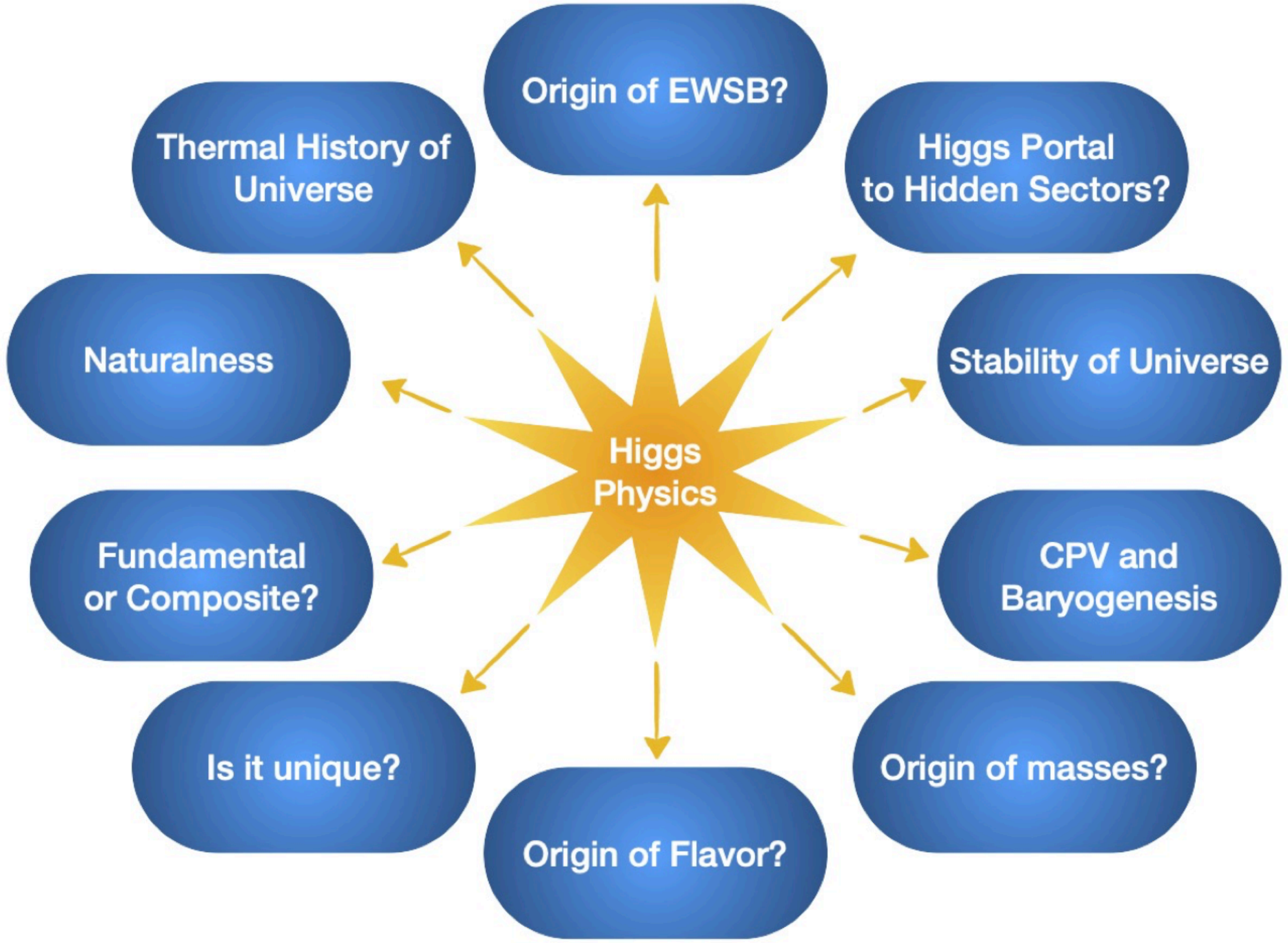
Higgs Boson

- Today we have a successful theory, the **Standard Model**, **that explains most of the experimental observations**
- **The Higgs boson, discovered in 2012 by ATLAS and CMS, is the last piece of this puzzle. Is it really completed or are we missing something?**

symmetrymagazine.org



- The **Higgs field gives mass to the particles**, therefore **Higgs Physics is connected to most of open questions in fundamental Physics**

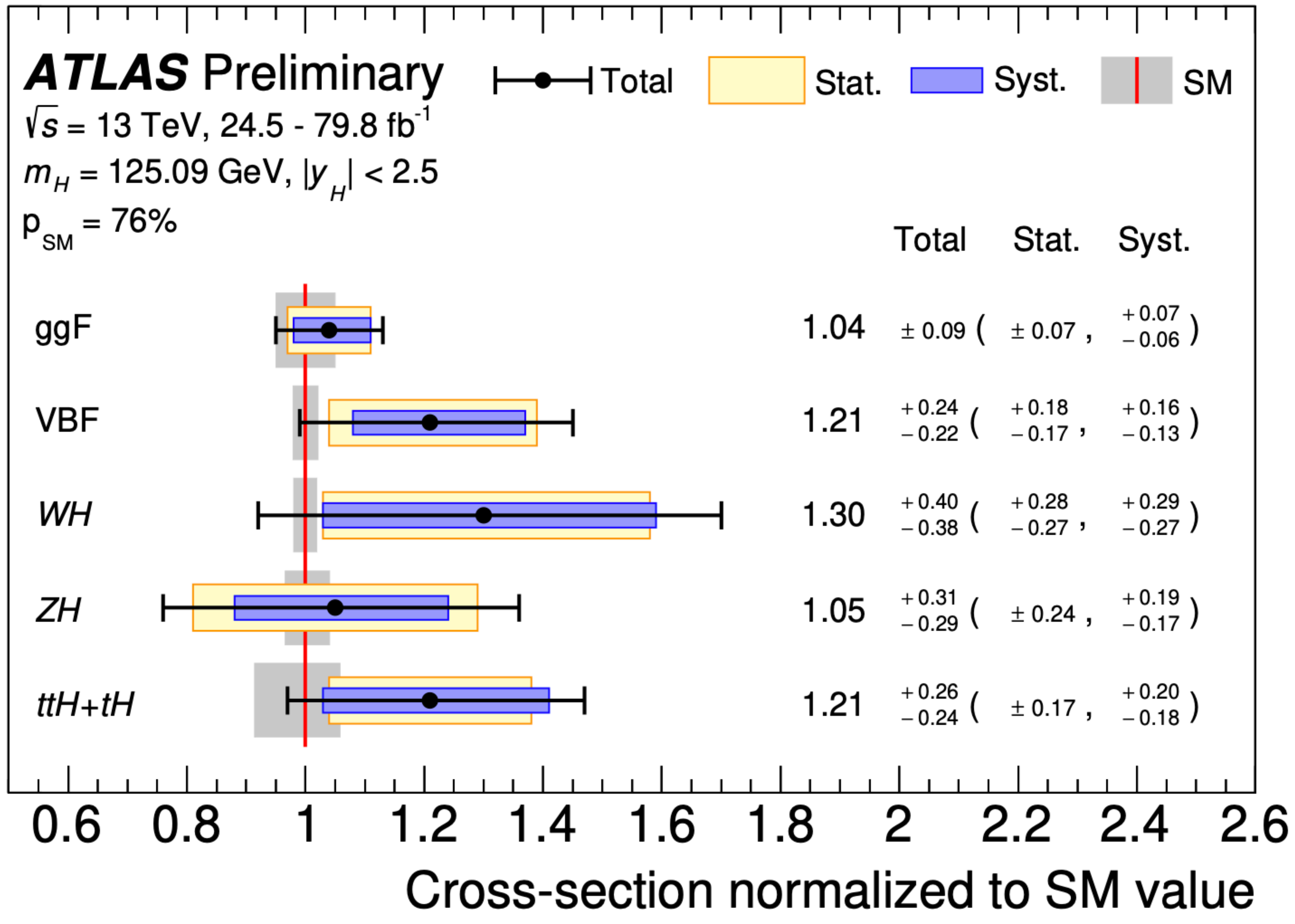


Snowmass forum report on Muon Colliders: https://doi.org/10.48550/arXiv.2209.01318

Higgs Physics: where we are now?

- Since the discovery a campaign for the **measurement of its properties** is on-going at the LHC experiments
- We would like to know if there are deviations from the Standard Model
- Until now, **the measured couplings follow the Standard Model expectation**

ATLAS-CONF-2019-005



Couplings in the Standard Model

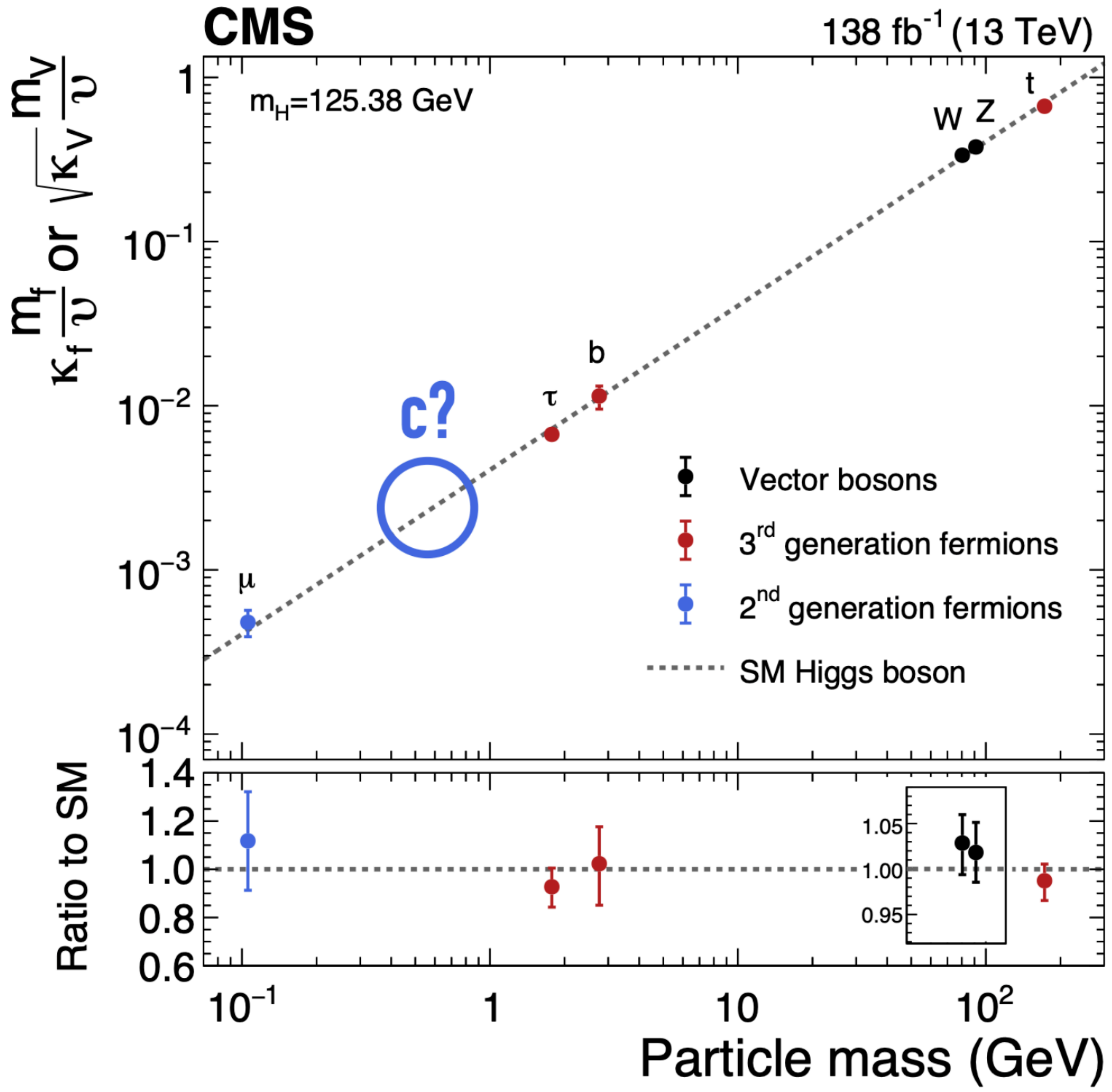
Fermions

$$g_{Hf\bar{f}} = \frac{m_f}{v}$$

Vector bosons

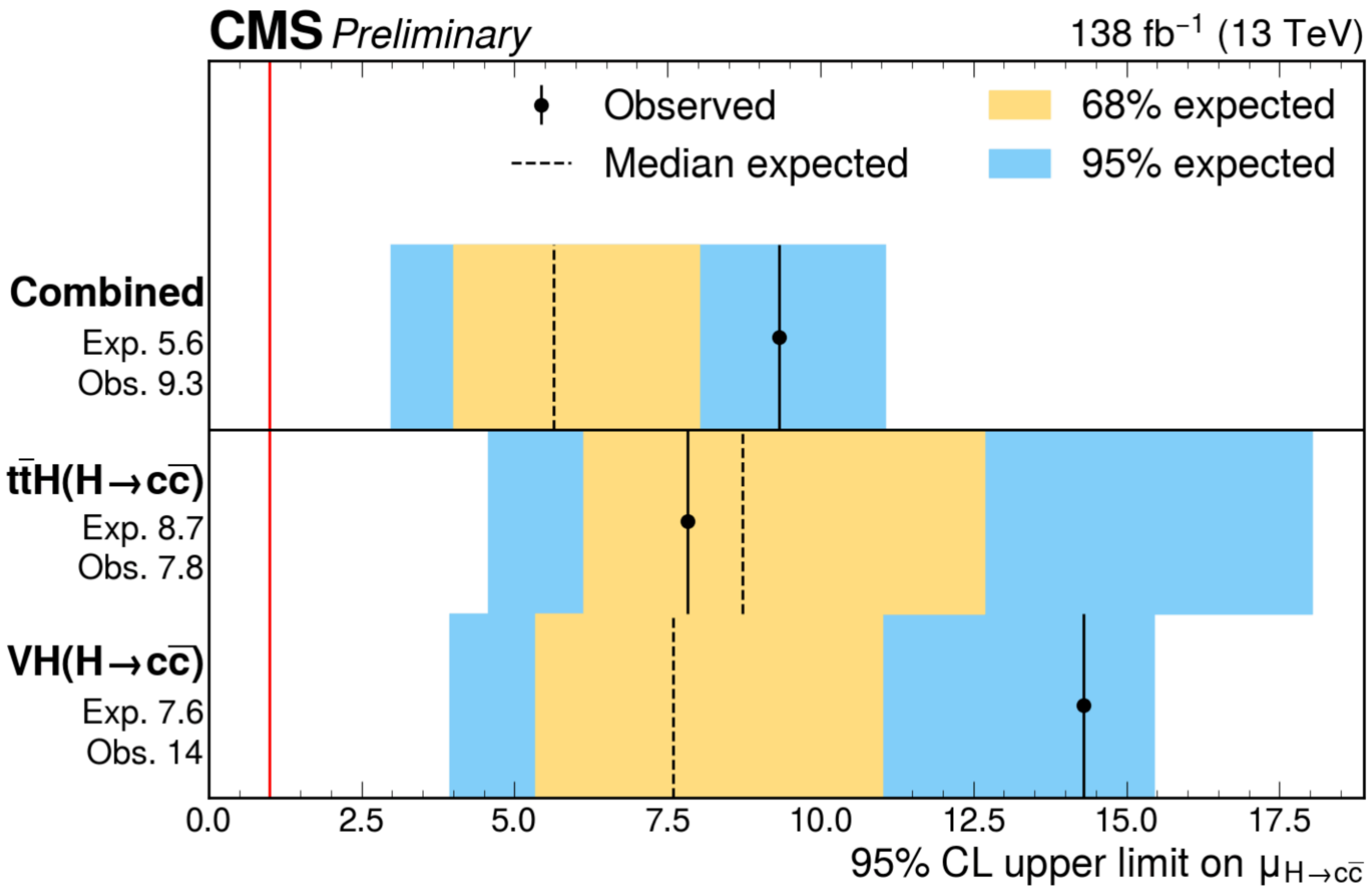
$$g_{HVV} = \frac{2m_V^2}{v}$$

Nature volume 607, pages 60–68 (2022)



Higgs Physics: where we are now?

- **Upper limits on Higgs to charm coupling**



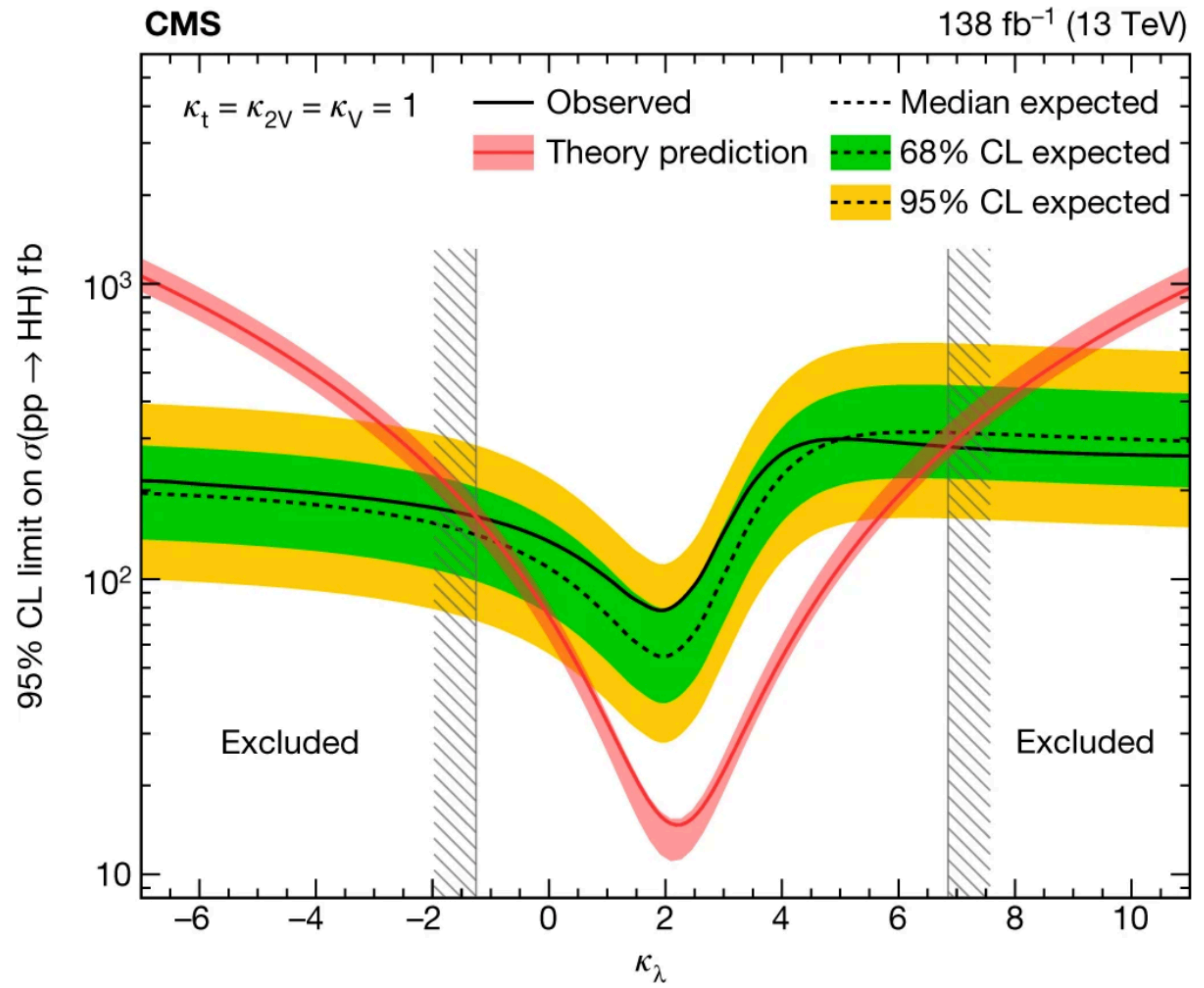
- **When accessible, it will be the first measurement of the Higgs coupling with a second generation quark**

- The Higgs boson has been discovered, but **the Higgs field, responsible of the Electroweak Symmetry Breaking and the generation of particle masses, is not measured yet!**

- It can be determined by measuring **the production of HH and HHH events**

$$V(H) = \frac{1}{2}m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4}\lambda_4 H^4,$$

Nature volume 607, pages 60–68 (2022)

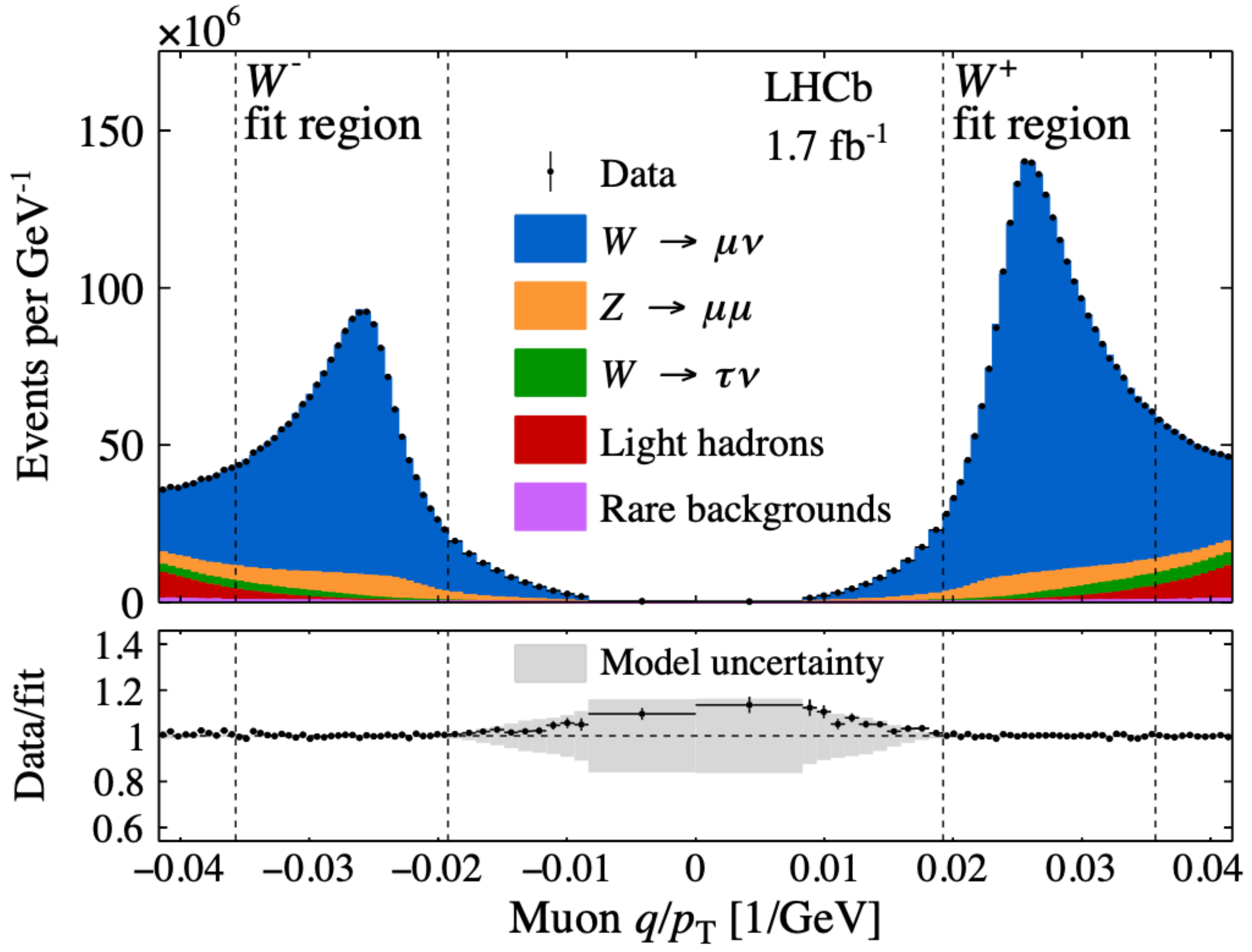


Limits on the trilinear coupling obtained by the CMS experiment

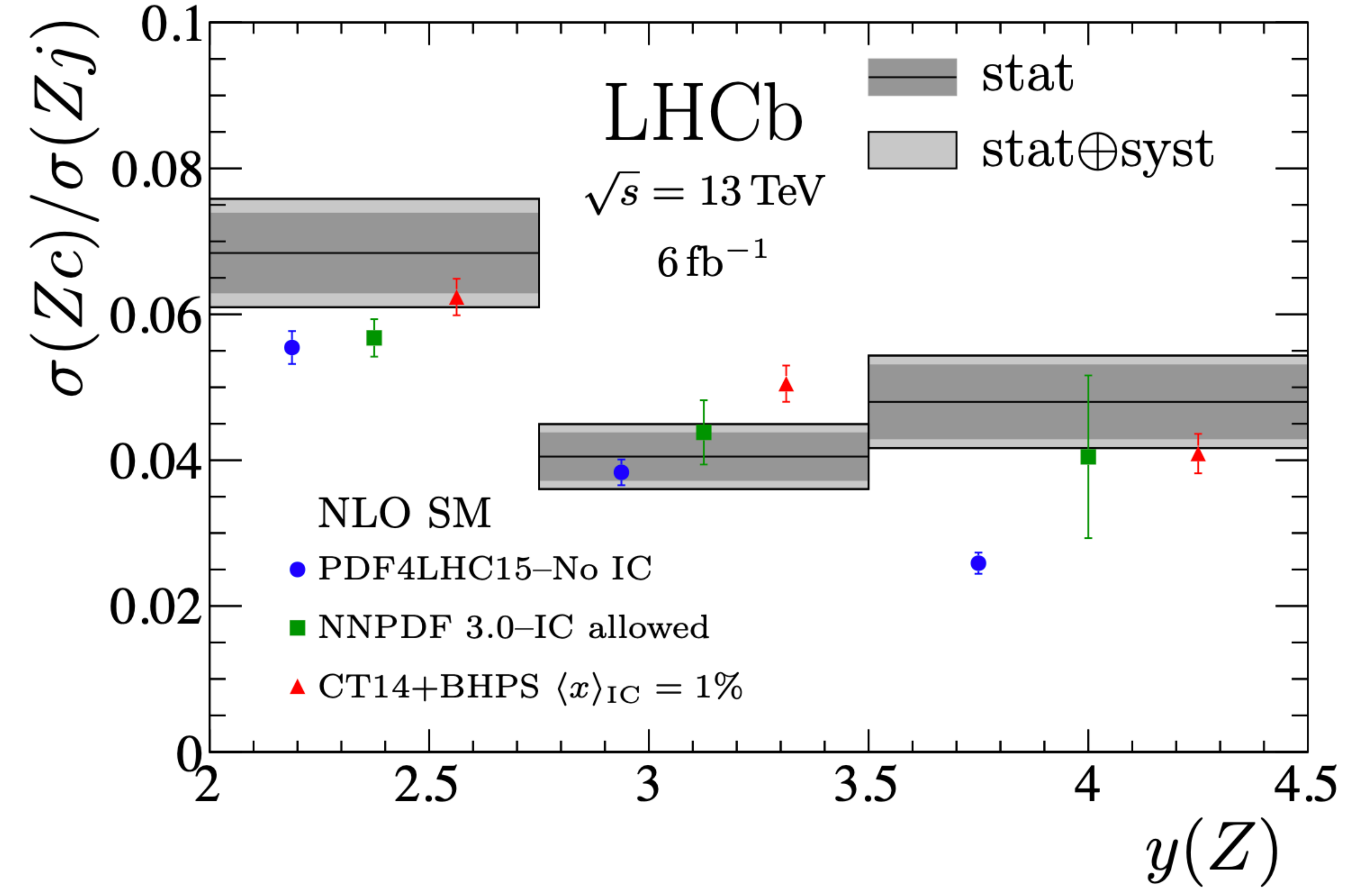
LHCb: not only flavour physics

- **What is the role that LHCb can have in Higgs 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**

W mass measurement JHEP 01 (2022) 036



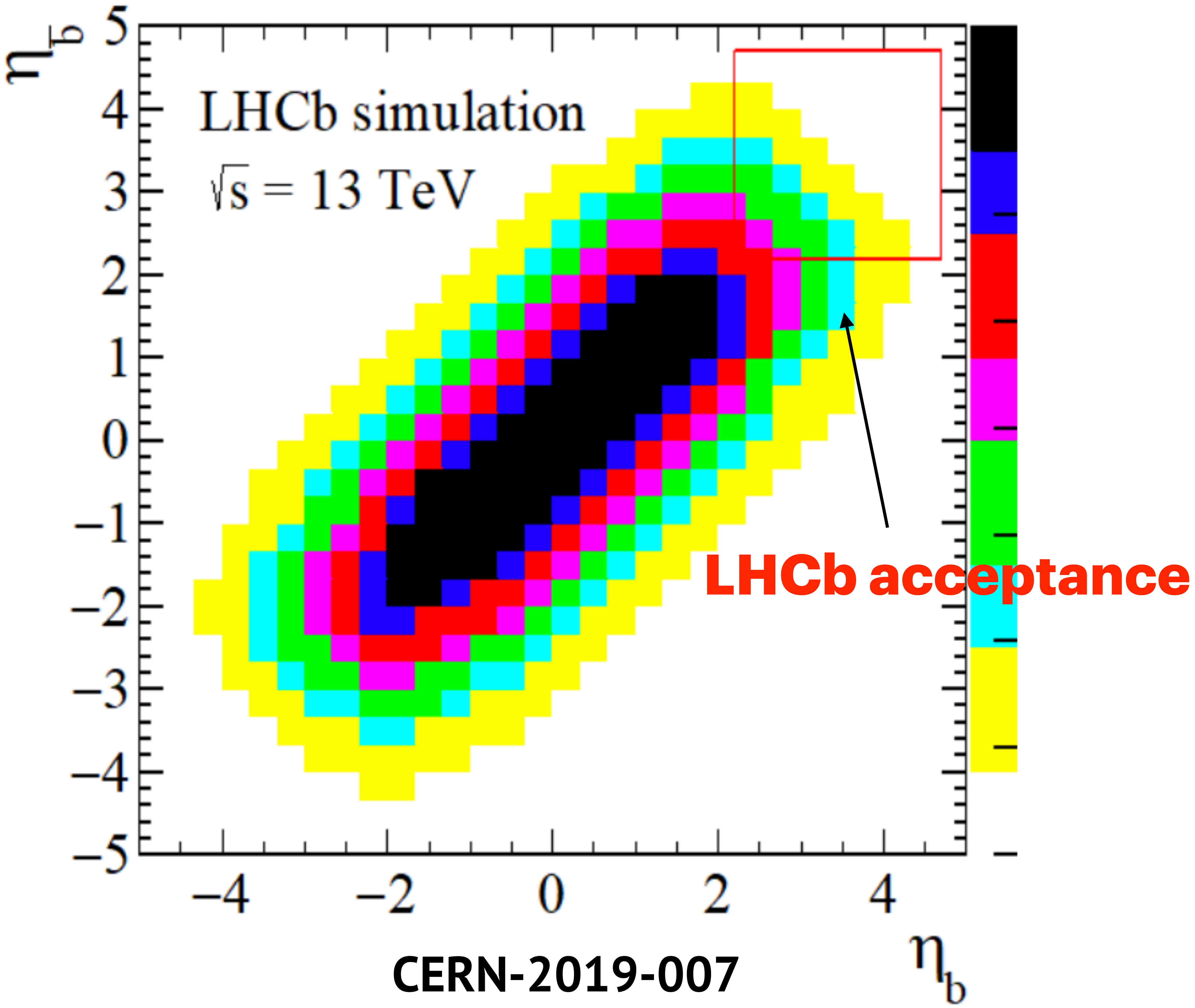
Z+c-jet measurement (intrinsic charm) Phys. Rev. Lett. 128 (2022) 082001



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

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



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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?

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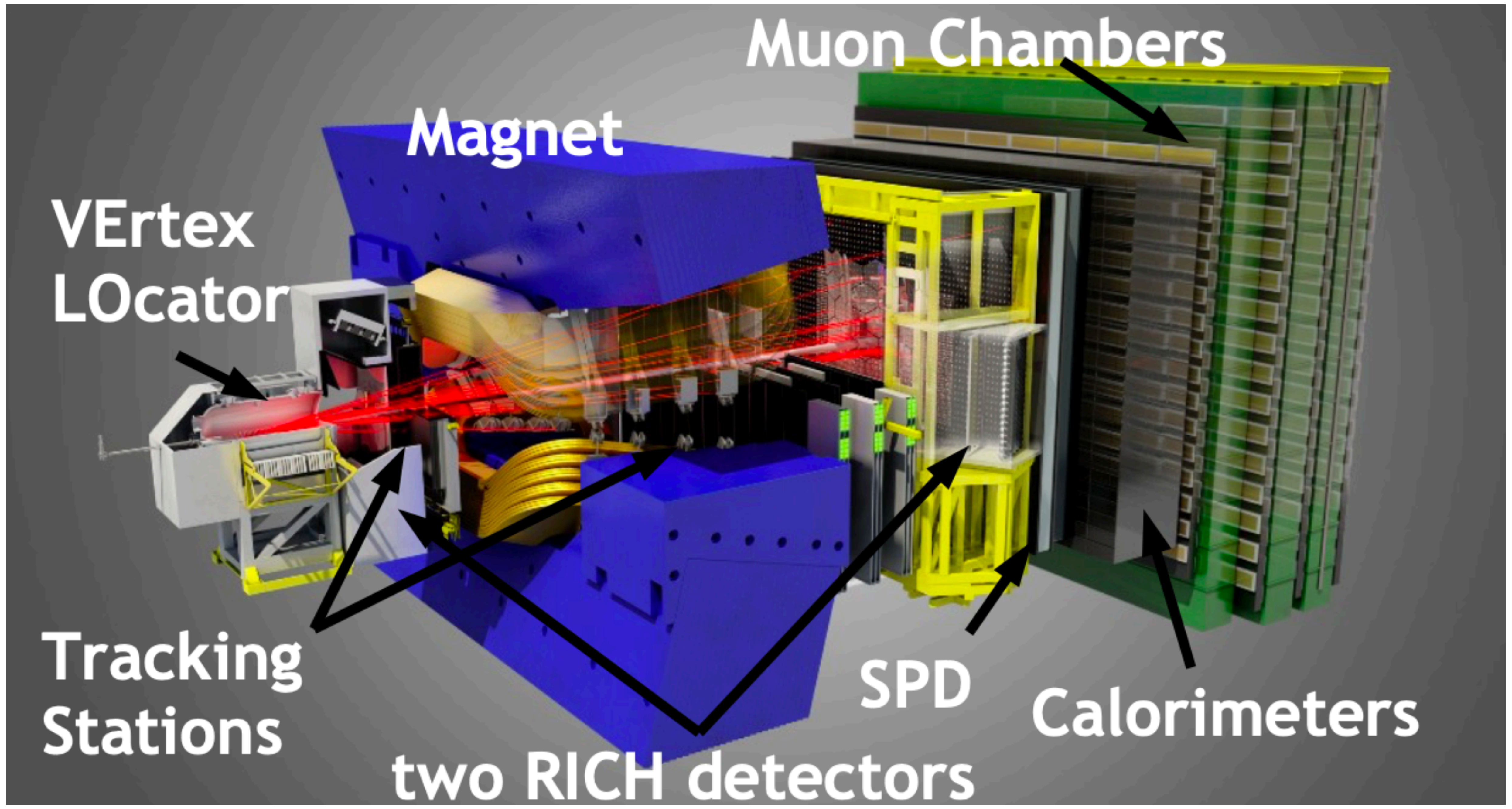
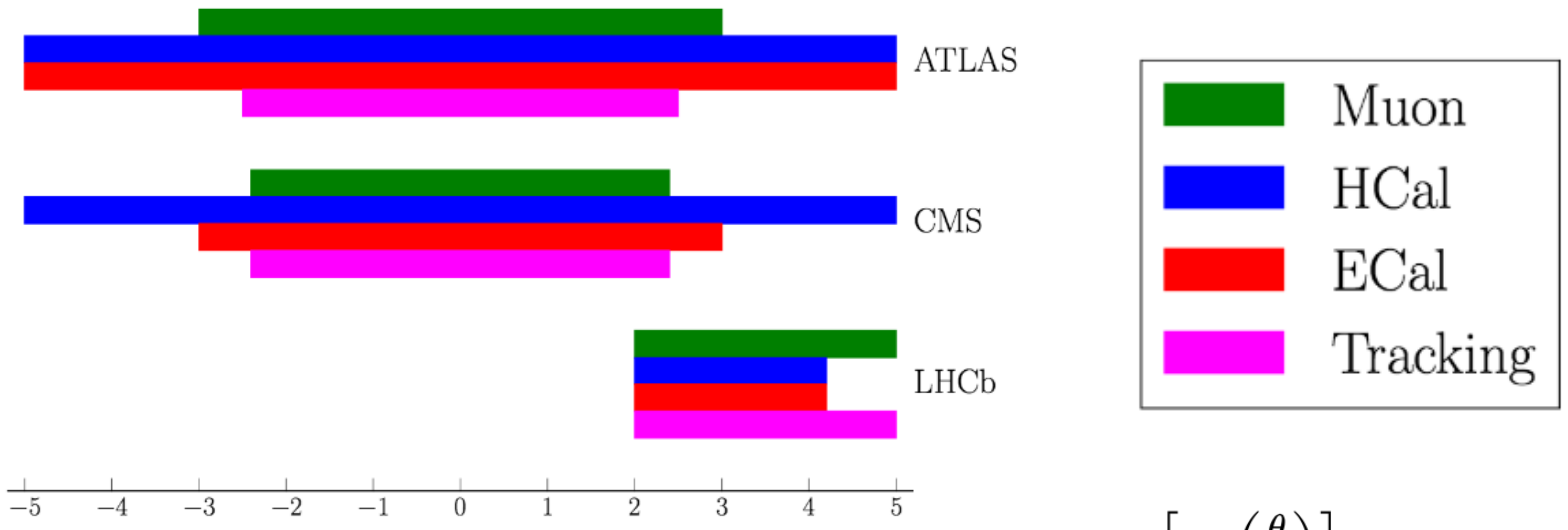
LHCb detector

JINST 3 (2008) S08005

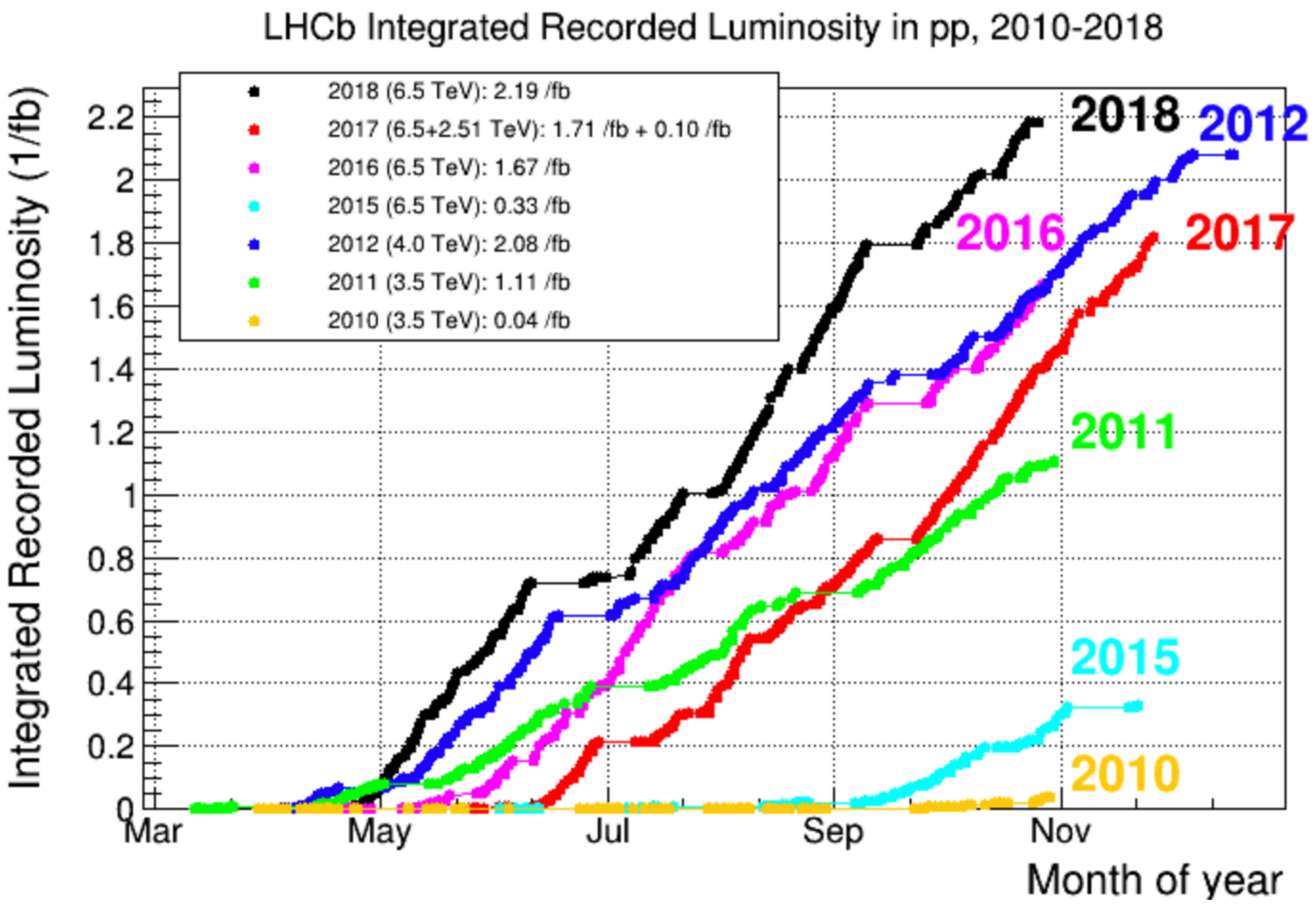


- LHCb is a spectrometer in the forward region
- Track momentum resolution: 0.4% at 5 GeV and 0.6% at 100 GeV
- **Excellent vertex reconstruction system**: impact parameter resolution of (15 + 29/p_T) µm, p_T in GeV
- Muon ID efficiency: 97% with 1-3% $\mu \rightarrow \pi$ mis-identification
- Electron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



2< η< 5

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

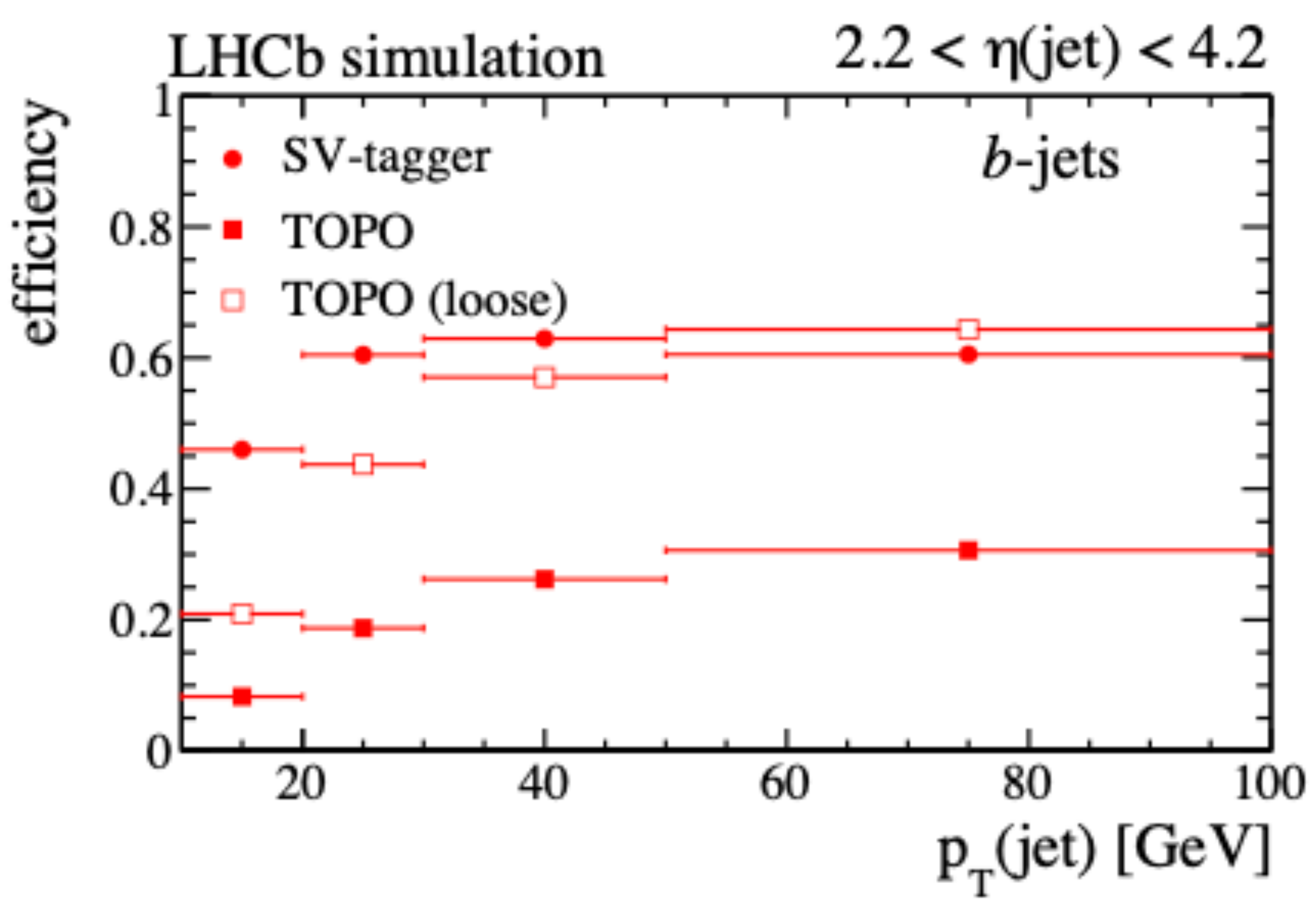


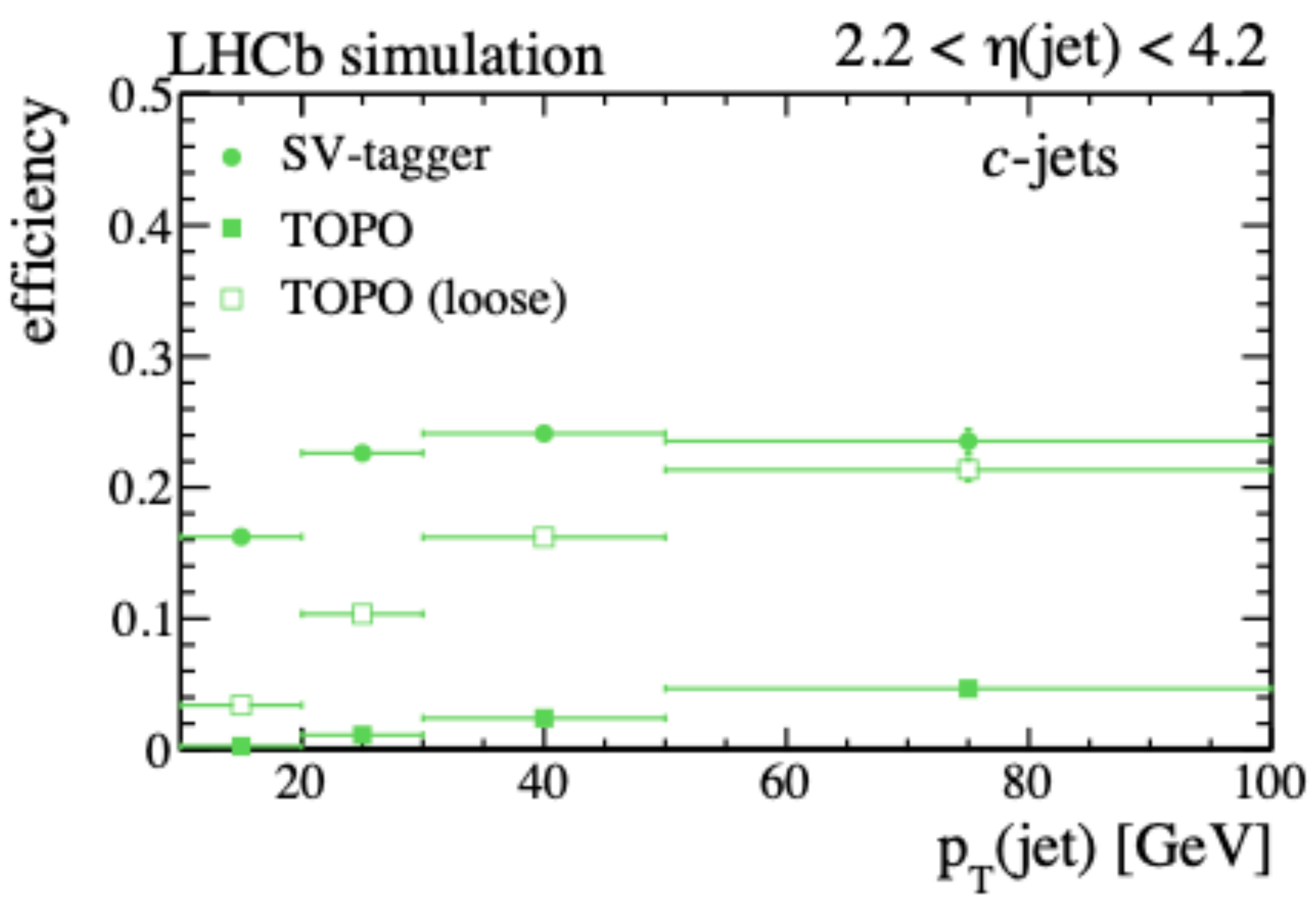
Run 1-2 data fully available for Higgs studies

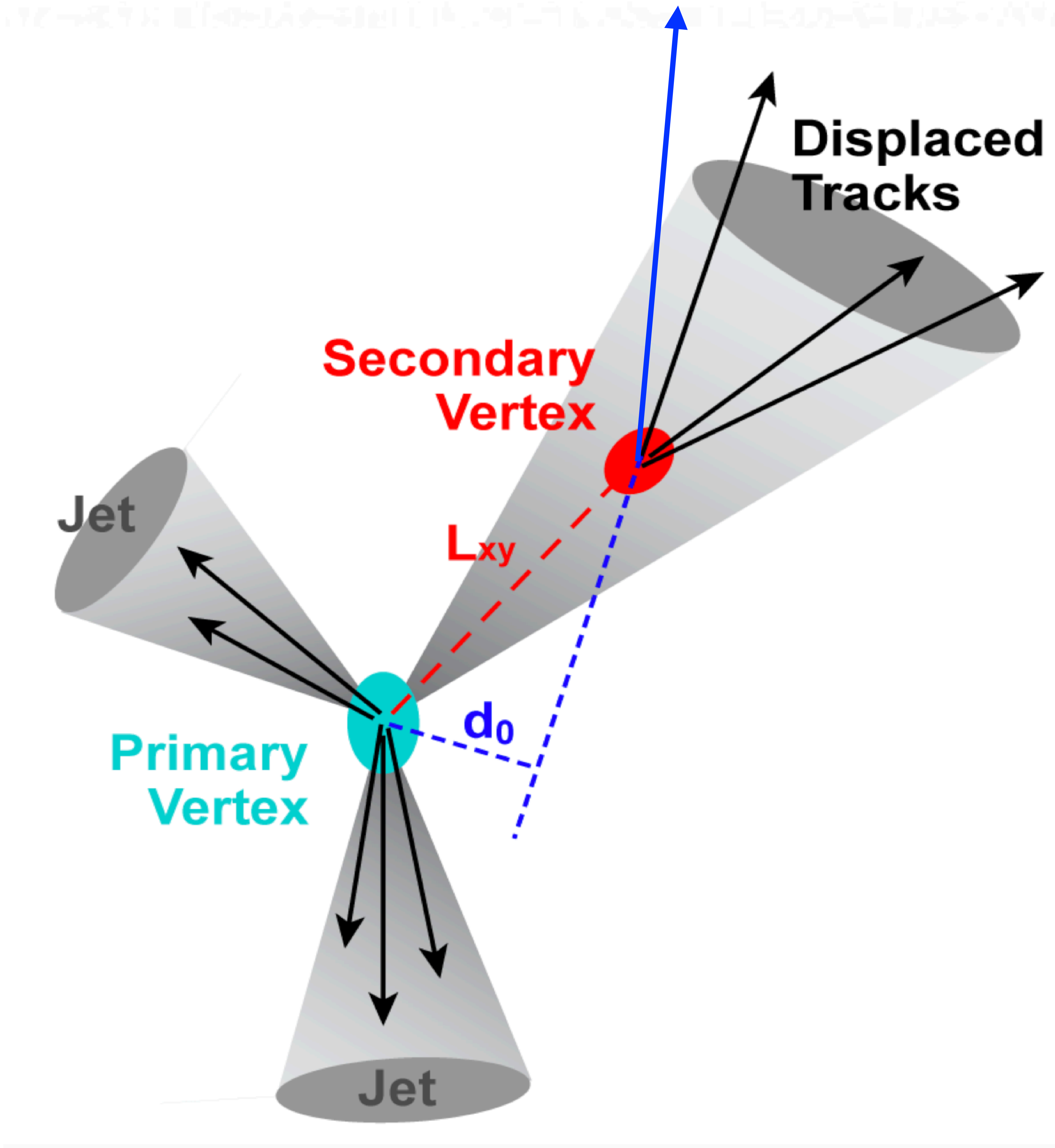
Run 3 data on their way

Jet identification at LHCb

- **Jet: stream of particles generated by the fragmentation and hadronization of a Parton**
- In Higgs physics we are usually interested in heavy flavor jets
- The jet tagging system takes advantage of LHCb features → **precise vertex reconstruction**
- In Run 1/2 **the efficiency for tagging a b-(c-) jets with a SV is of about 60% (25%), with a light jet misidentification below 0.1%**







JINST 10 (2015) P06013

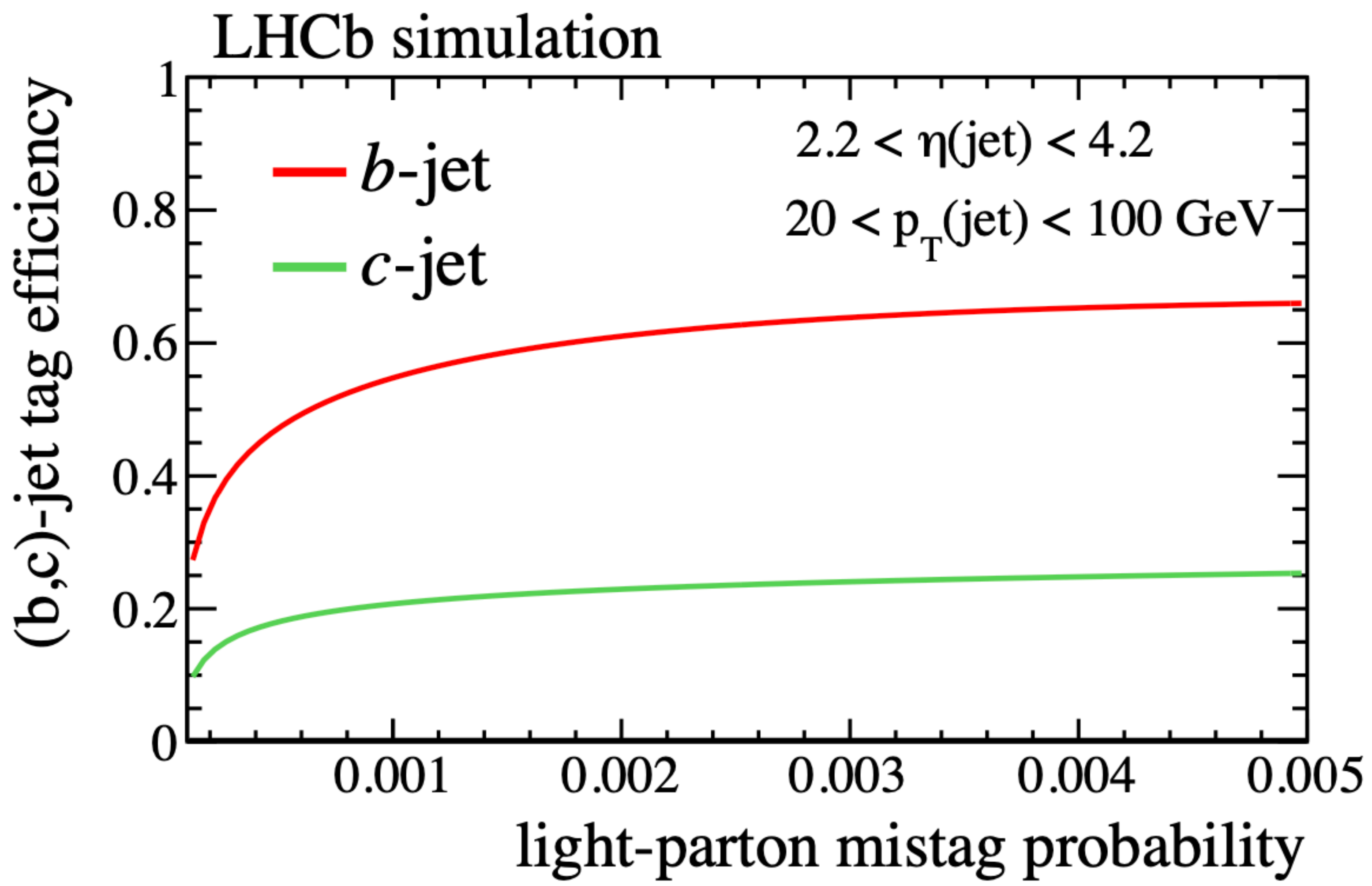
Jet identification at LHCb

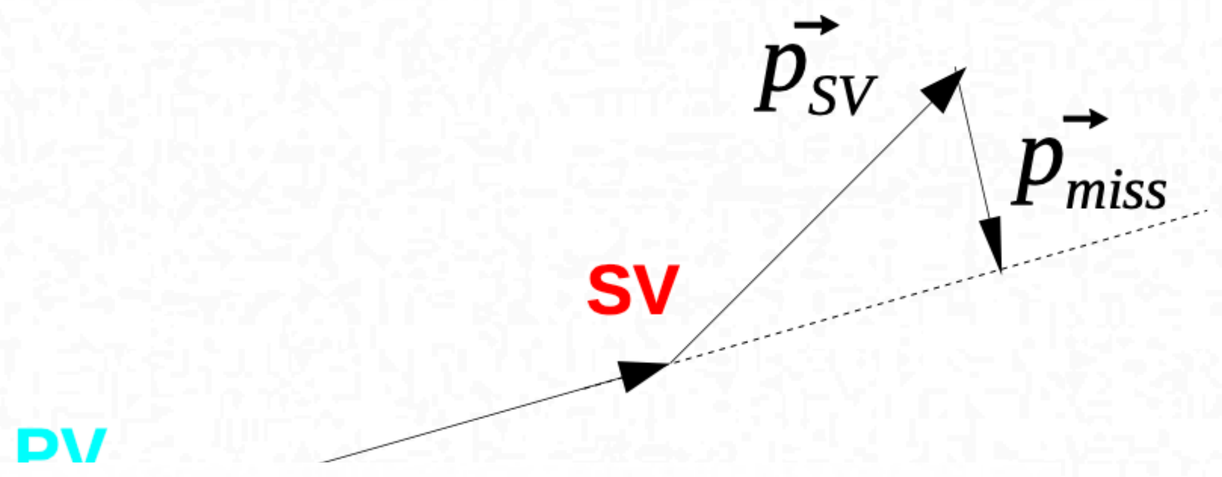
- Two **Boosted Decision Trees** (BDT) are used to identify b and c jets.

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

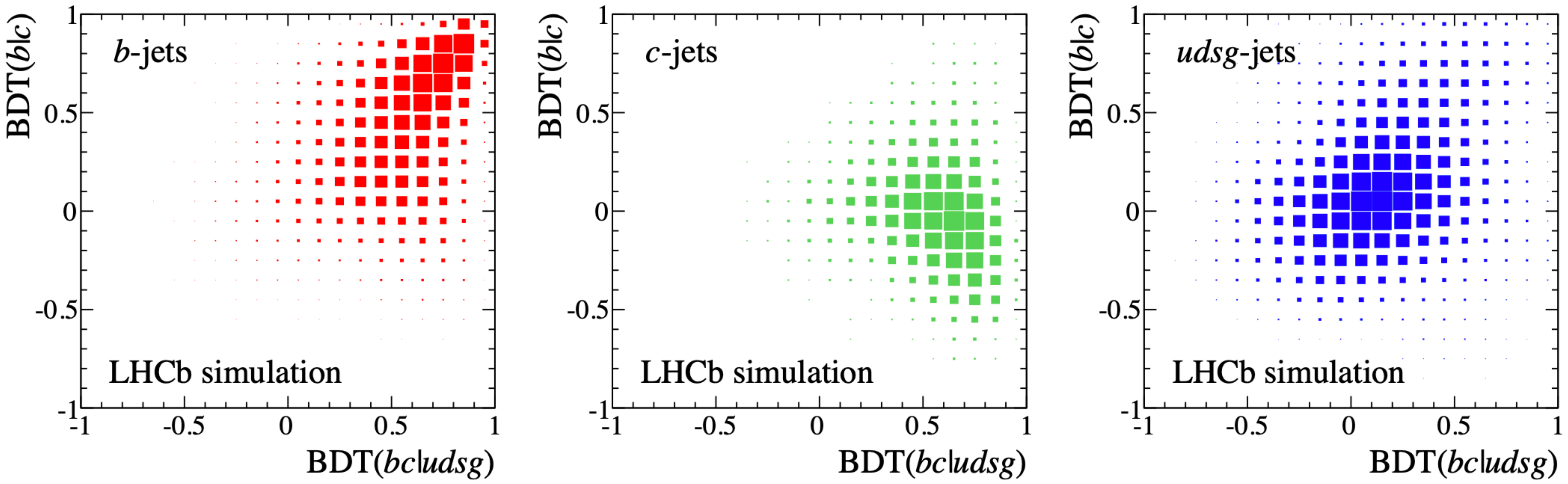
BDT(b|c)
To separate **b-jets** from **c-jets**

- **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**





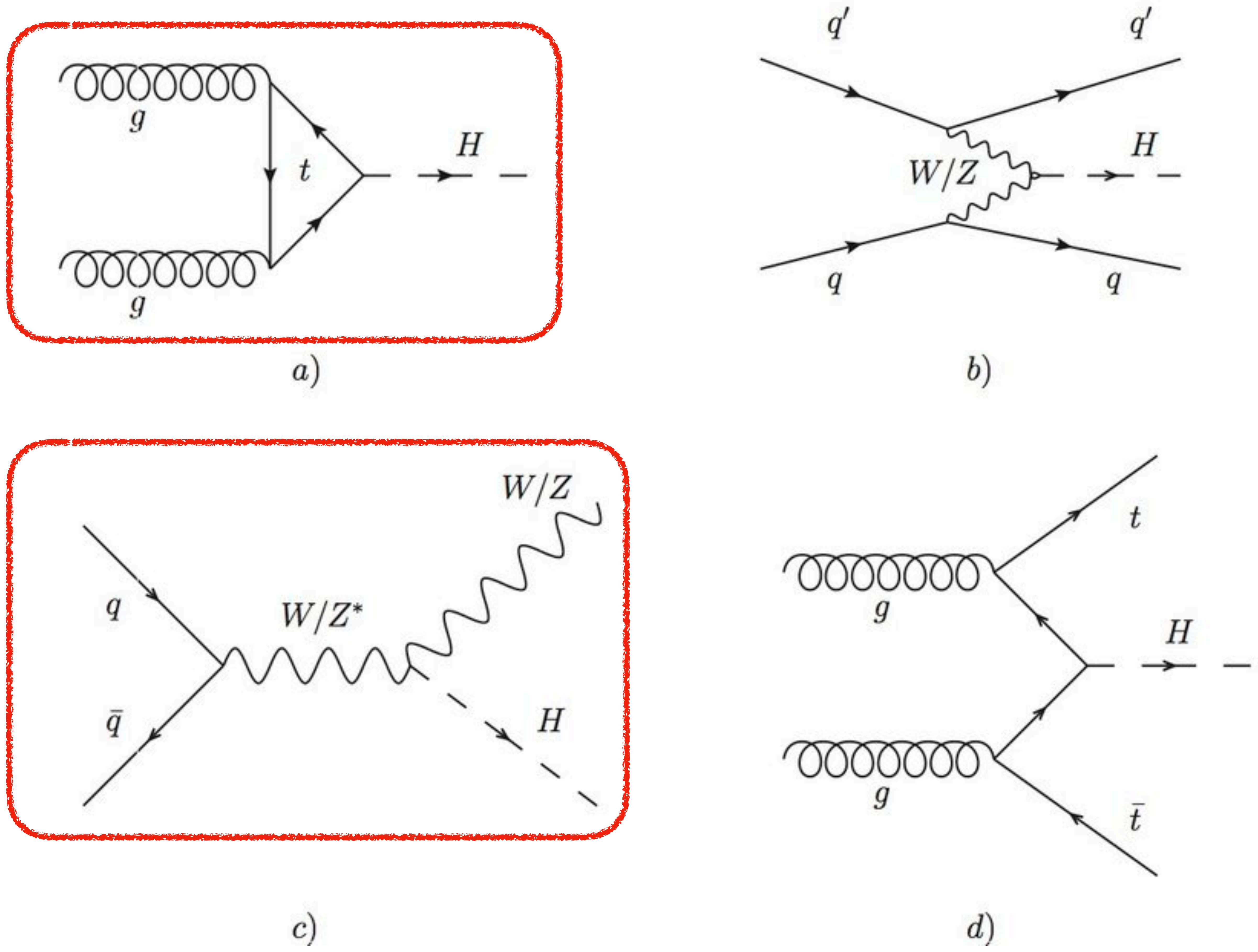
$$M_{corr} = \sqrt{M_{SV}^2 + p_{miss}^2} + p_{miss}$$



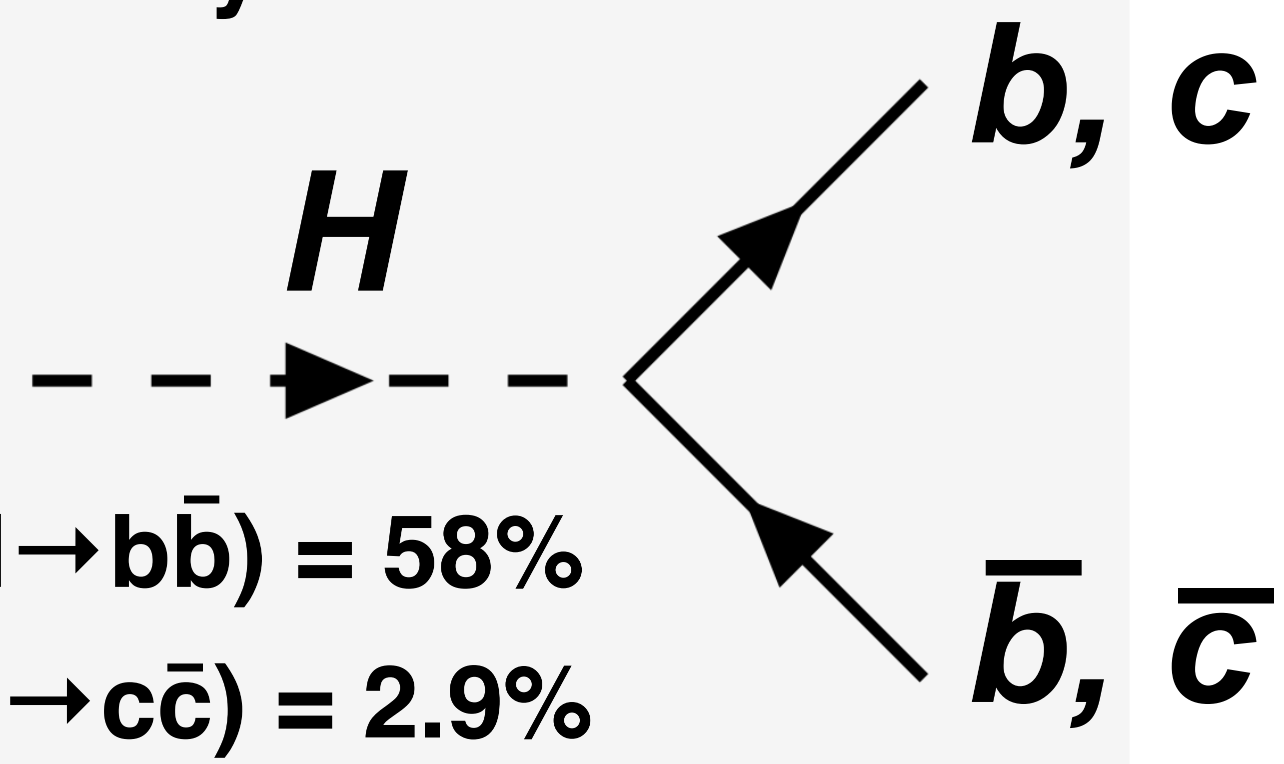
Standard Model Higgs

SM Higgs at LHCb

Production modes

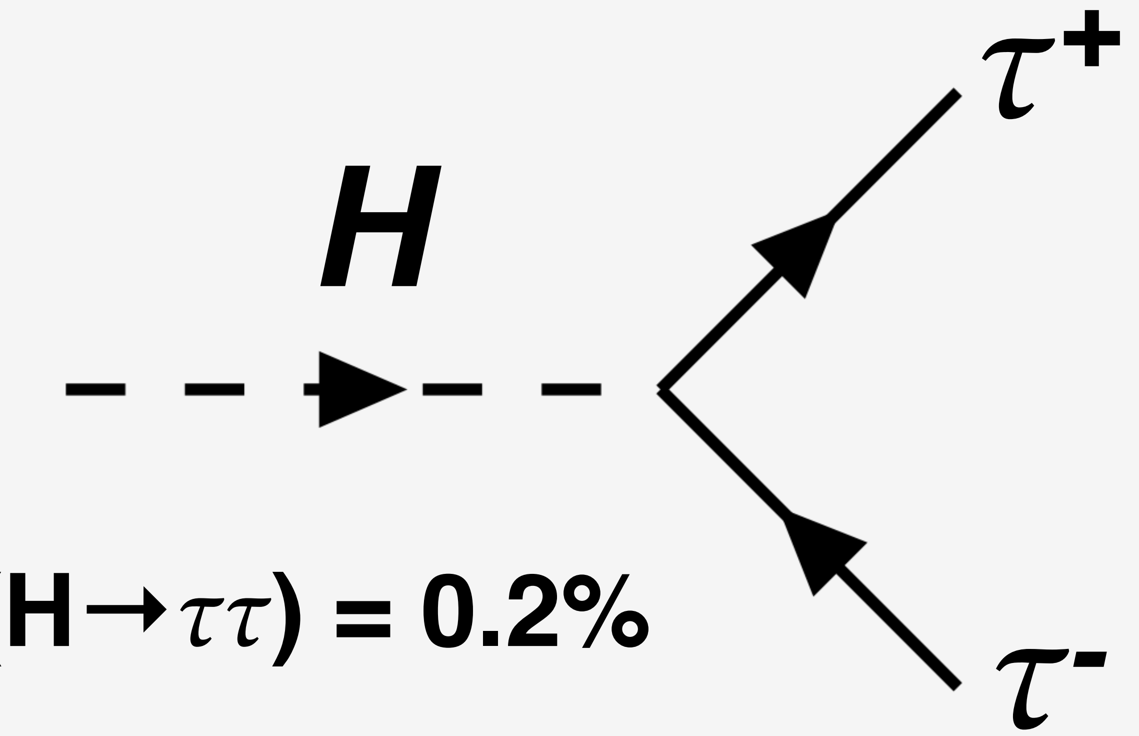


Decay modes



BR($H \to b\bar{b}$) = 58%

BR($H \to c\bar{c}$) = 2.9%



BR($H \to \tau\tau$) = 0.2%

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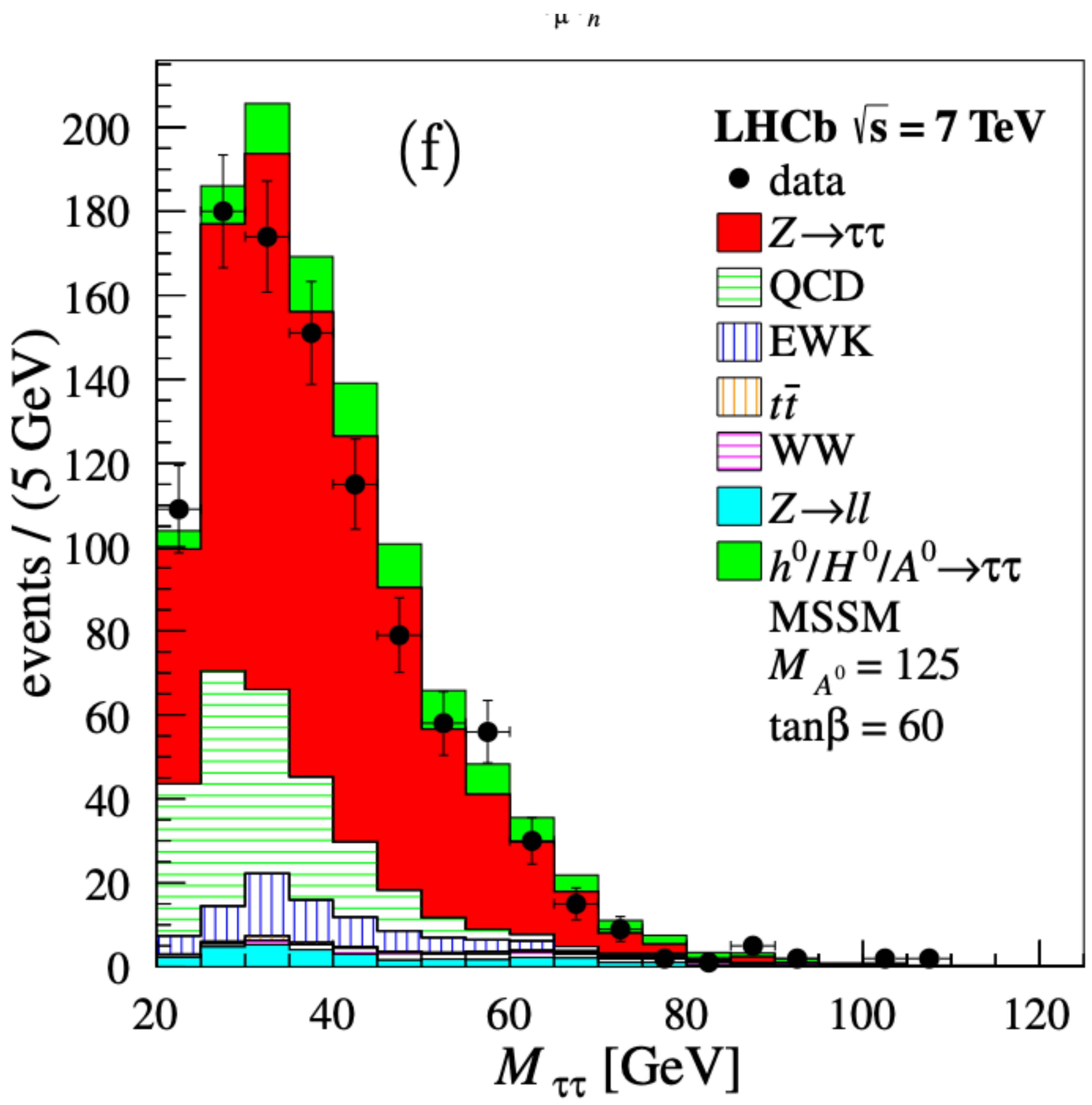
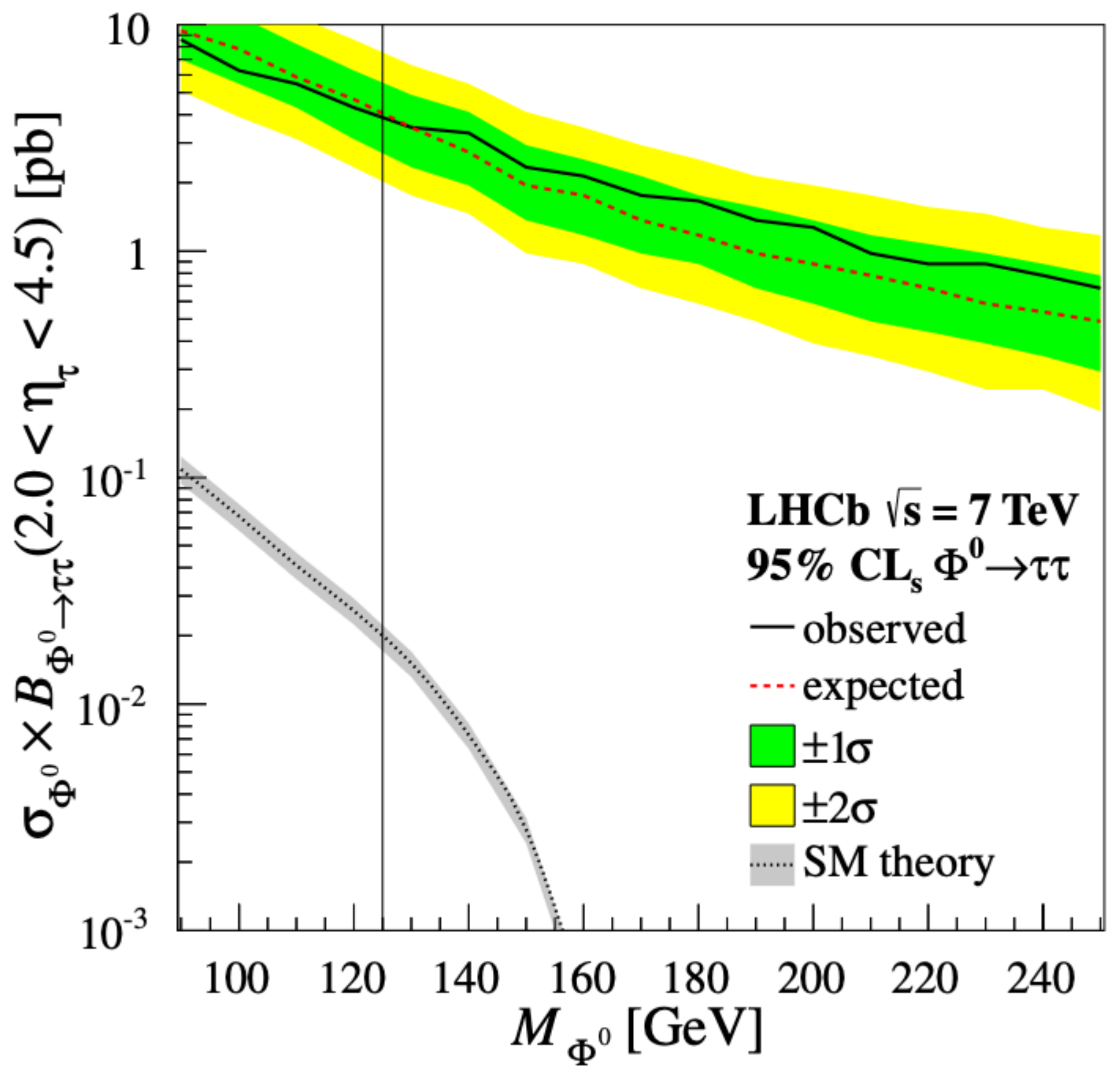
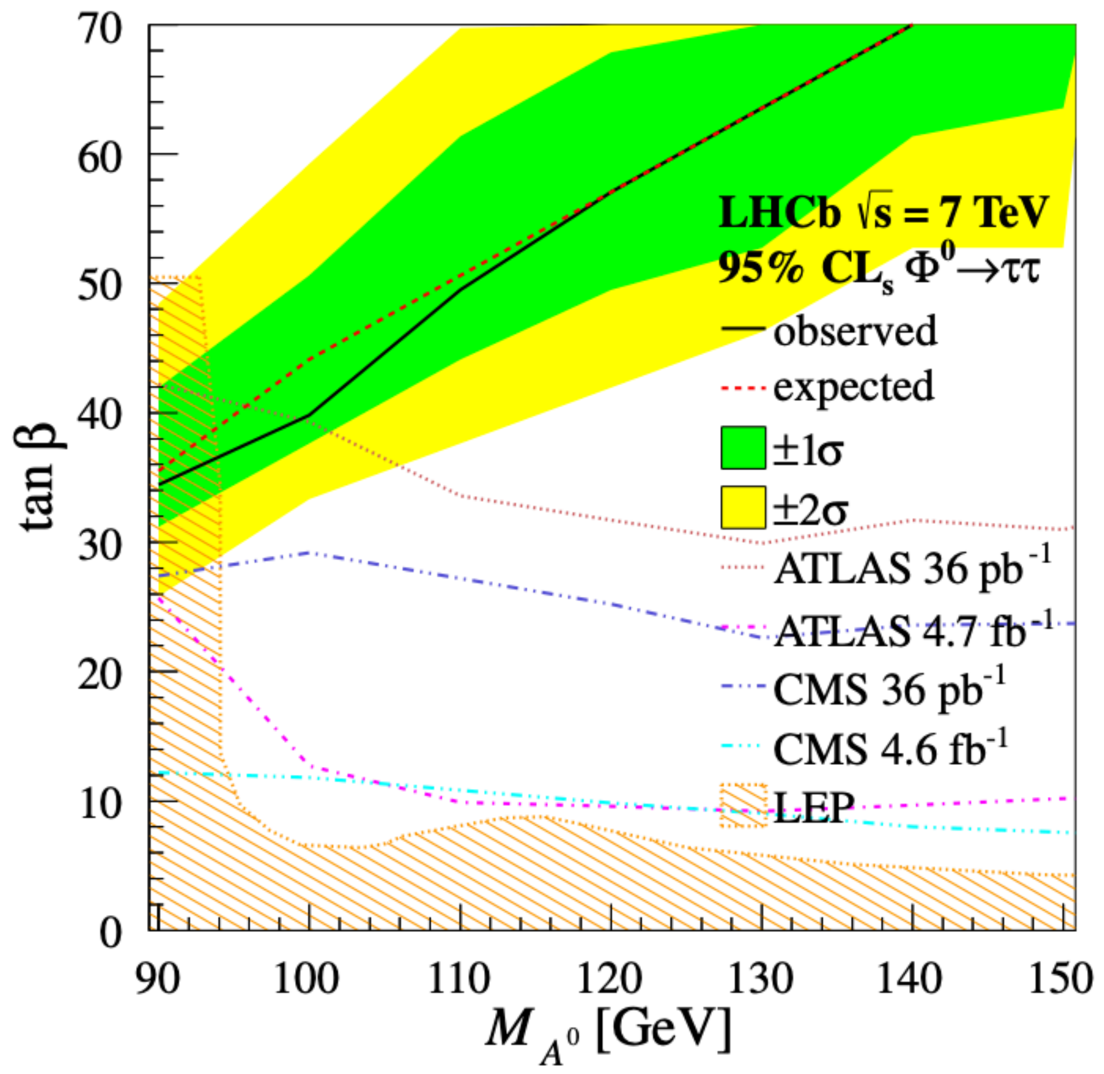
The first LHCb result on Higgs: H→$\tau\tau$



JHEP 05 (2013) 132

- **Performed using Run 1 dataset at 7 TeV collisions** (1.0 fb^{-1})
- Both SM (H→$\tau\tau$) and BSM (H→AA, A→$\tau\tau$) processes tested
- Taus reconstructed in muon, electron, hadron and 3-hadron final state
- **Not really competitive with ATLAS and CMS**

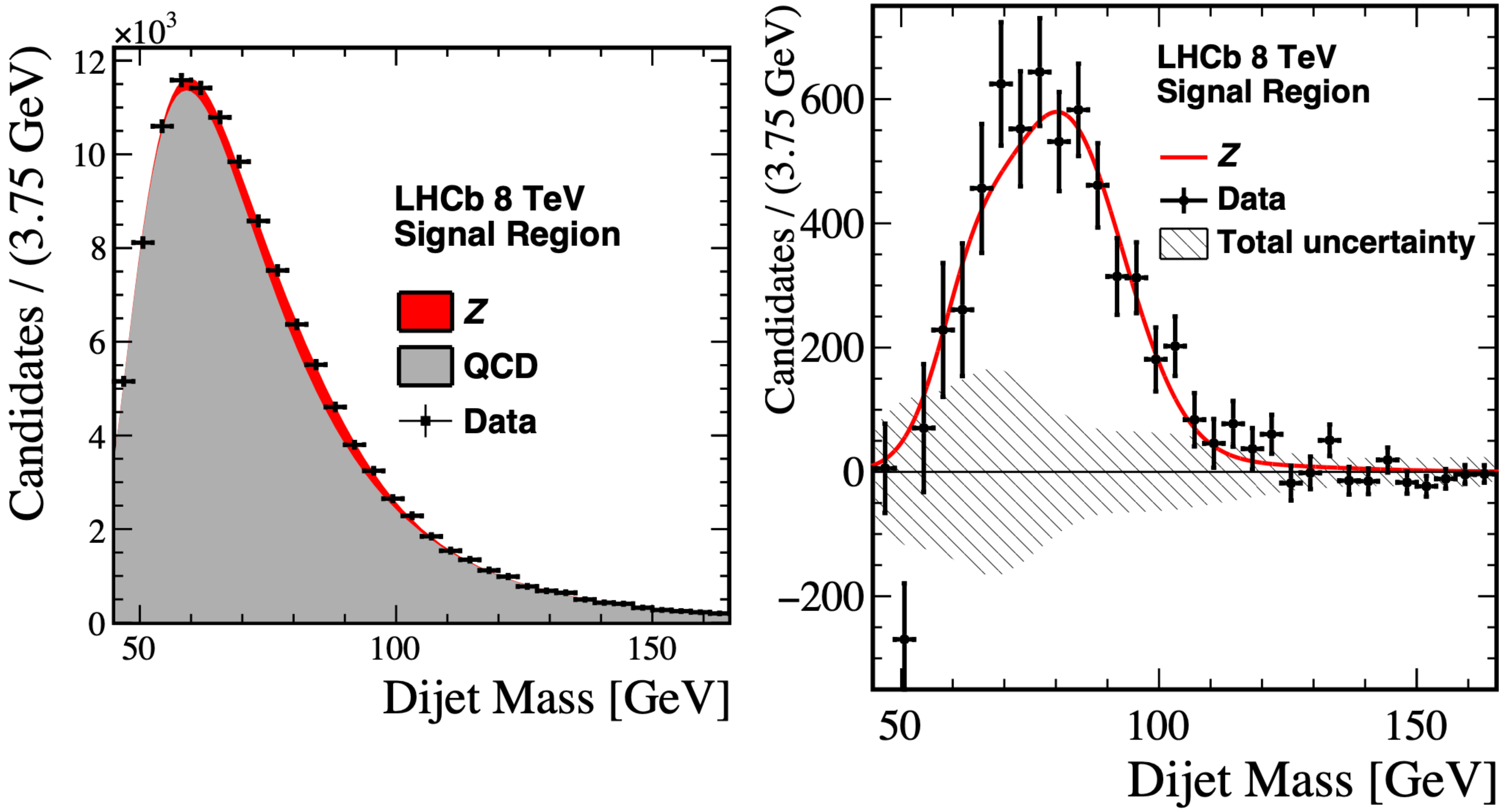




Dijet resonances

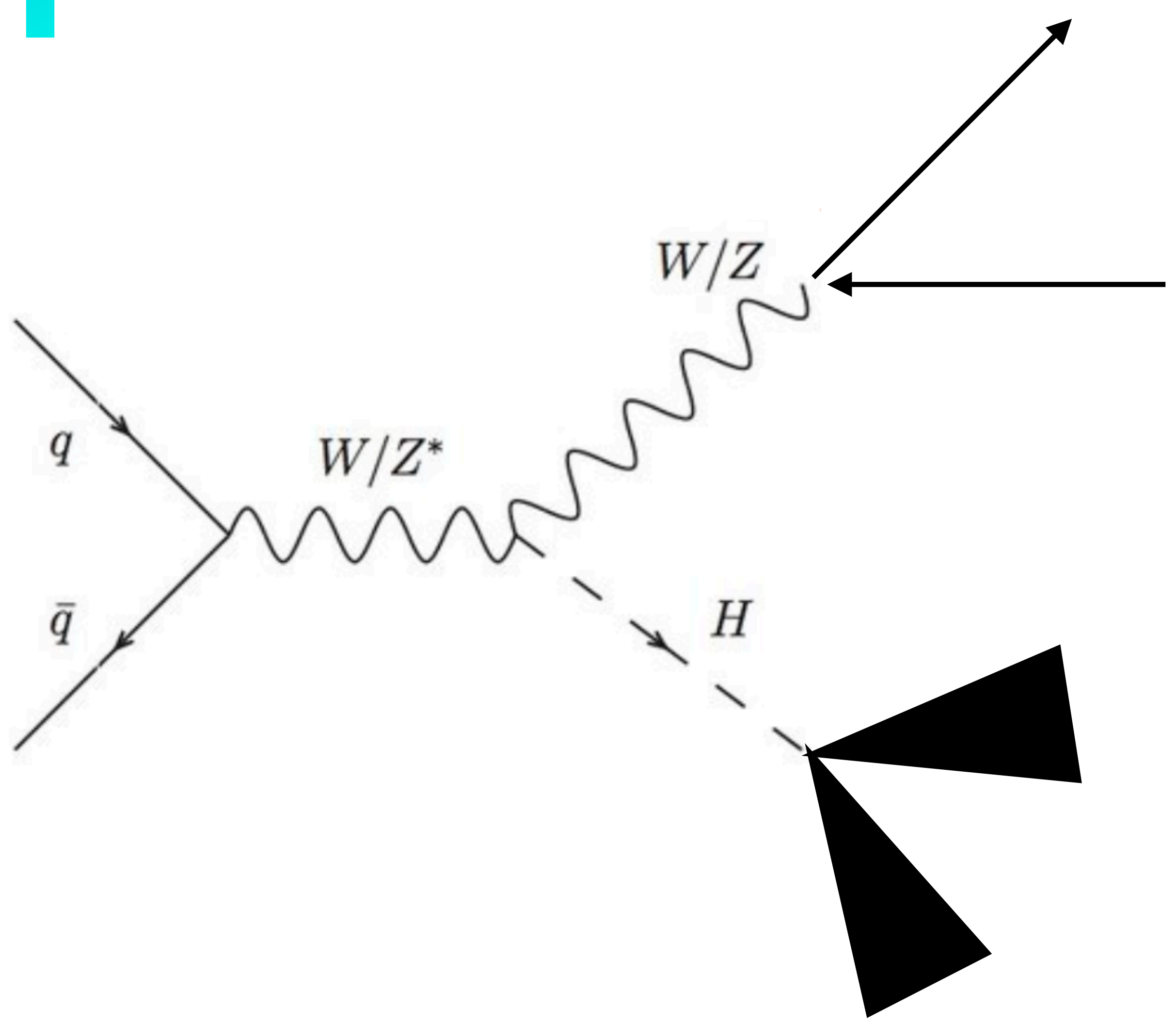
- **LHCb has the potential to look for the decay of the Higgs to $b\bar{b}$ and $c\bar{c}$ quarks**:
  - Excellent jet reconstruction
  - Excellent SV reconstruction
  - Low p_T thresholds triggers (selecting SV-tagged jets with p_T>17 GeV in Run 2)
  - Separation between b and c quarks
- The **measurement of the $Z\to b\bar{b}$ process** is a a proof of LHCb capabilities

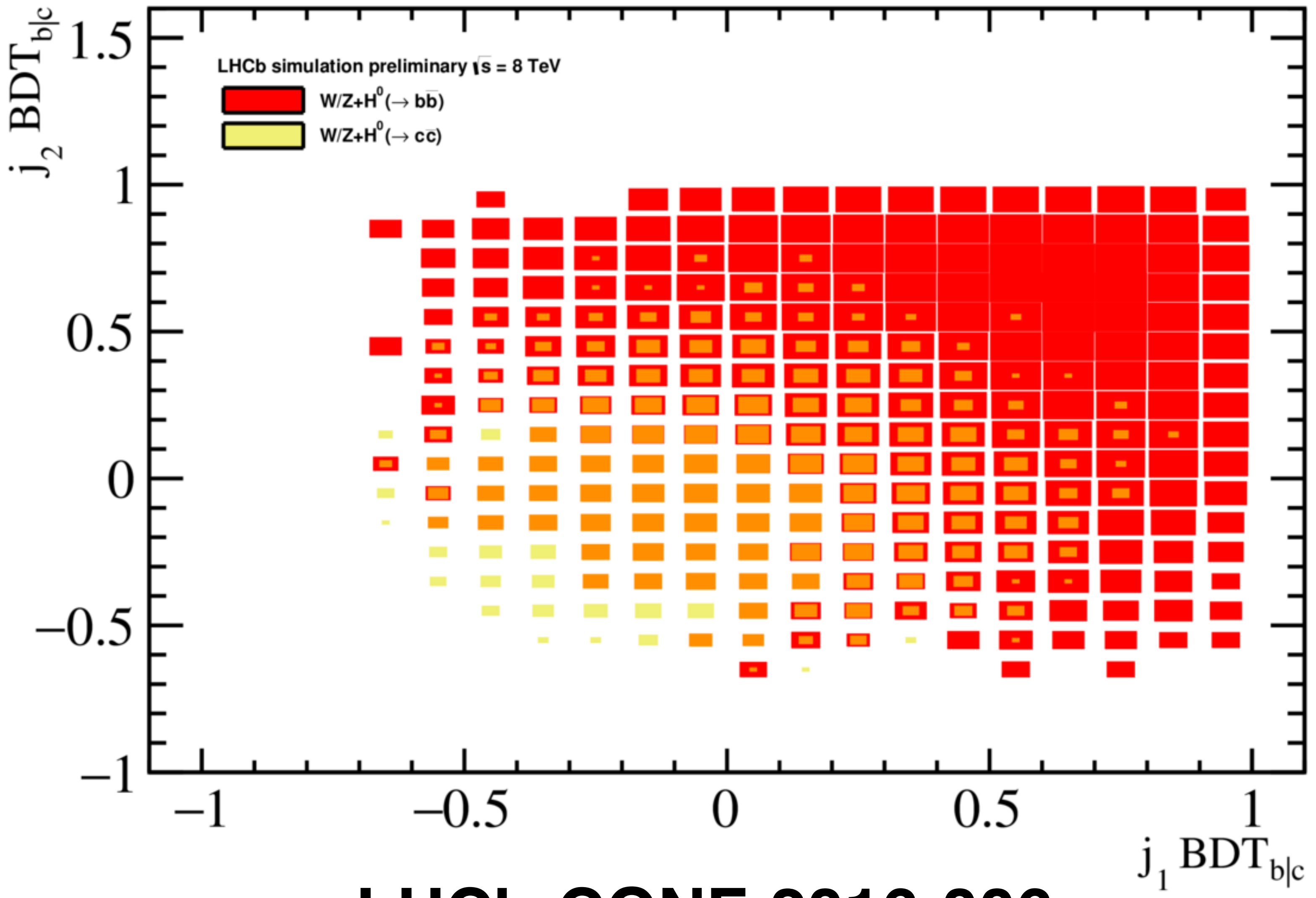
Phys. Lett. B776 (2018) 430



V+H production

- LHCb searched for **V+H** (V can be W or Z) 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→b$\bar{b}$ is an irreducible background for H→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→b$\bar{b}$ while keeping 62% of H→c$\bar{c}$.**

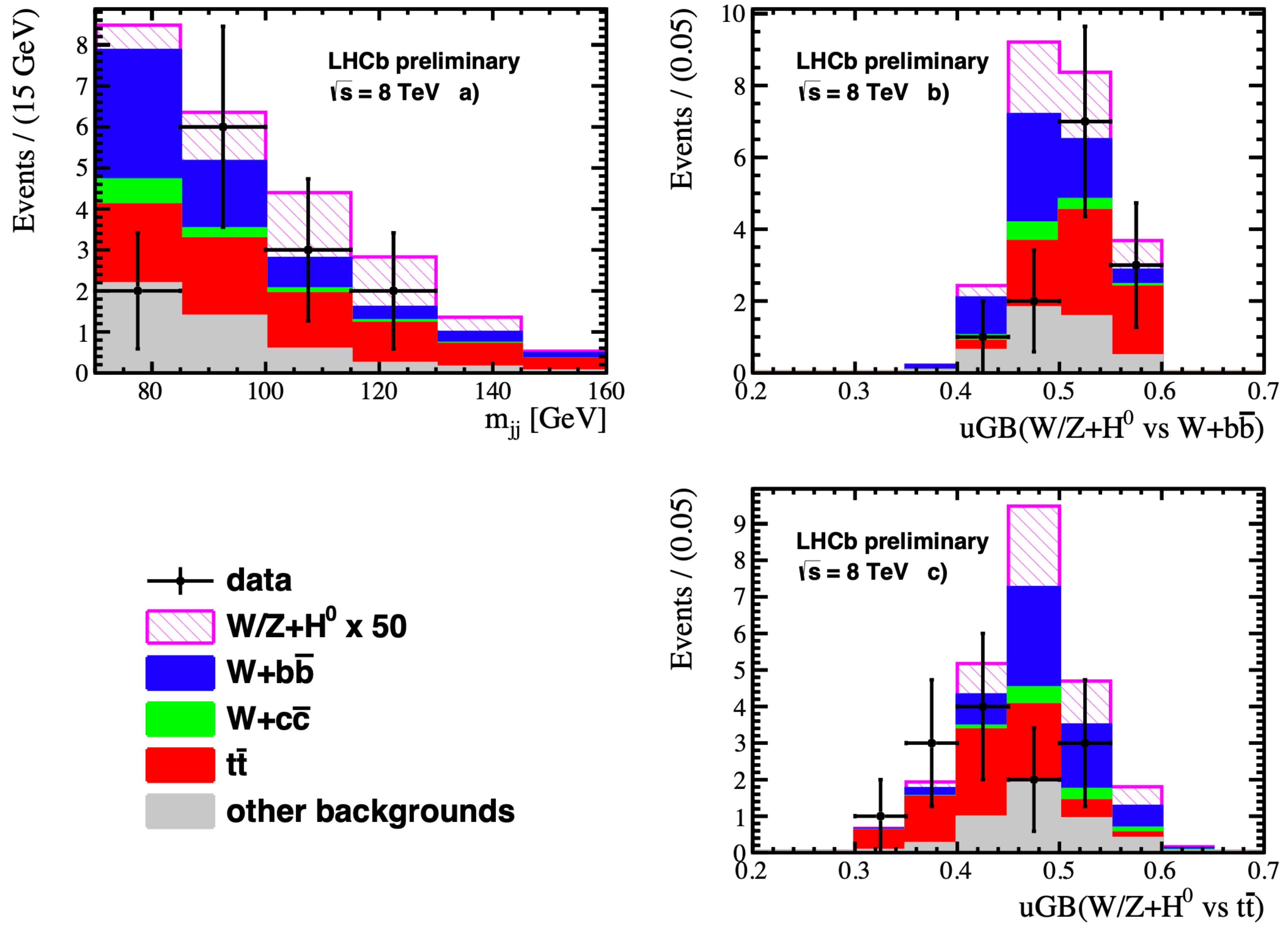




LHCb-CONF-2016-006

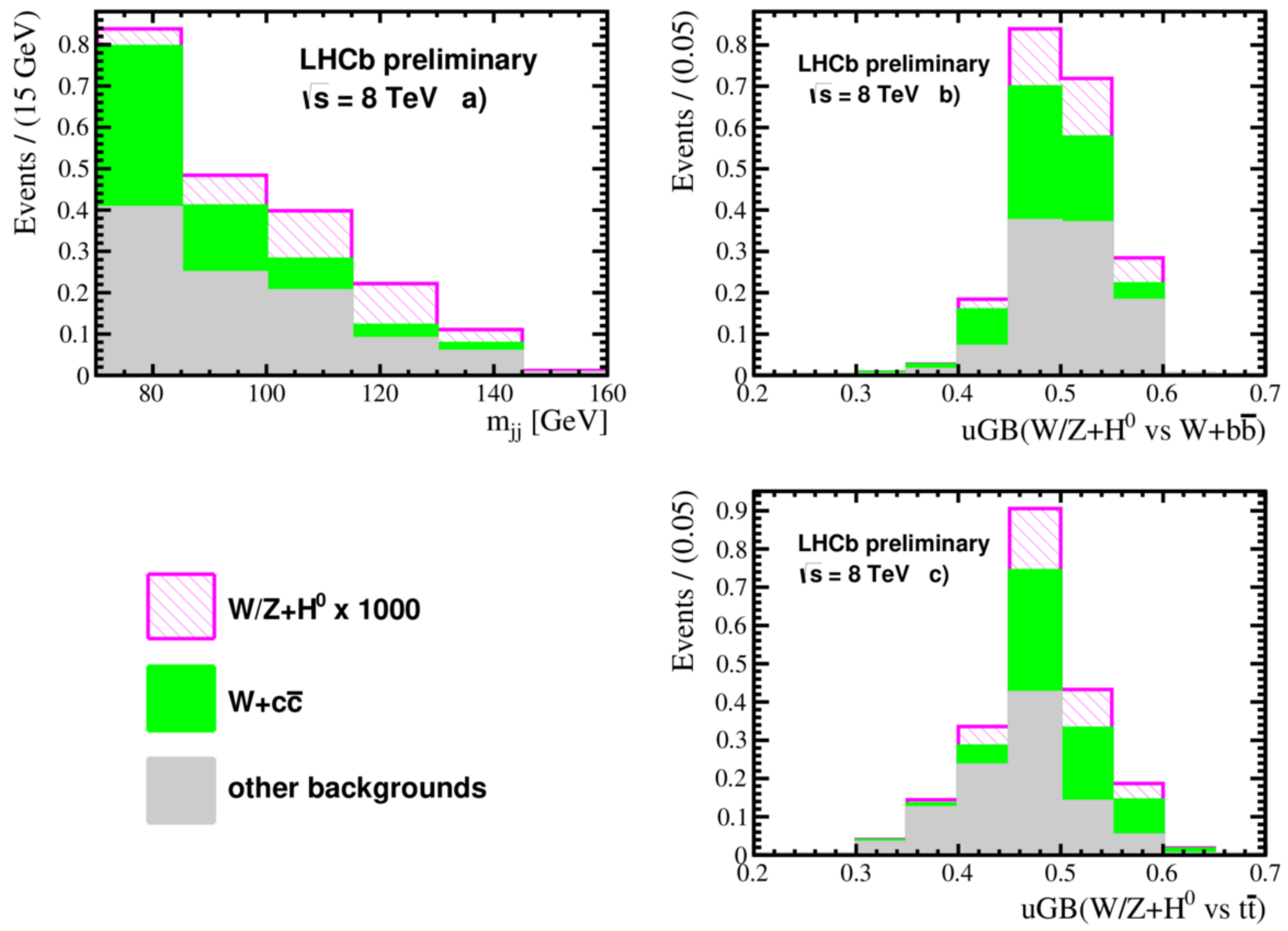
V+H production

V+H→$b\bar{b}$



LHCb-CONF-2016-006

V+H→$c\bar{c}$



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

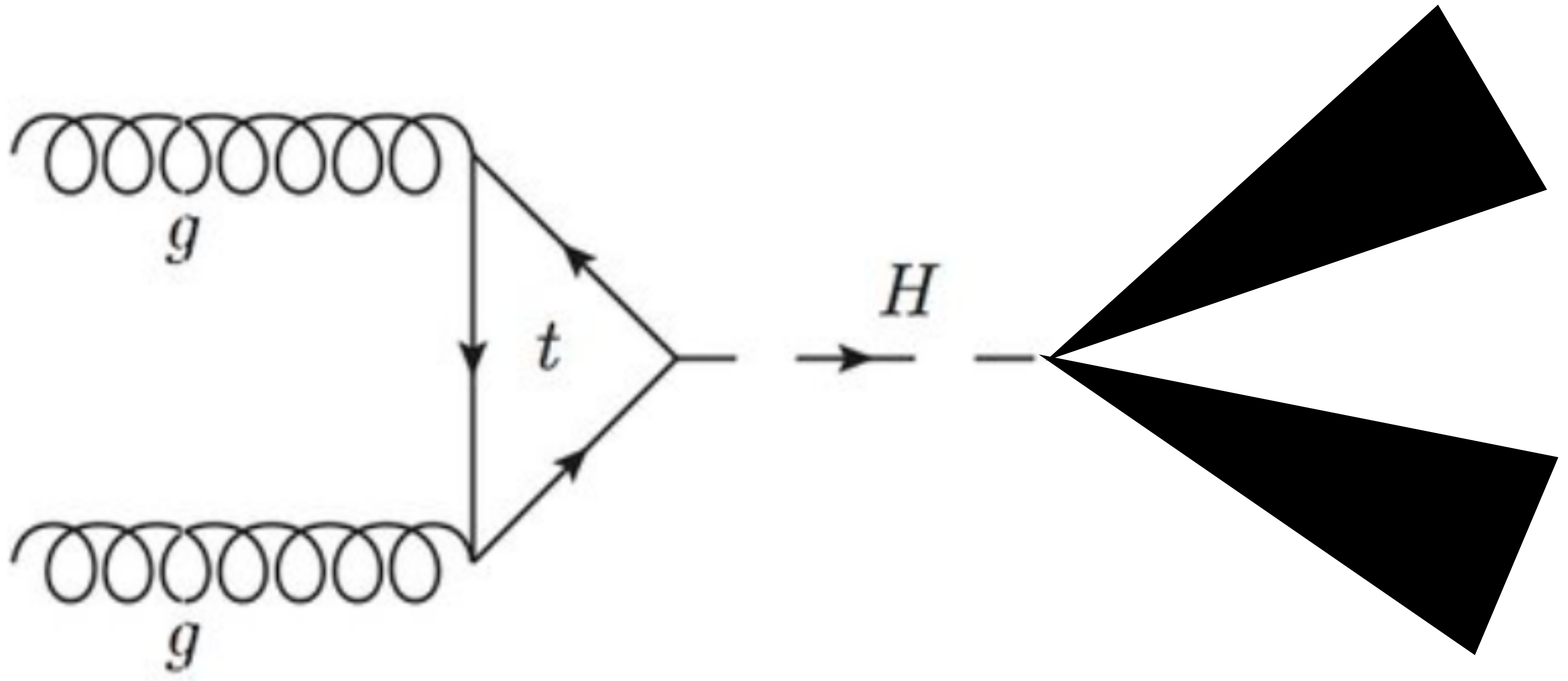
- **2.6 events expected → 0 observed.**
- **σ x BR(H→$c\bar{c}$) < 6400** times the SM expectation at 95% CL

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

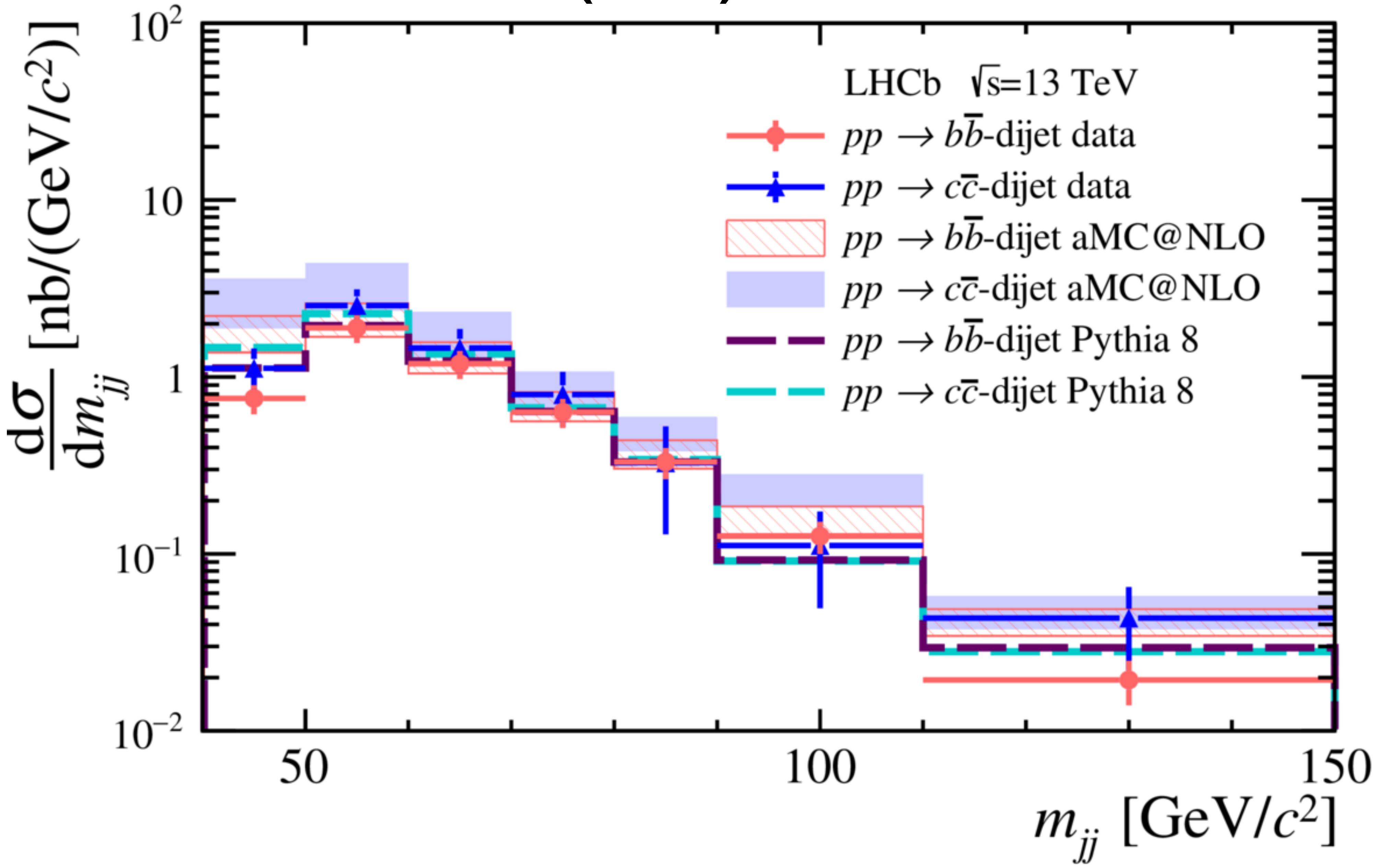
Cannot appear so good, but it was the starting point for our extrapolation

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

- As first step, 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 (using tagging BDTs) has been demonstrated, and the the measured cross sections are compatible with the expectations.
- This was an important step for the **search for inclusive H→$b\bar{b}$ and H→$c\bar{c}$ (so mainly produced by gg fusion)**



JHEP 02 (2021) 023



New jet techniques at LHCb

LHCb-PAPER-2025-034

GBR = Gradient Boosting Regressor

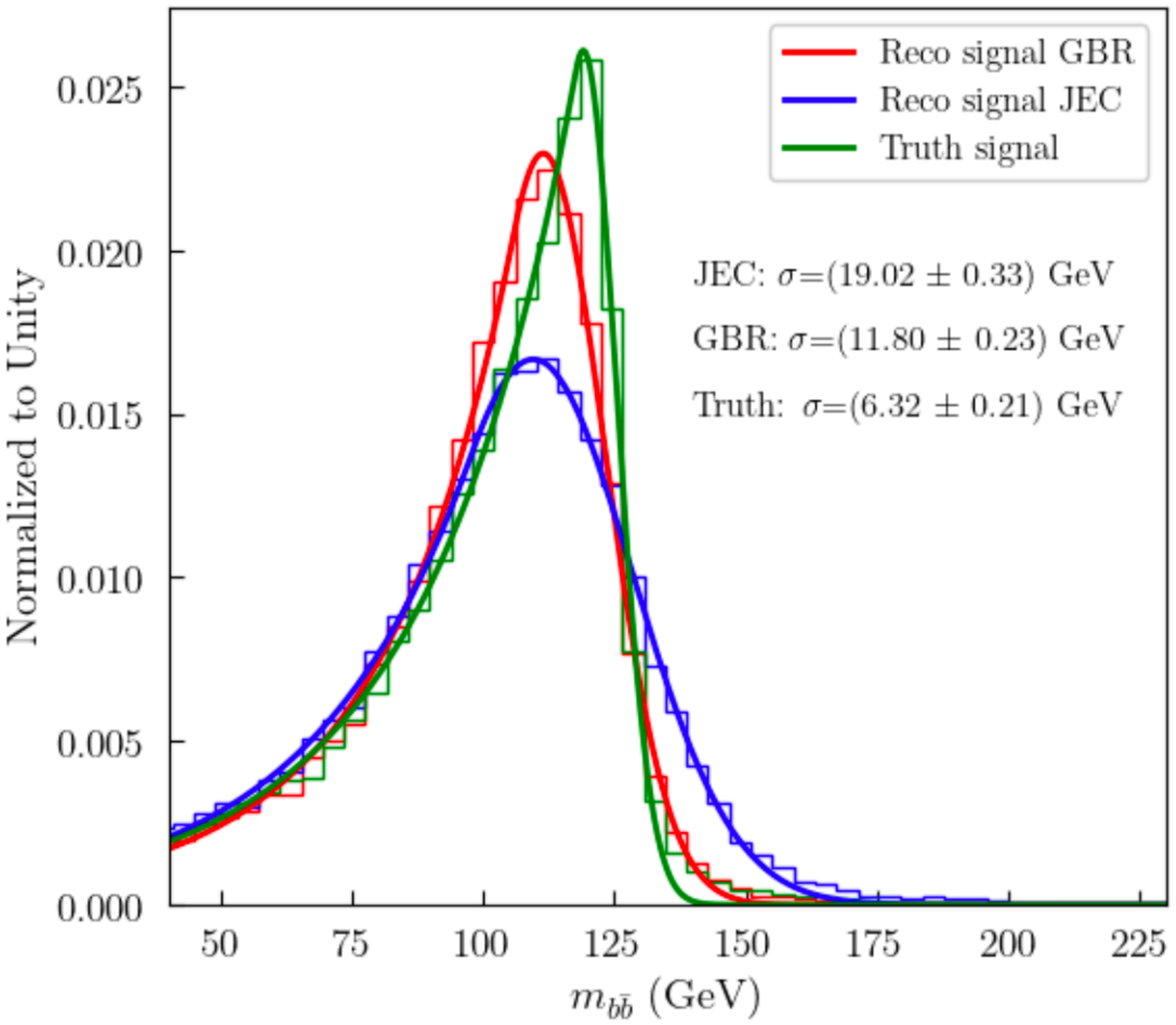
• Inputs: 51 observables from the jet kinematic and substructure

• The $H \rightarrow b\bar{b}$ simulation has been used for the training**, this technique targets specifically the Higgs reconstruction**

• Improvement on the Higgs invariant mass resolution, with respect to default Jet Energy Correction (JEC)

• **By applying it to signal and background, we expect an improvement in the Higgs significance of 22%**

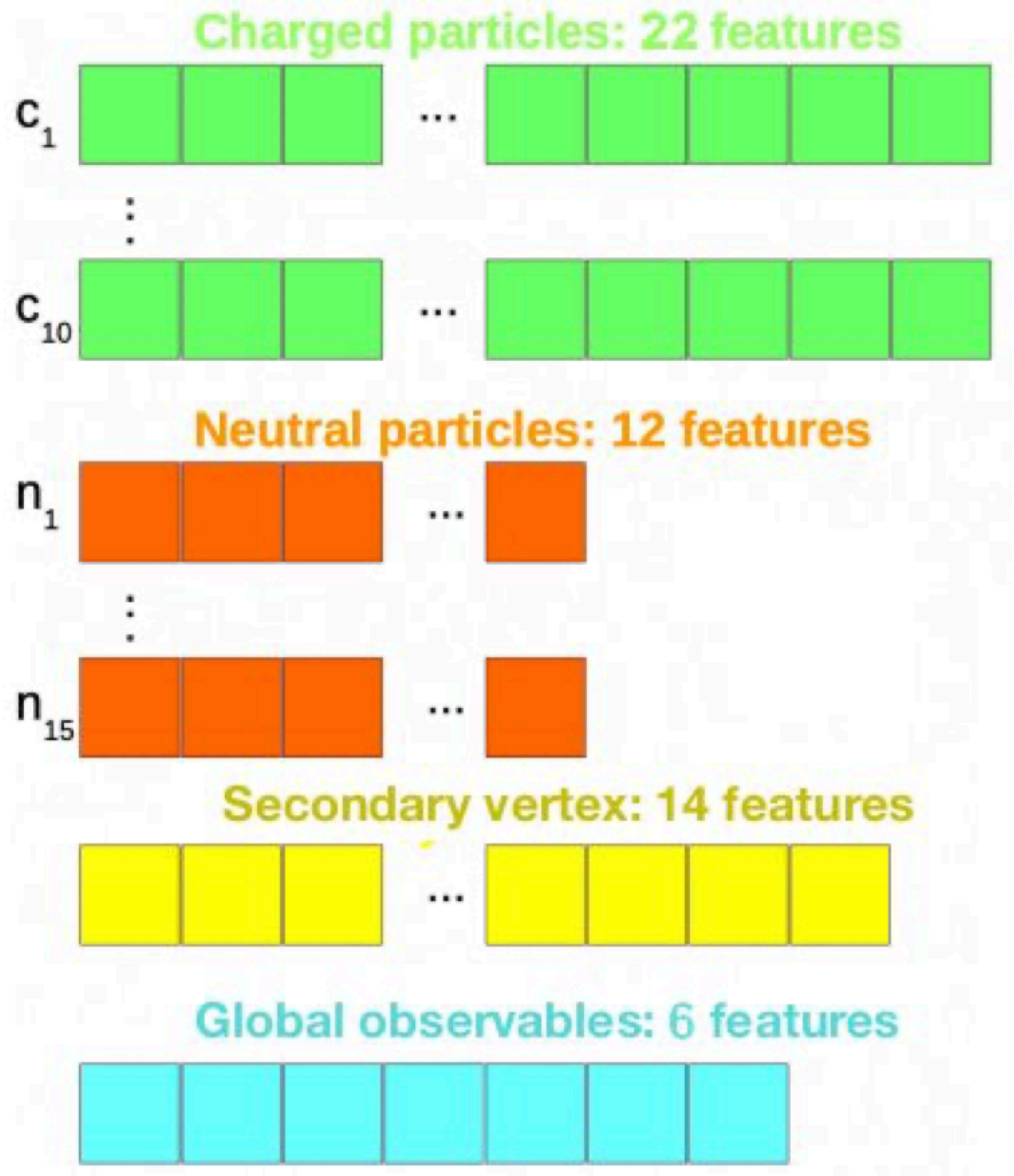
Regression technique for improving the Higgs mass reconstruction



New jet techniques at LHCb

- Network goal: **distinguish between b, c and light (labeled as q) jets**
- Of about 400 jet observables as inputs, related to **jet constituents and sub-structure** (divided in 4 categories)
- 3 outputs: b-probability (P_b), c-probability (P_c) and light probability (P_q)
- Trained with $b\bar{b}$, $c\bar{c}$ and light dijets simulation
- **Secondary Vertex is not strictly required**

Input features to the DNN



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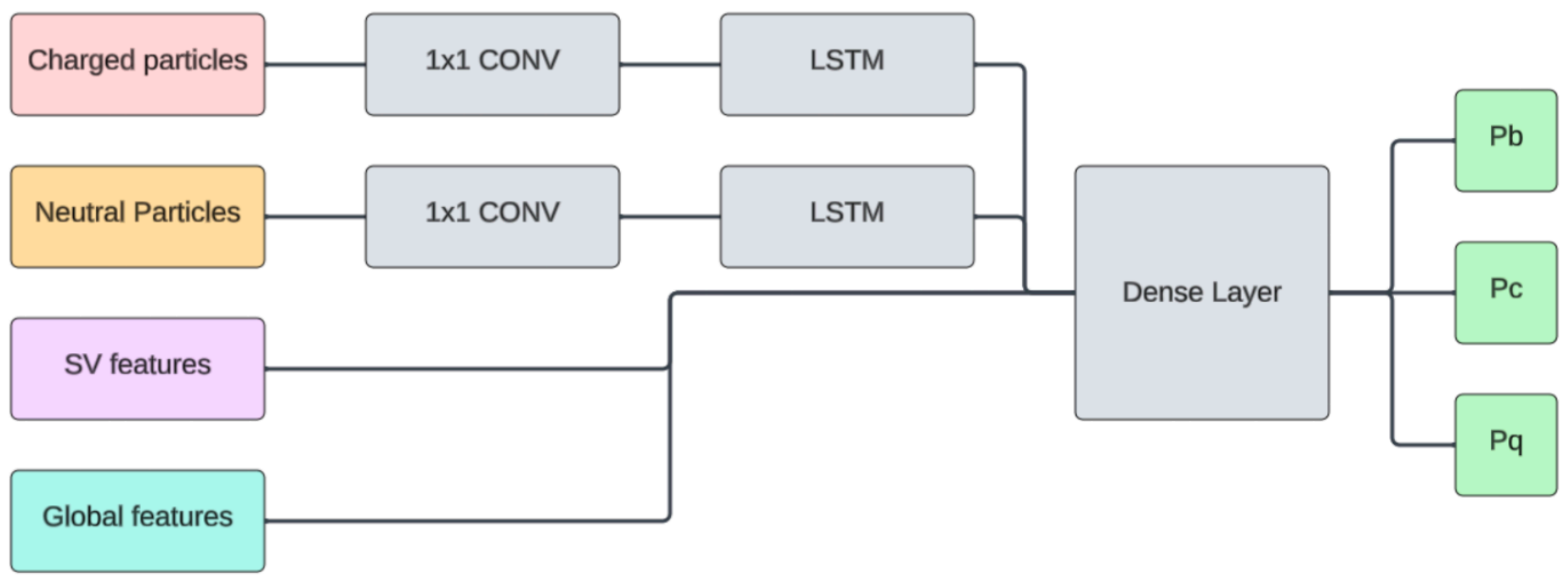
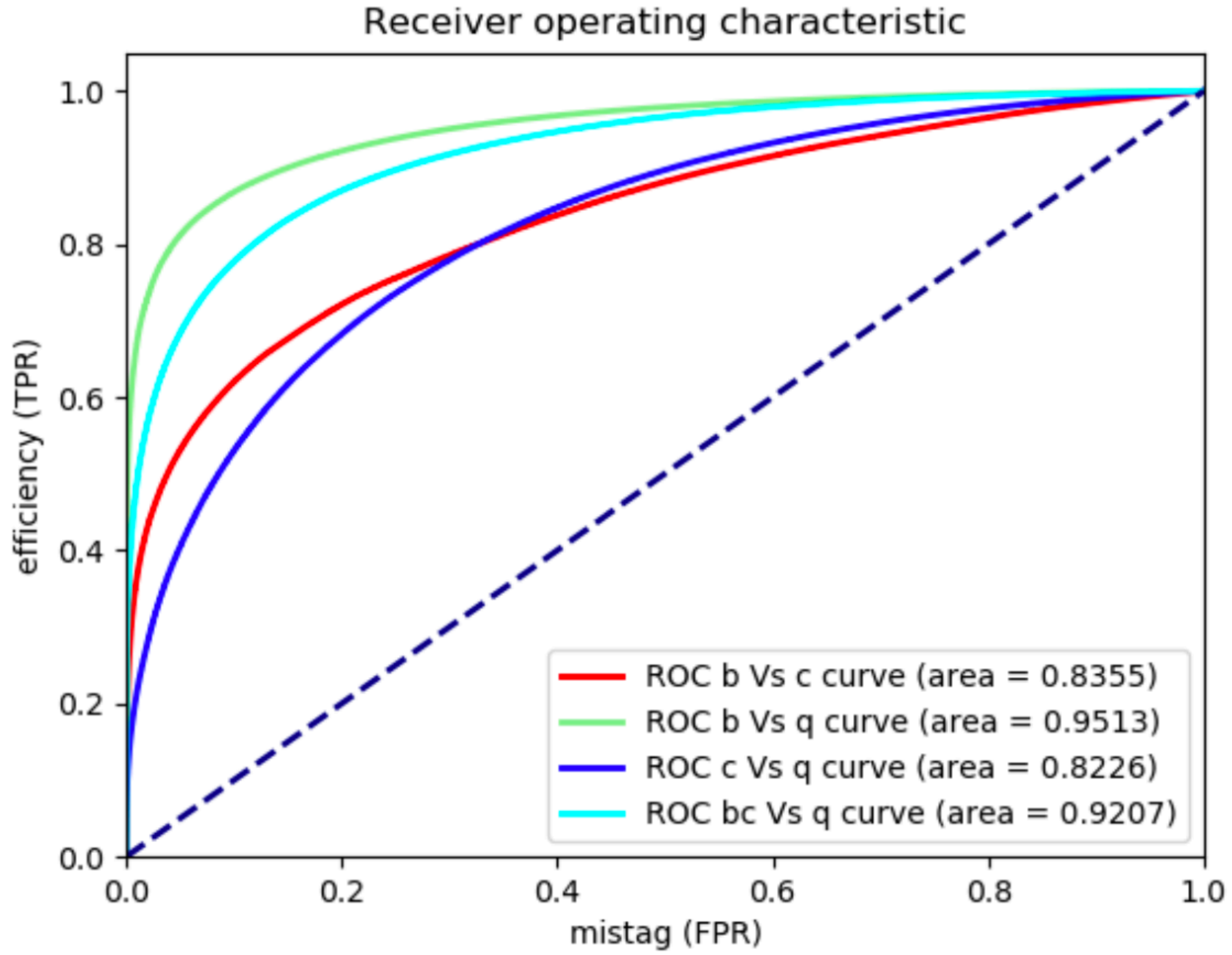
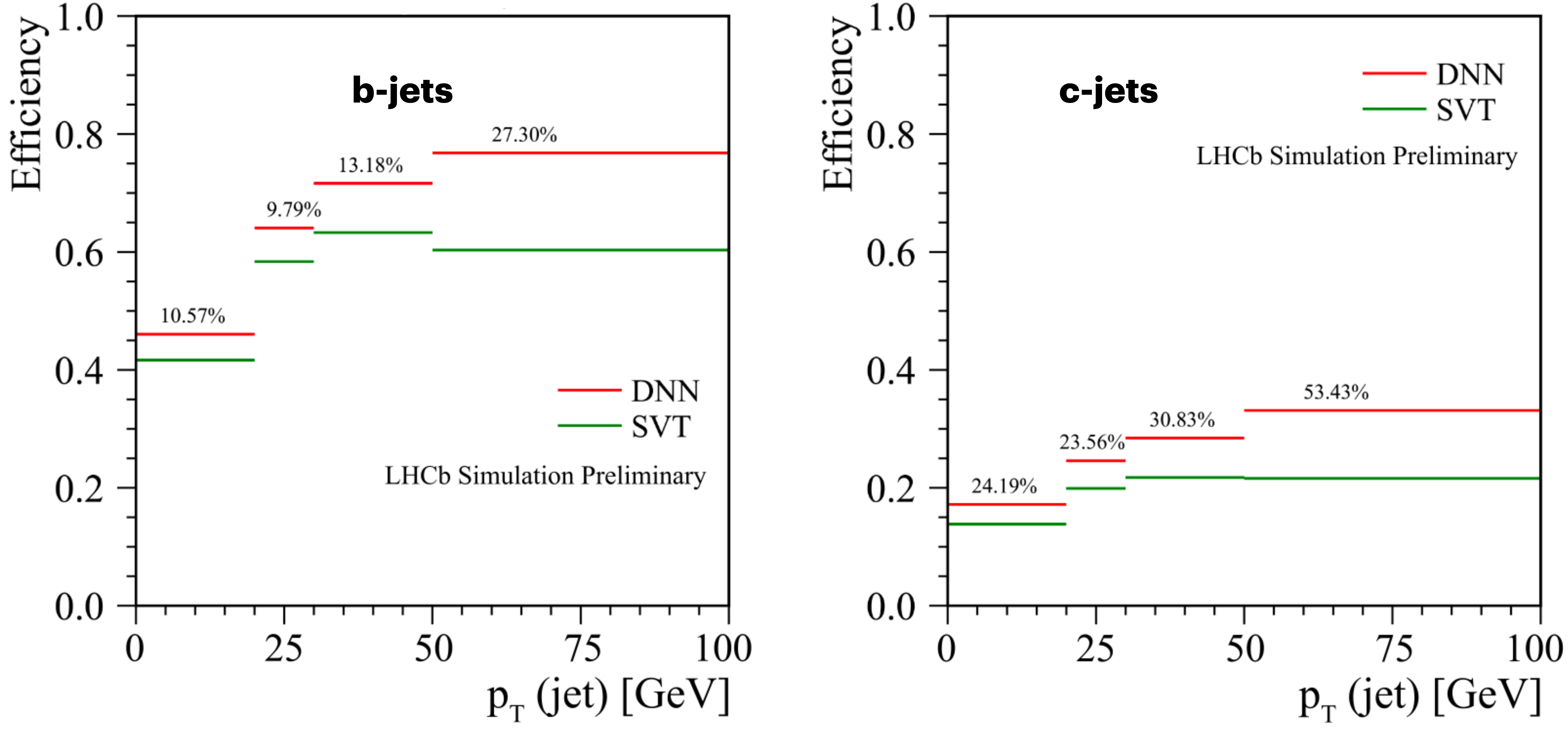




Exploiting the jet substructure: Deep Neural Network for jet flavour identification

New jet techniques at LHCb

LHCb-PAPER-2025-034



Tagging efficiency obtained assuming the same mis-ID of the SV tagging (around 1%)

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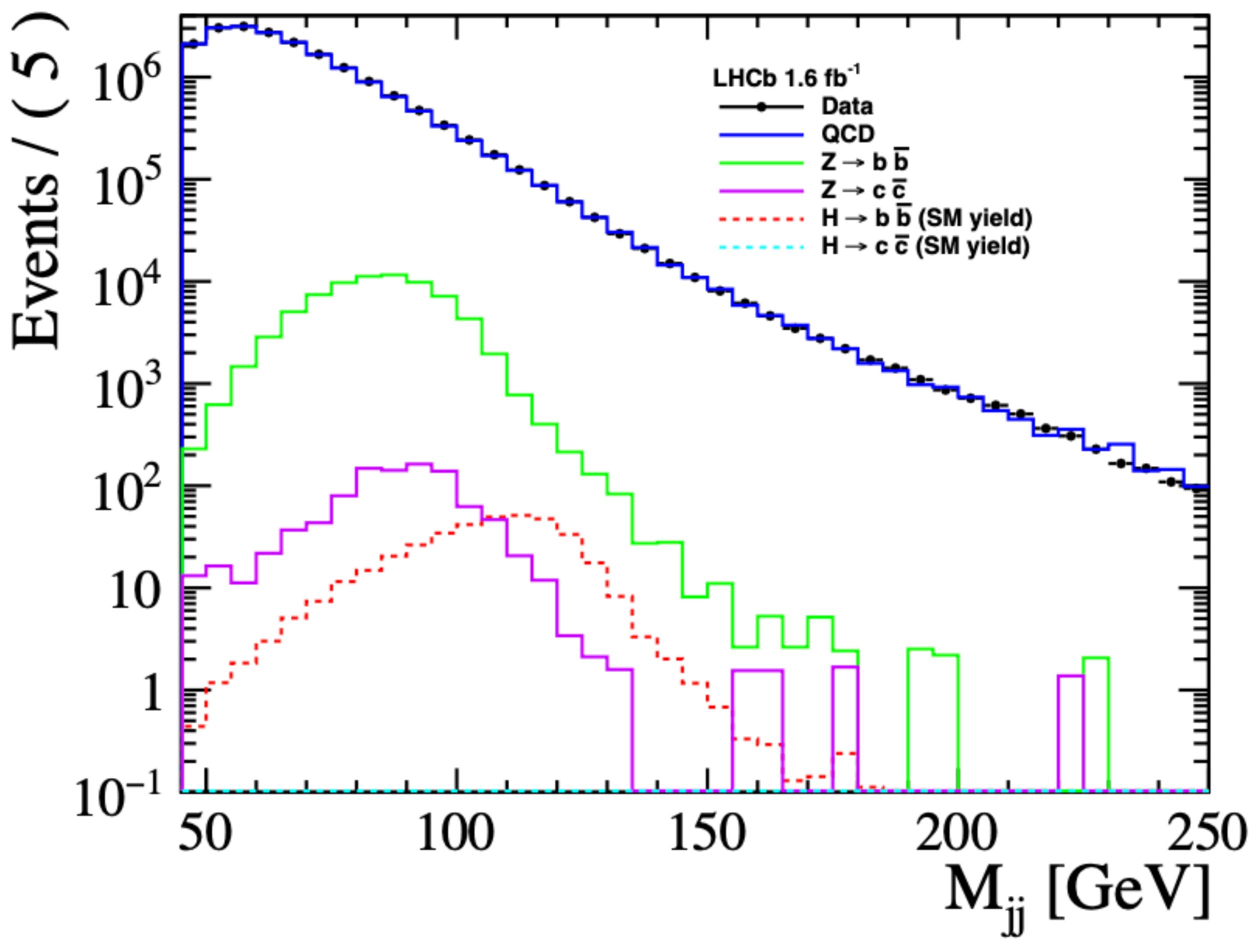
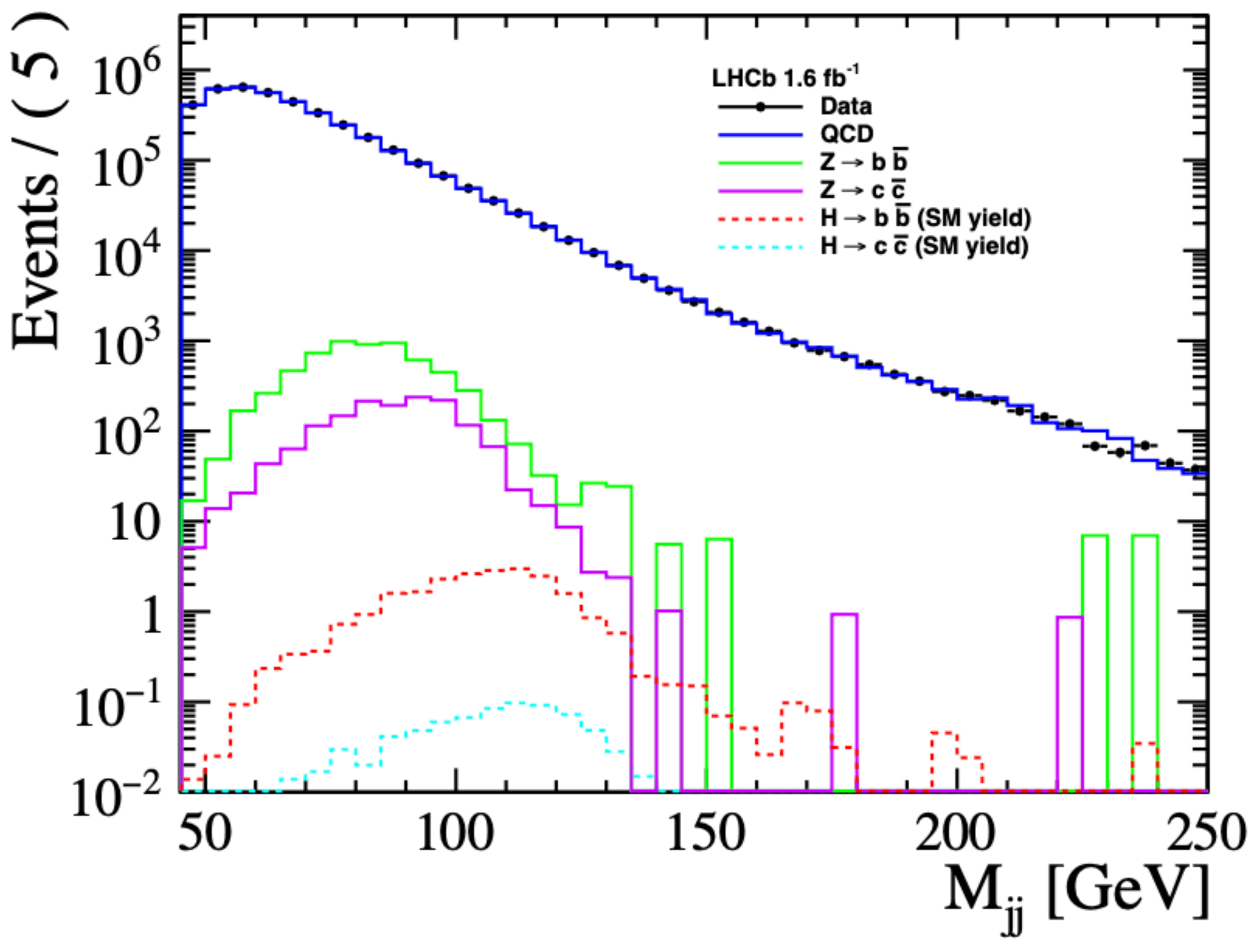
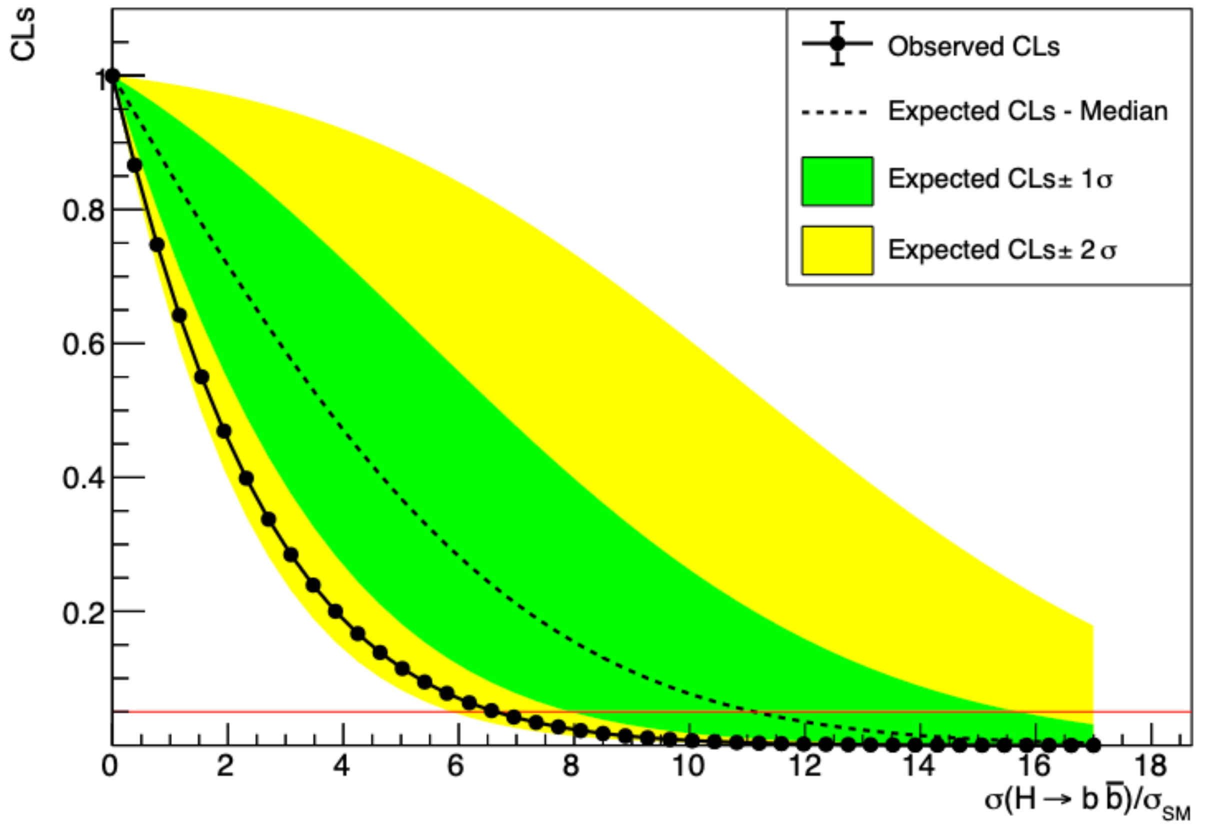
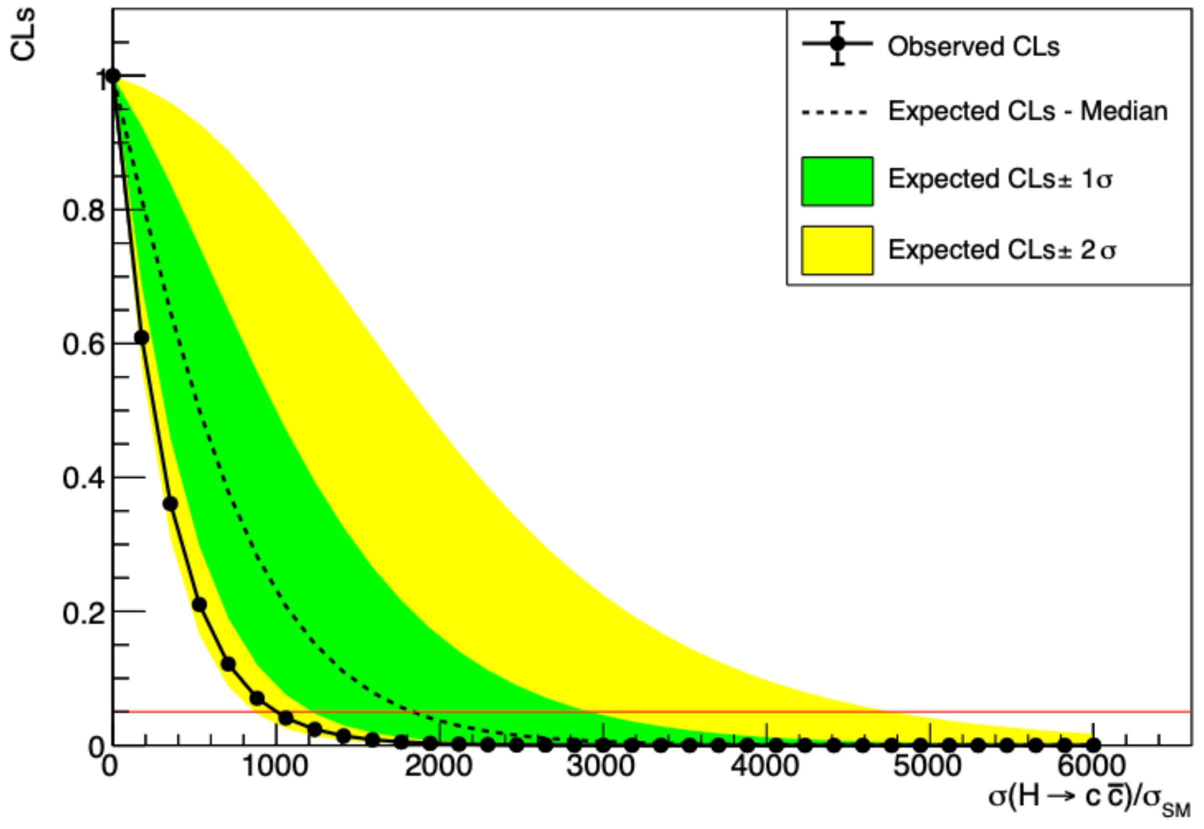
Inclusive $H\rightarrow b\bar{b}$ and $H\rightarrow c\bar{c}$ searches









LHCb-PAPER-2025-034

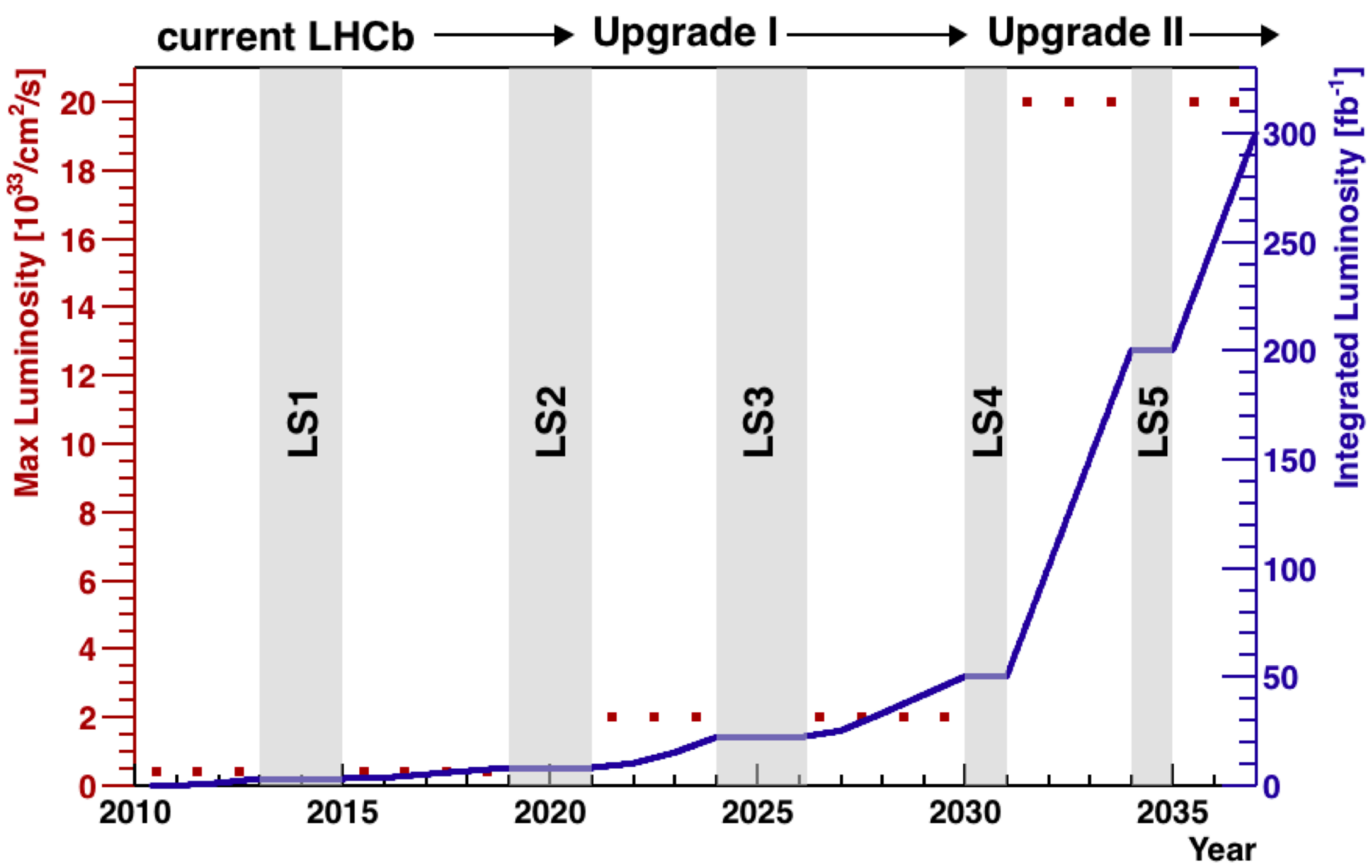
- **Both techniques, energy regression and tagging DNN, have been applied to the inclusive search for $H\rightarrow b\bar{b}/H\rightarrow c\bar{c}$** (dijet final state)
- Performed using Run 2 dataset at 13 TeV collisions collected in 2016 (1.6 fb^{-1})
- **Jets are SV-tagged by the trigger, but DNN requirements are applied to improve the signal significance**
- Data-driven method for the determination of the QCD background: DNN is used to select a mixed flavor data sample without SM resonances

Observed upper limits

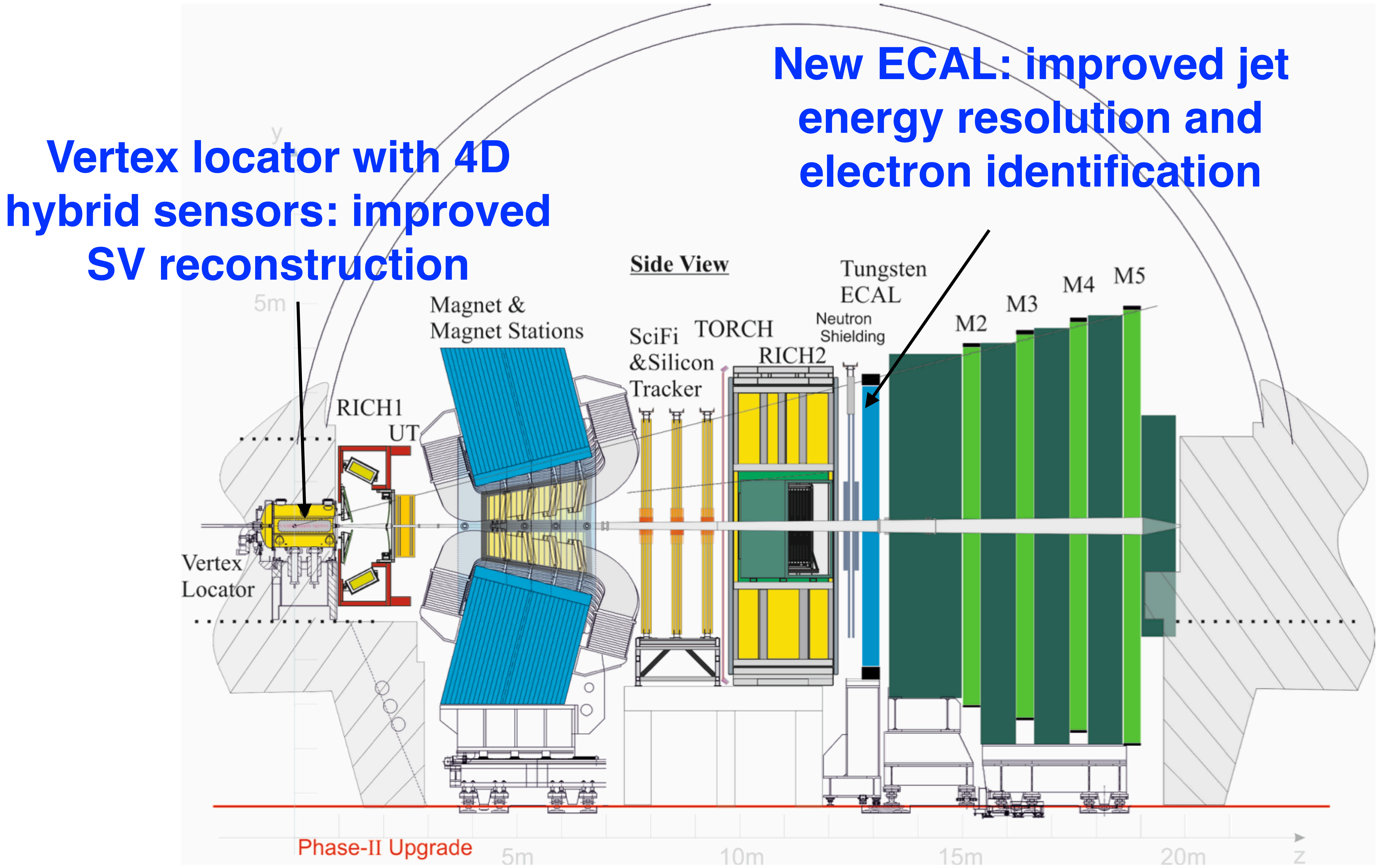
Process	σ_{UP}/σ_{SM}	N_{UP}	σ_{UP} [pb]
$H\rightarrow b\bar{b}$	6.64	1587	211
$H\rightarrow c\bar{c}$	1003	722	1605

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**



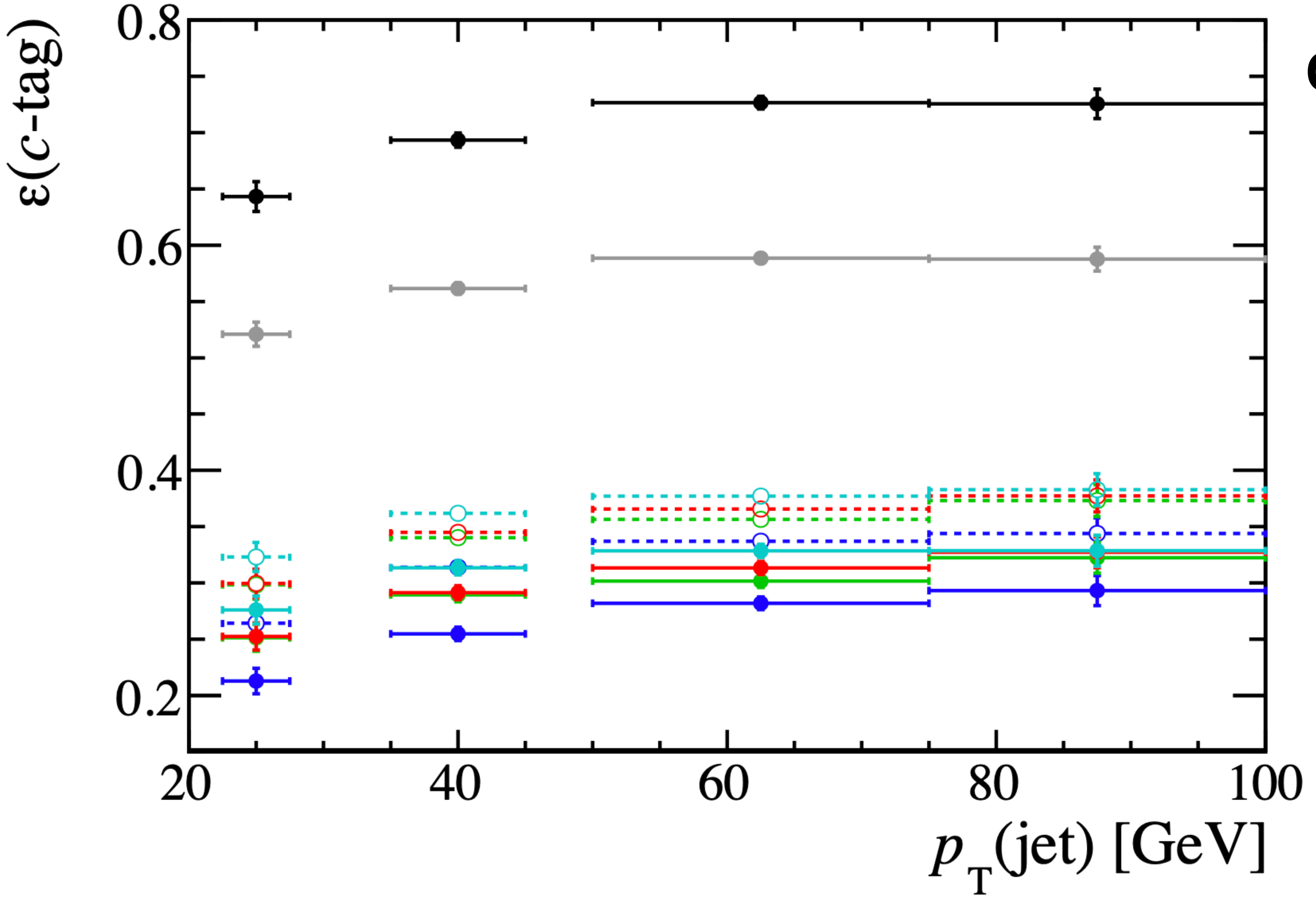
CERN-LHCC-2018-027



Prospects on H→ $c\bar{c}$ 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%**.

per-c-jet SV-tagging efficiency



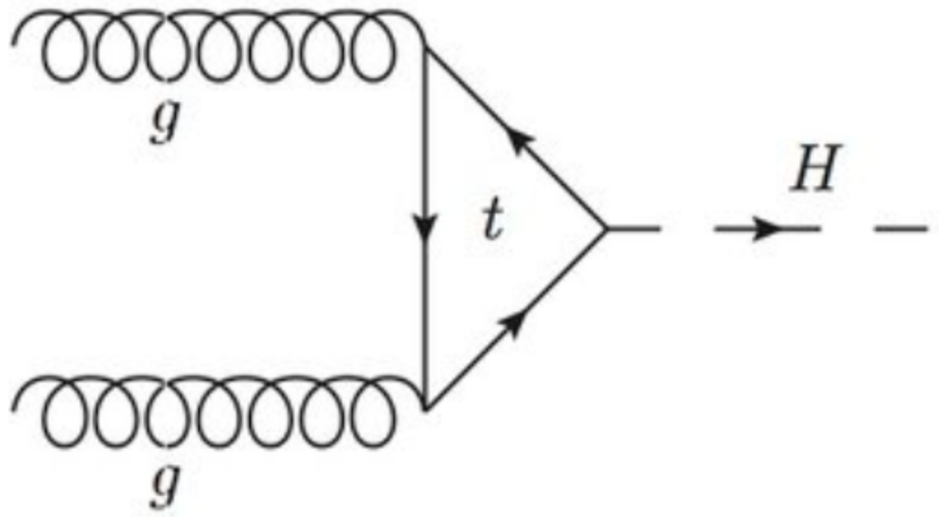
CERN-2019-007

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.

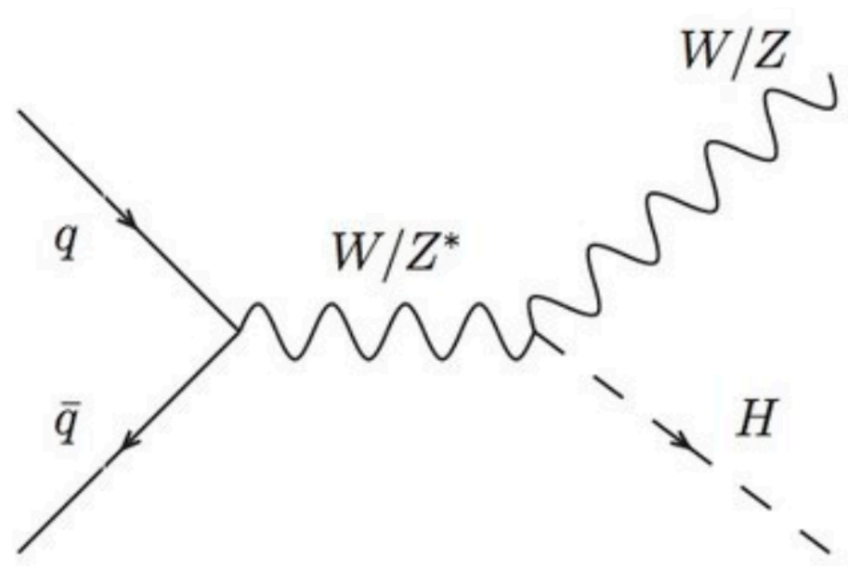
Phase-II Scenario 2
Phase-II Scenario 1
Run 3
Run1
Solid: IP $X^2 > 16$ (as in Run 1)
Dashed: IP $X^2 > 9$

$H\to b\bar{b}$ and $H\to c\bar{c}$ searches with 300 fb^{-1}



LHCb-PAPER-2025-034

Extrapolations done starting from Run 1 and Run 2 results



CERN-2019-007

- **Expected $H\to b\bar{b}$ limit with U2 → 0.2 x SM**
- **Expected $H\to c\bar{c}$ limit with U2 → 27 x SM.**
- Upper limit of **$y^c < 5\ y^c_{SM}$** on the Hcc coupling

- **Expected $V+H\to b\bar{b}$ limit with U2 → 1.5 x SM**
- **Expected $V+H\to c\bar{c}$ limit with U2 → 6 x SM.**
- Upper limit of **$y^c < 2\text{-}3\ y^c_{SM}$** on the Hcc coupling

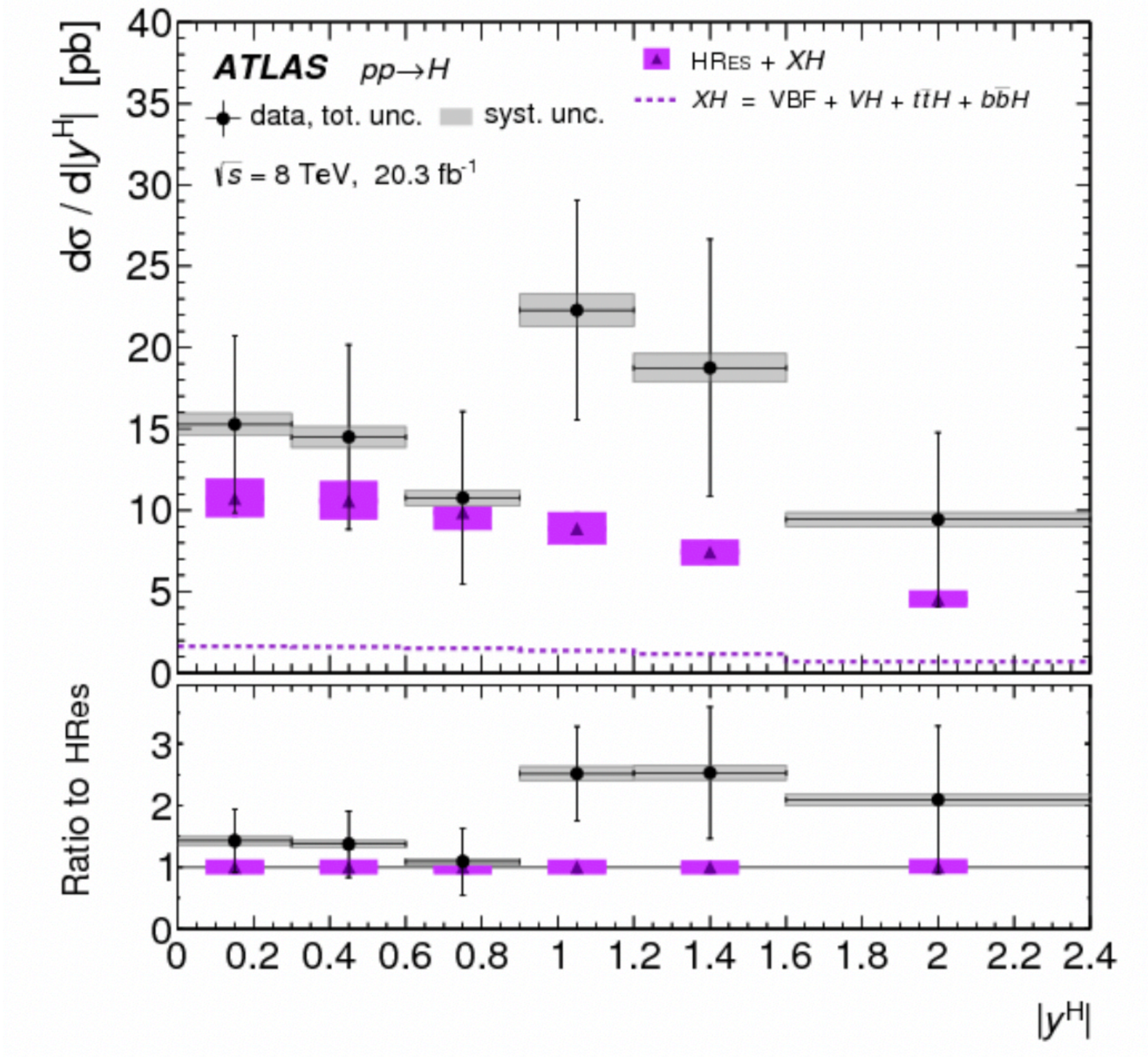
ATLAS/CMS HL-LHC y^c: 1.5 times the SM

↓

LHCb expected sensitivity on y^c could be very close to ATLAS/CMS

Measuring Higgs cross section at LHCb

Phys. Rev. Lett. 115, 091801 (2015)

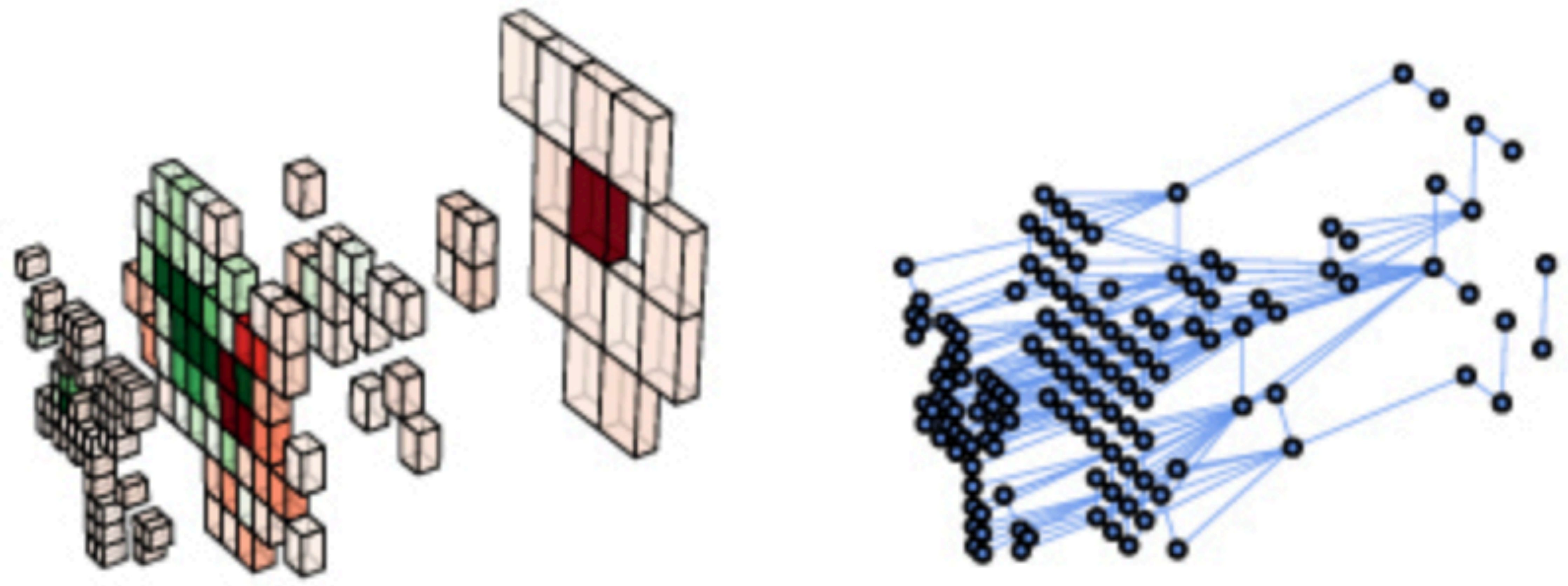


- **At LHCb we should have enough sensitivity to measure $H \rightarrow b\bar{b}$ with the Upgrade 2 detector**
- Phase space complementarity with respect to ATLAS/CMS is the selling point
- Differential cross sections are very important for testing the Higgs theory
- **If deviations exists in the forward region of pp collisions ATLAS and CMS won't be able to catch them**

Further improvements: jet substructure

Graph Neural Networks

Jonathan Shlomi *et al* 2021 *Mach. Learn.: Sci. Technol.* **2** 021001



- **ATLAS and CMS already demonstrated that this kind of advanced tagging techniques can improve a lot the Higgs measurements**
- **Dedicated trigger lines with optimized tagging requirements can help a lot**

ParticleNet

Phys. Rev. D 101, 056019 (2020)

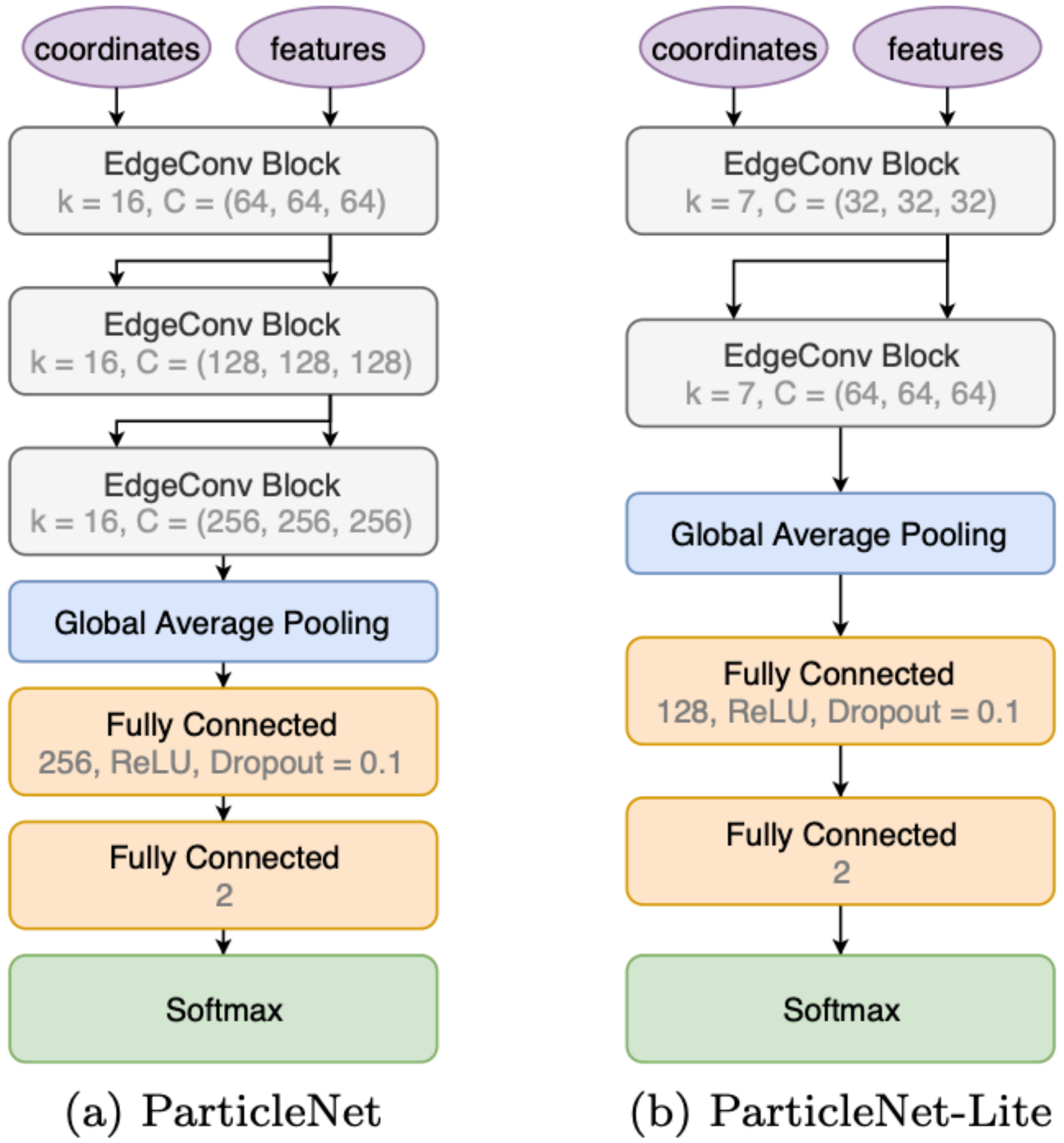
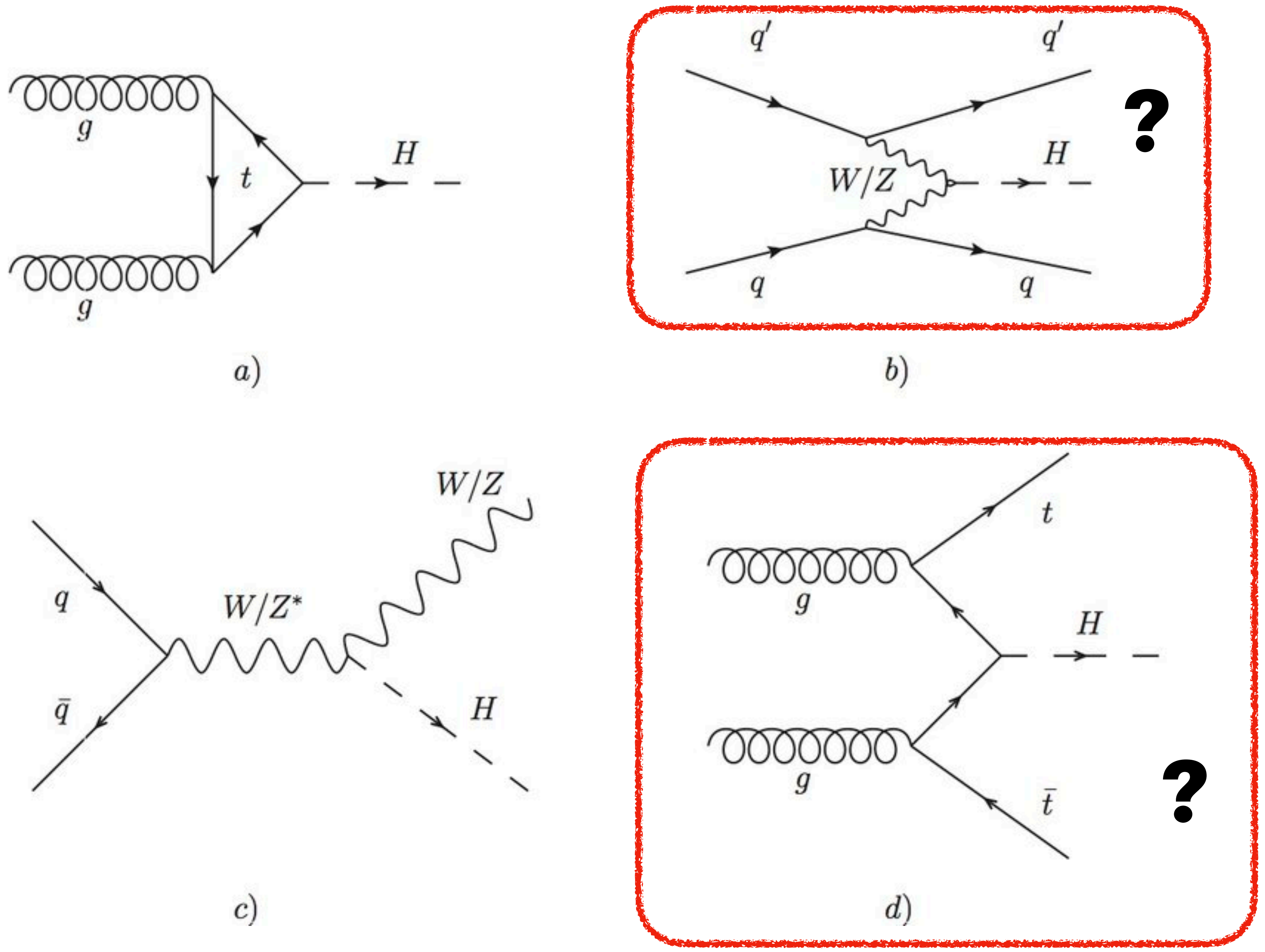


FIG. 2: The architectures of the ParticleNet and the ParticleNet-Lite networks.

Further improvements: other channels

Jonathan Shlomi *et al* 2021 *Mach. Learn.: Sci. Technol.* **2** 021001



Decay channel	Branching ratio	Rel. uncertainty
$H \to \gamma\gamma$	2.27×10^{-3}	2.1%
$H \to ZZ$	2.62×10^{-2}	±1.5%
$H \to W^+W^-$	2.14×10^{-1}	±1.5%
$H \to \tau^+\tau^-$	6.27×10^{-2}	±1.6%
$H \to b\bar{b}$	5.82×10^{-1}	$^{+1.2\%}_{-1.3\%}$
$H \to c\bar{c}$	2.89×10^{-2}	$^{+5.5\%}_{-2.0\%}$
$H \to Z\gamma$	1.53×10^{-3}	±5.8%
$H \to \mu^+\mu^-$	2.18×10^{-4}	±1.7%

Other decay channels?

Beyond Standard Model Higgs

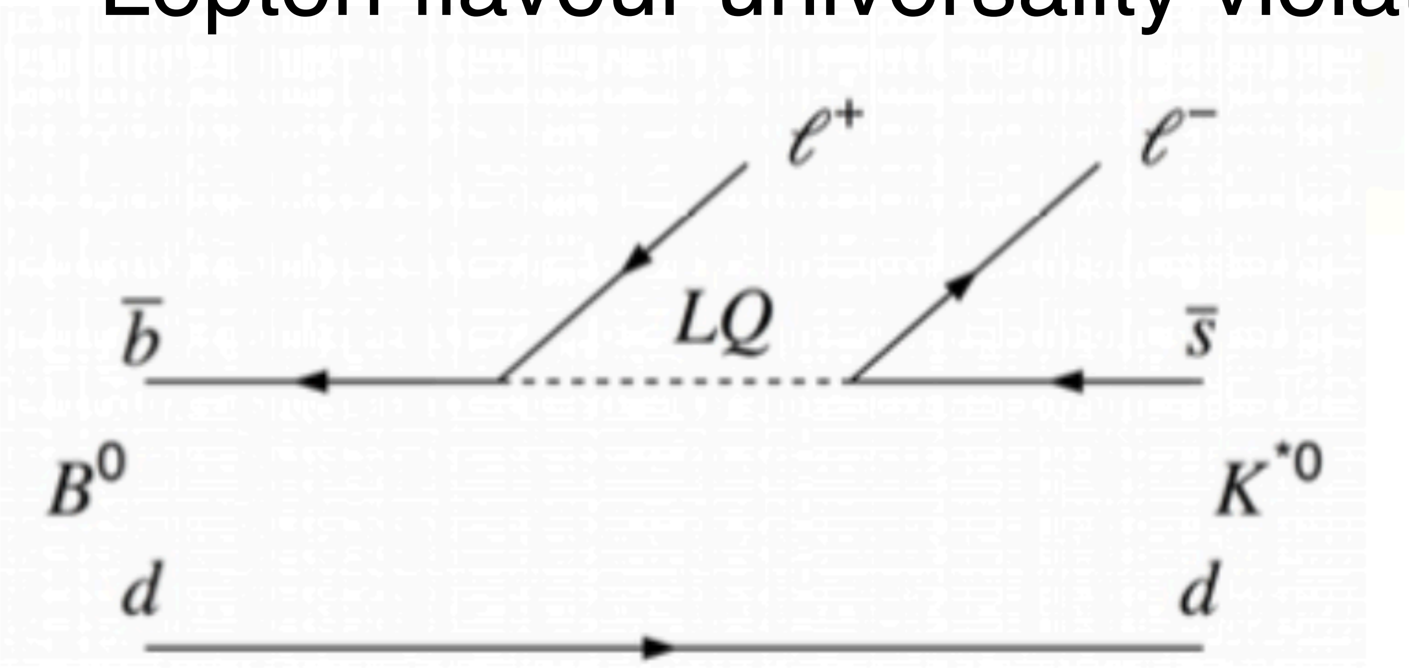
INFN
Istituto Nazionale di Fisica Nucleare

Search for new physics

Quest for New Physics

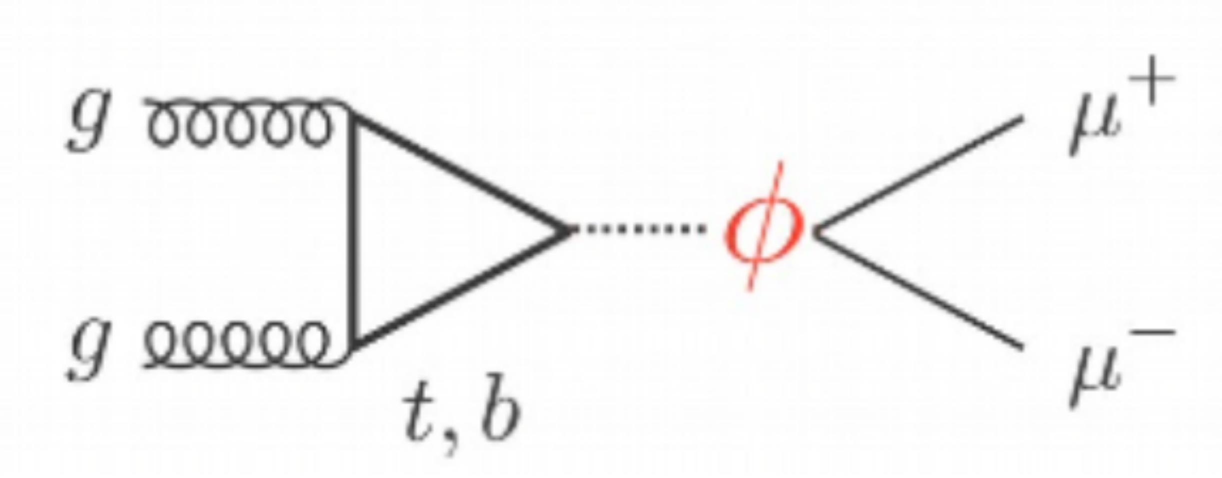
Indirect searches | **Direct searches**

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



Both approaches followed at LHCb

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



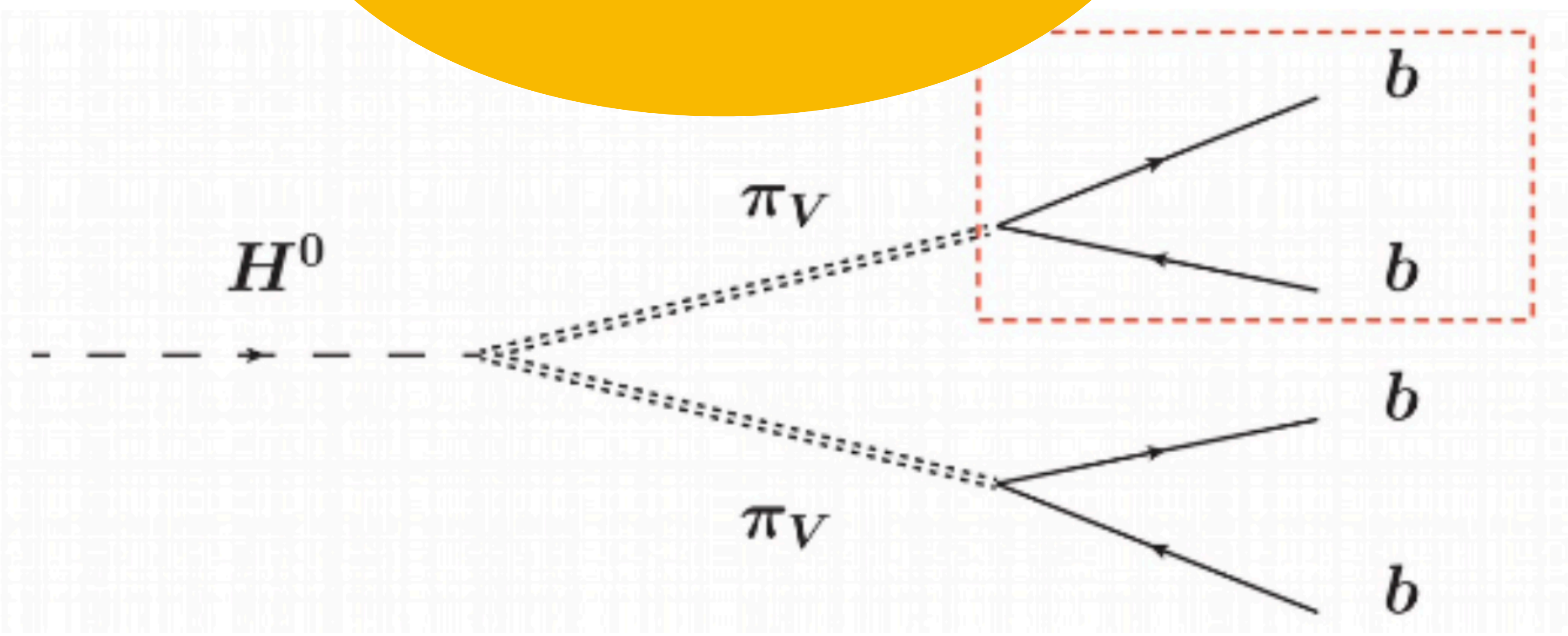
Direct searches: Exotic Higgs decays

Higgs decay to Long Lived Particles

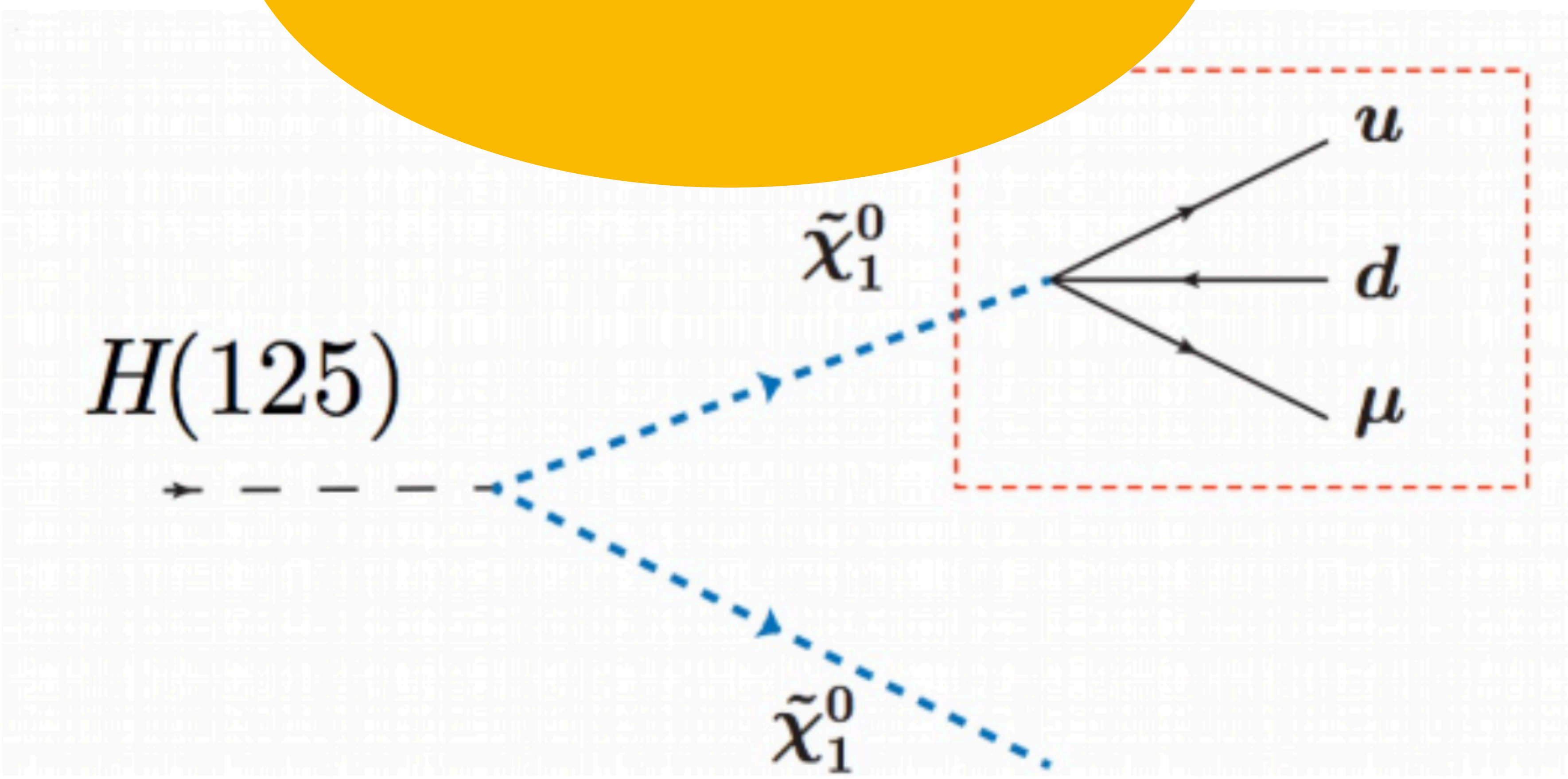
Search for particles with long life-time, coming from the decay of the SM Higgs

Exploit the LHCb vertex reconstruction

Hidden valley pions



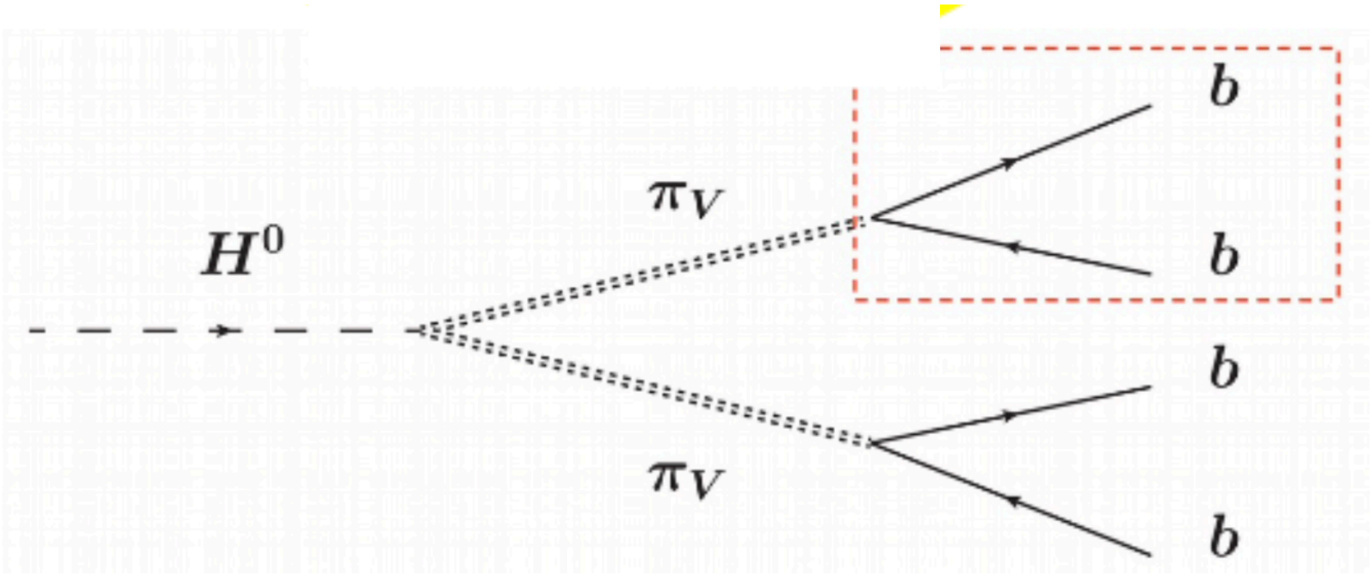
R-parity violating neutralinos (mSUGRA)

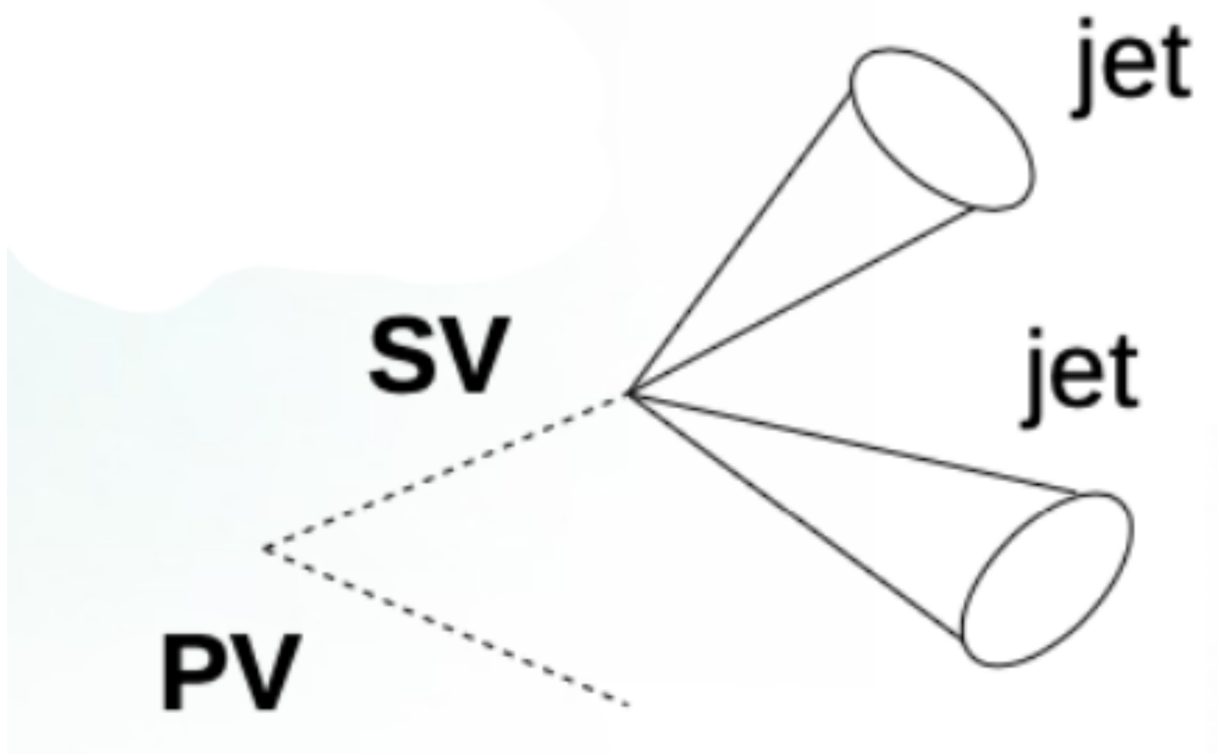


At LHCb we have mainly considered two benchmark models for LLP
But results are available for re-interpretation

LLP decaying to jets

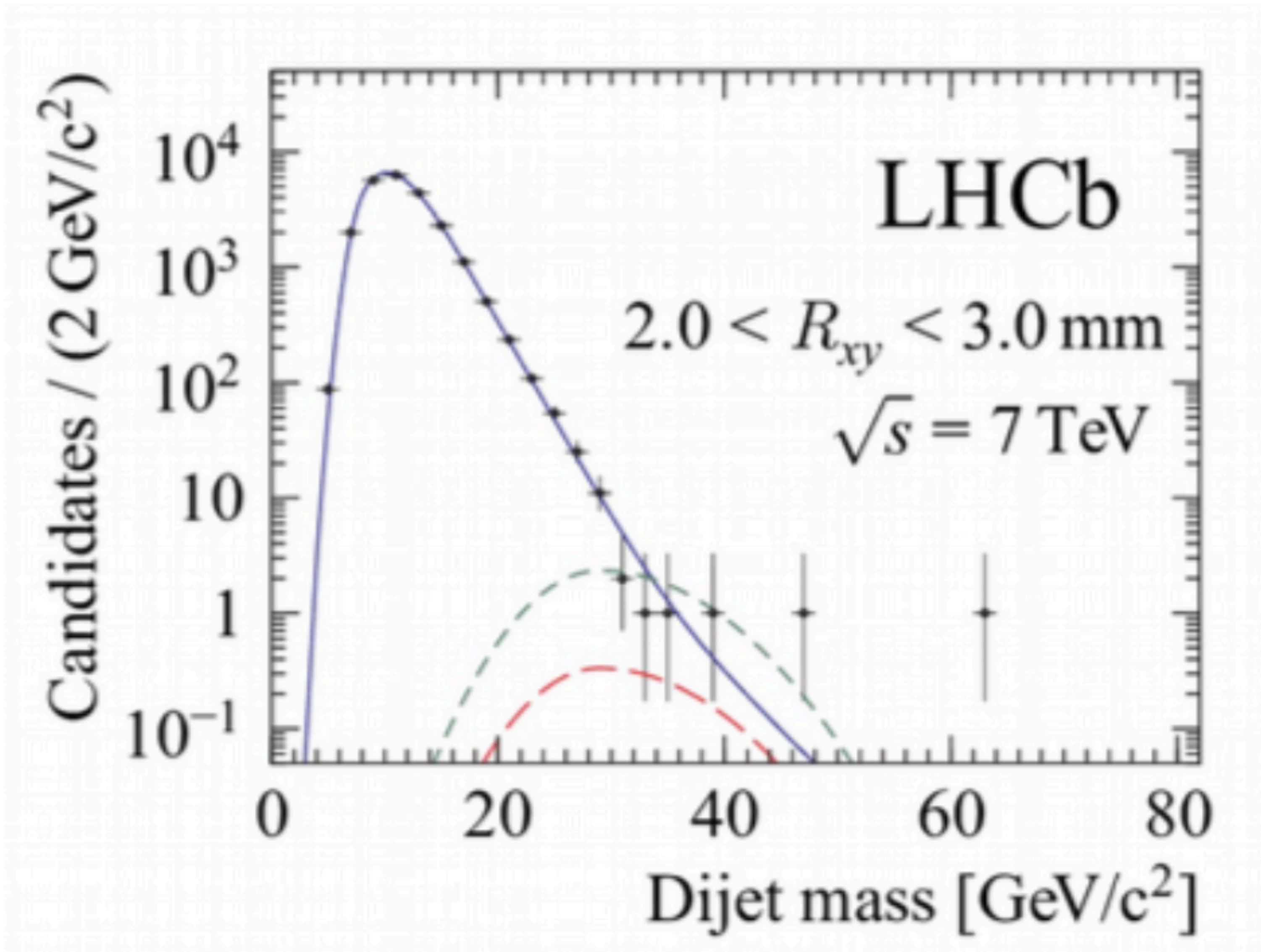
Eur. Phys. J. C77 (2017) 812





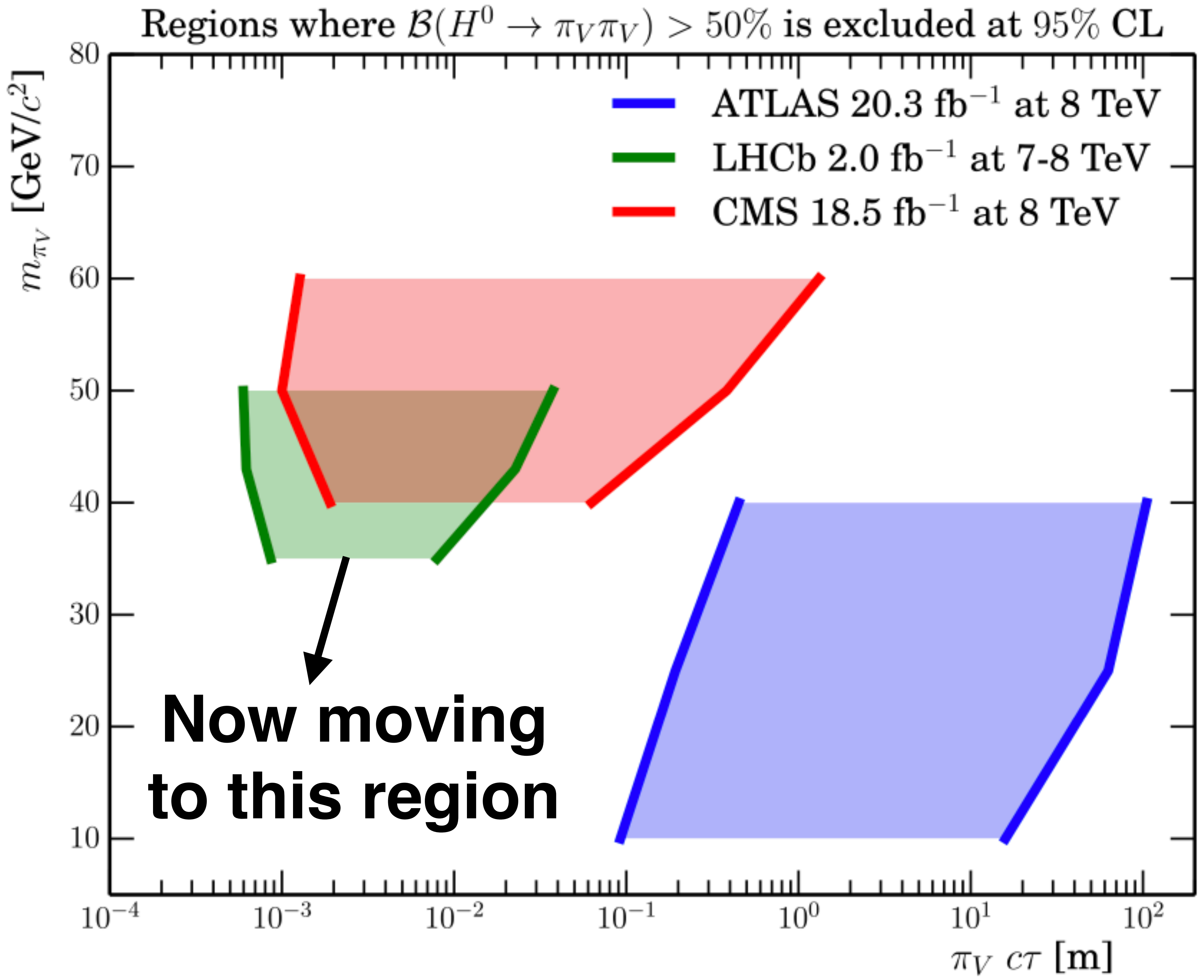
Signature: **two b-jets associated to a displaced SV**

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



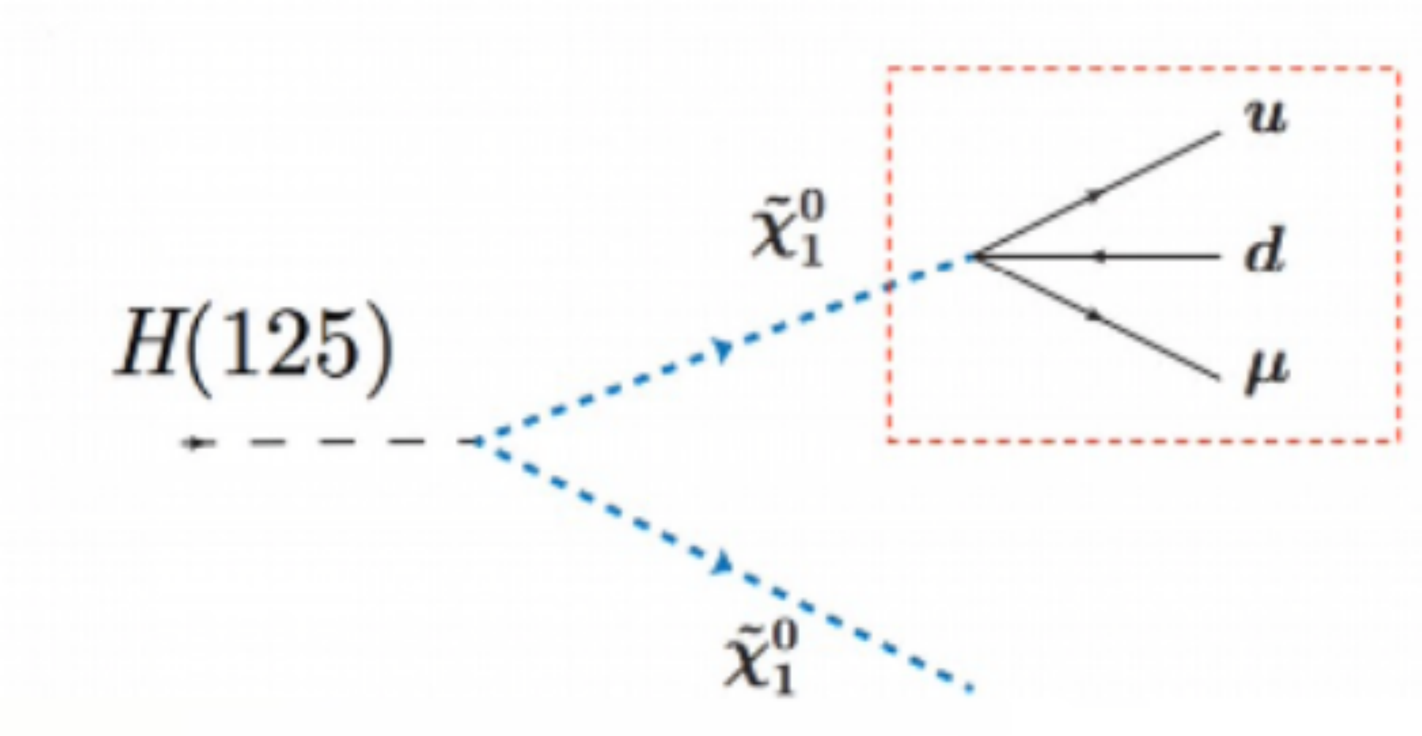
Upper limit to

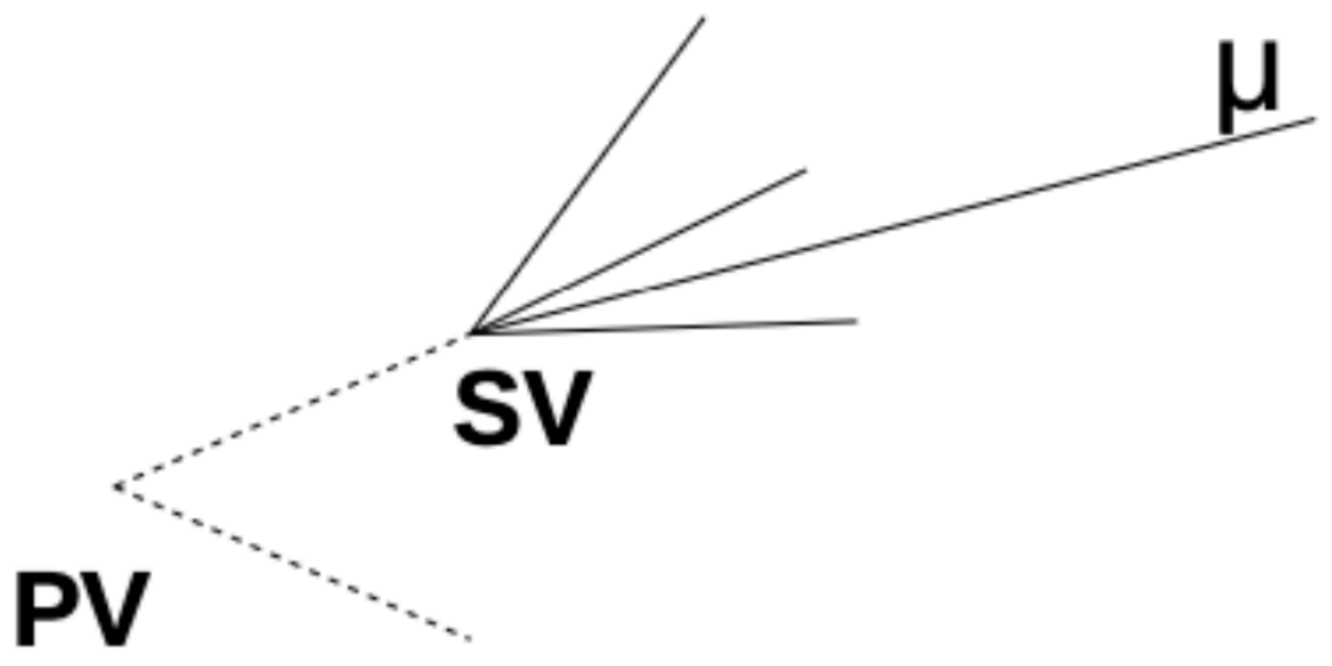
$$\frac{\sigma(gg \to H)}{\sigma_{SM}(gg \to H)} \cdot BR(H \to \pi_v \pi_v)$$



ATLAS and CMS limits not up-to-date

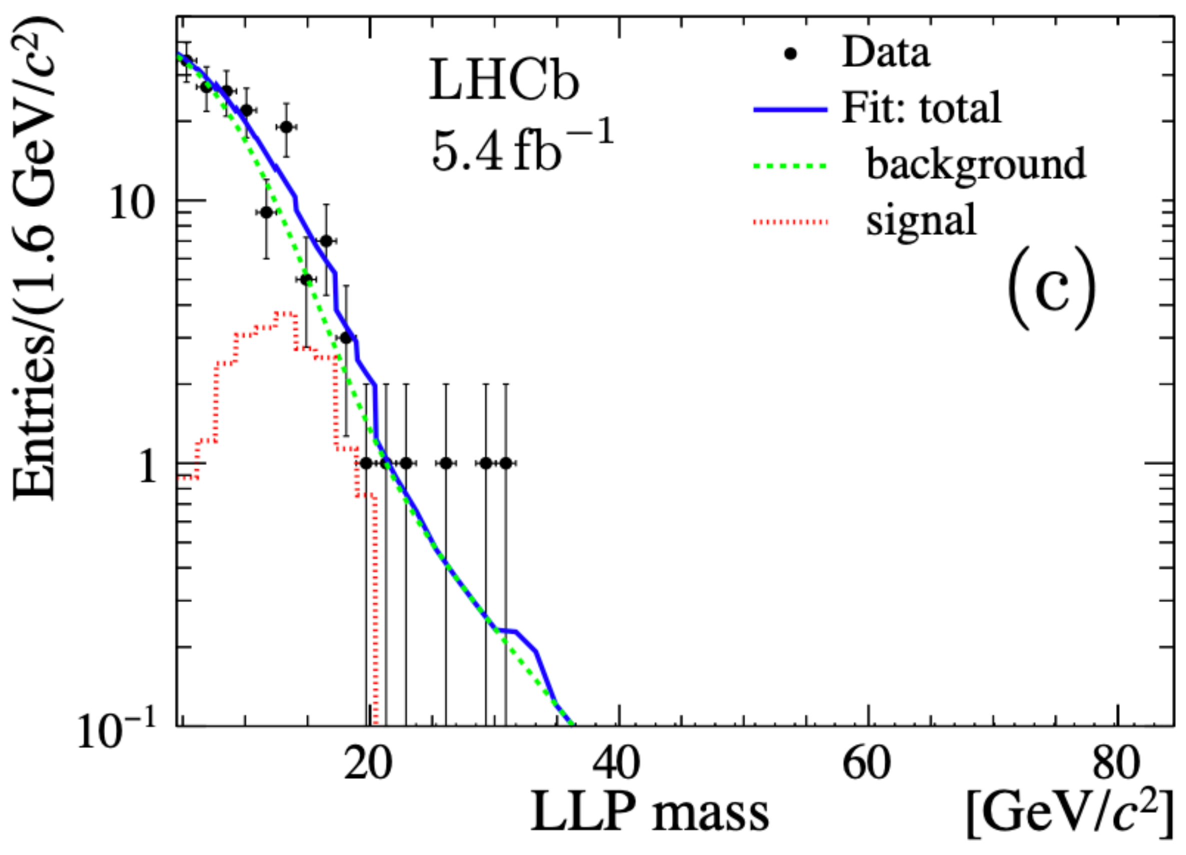
LLP decaying semileptonically





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

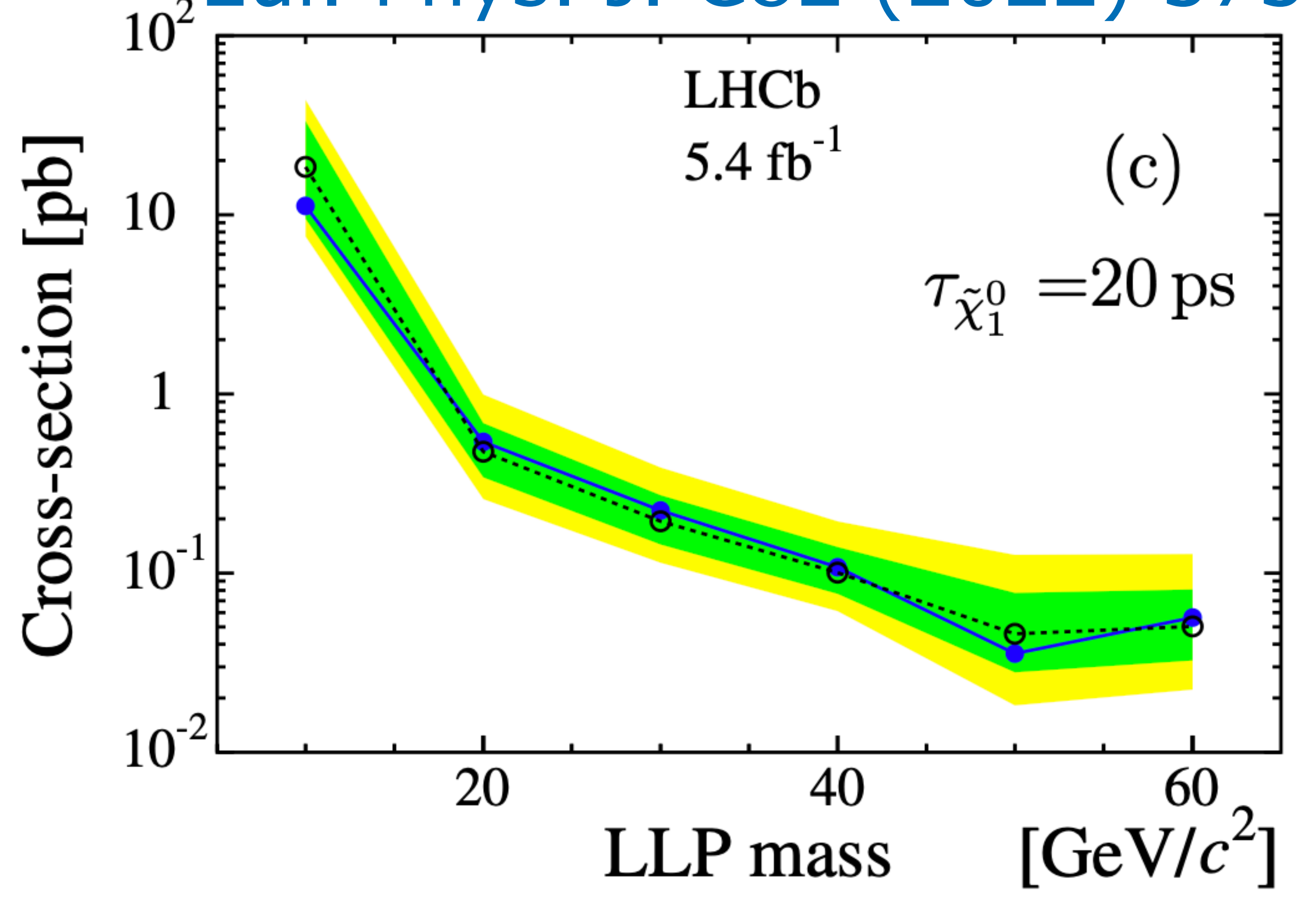
Fit to the neutralino mass
Background from bb events

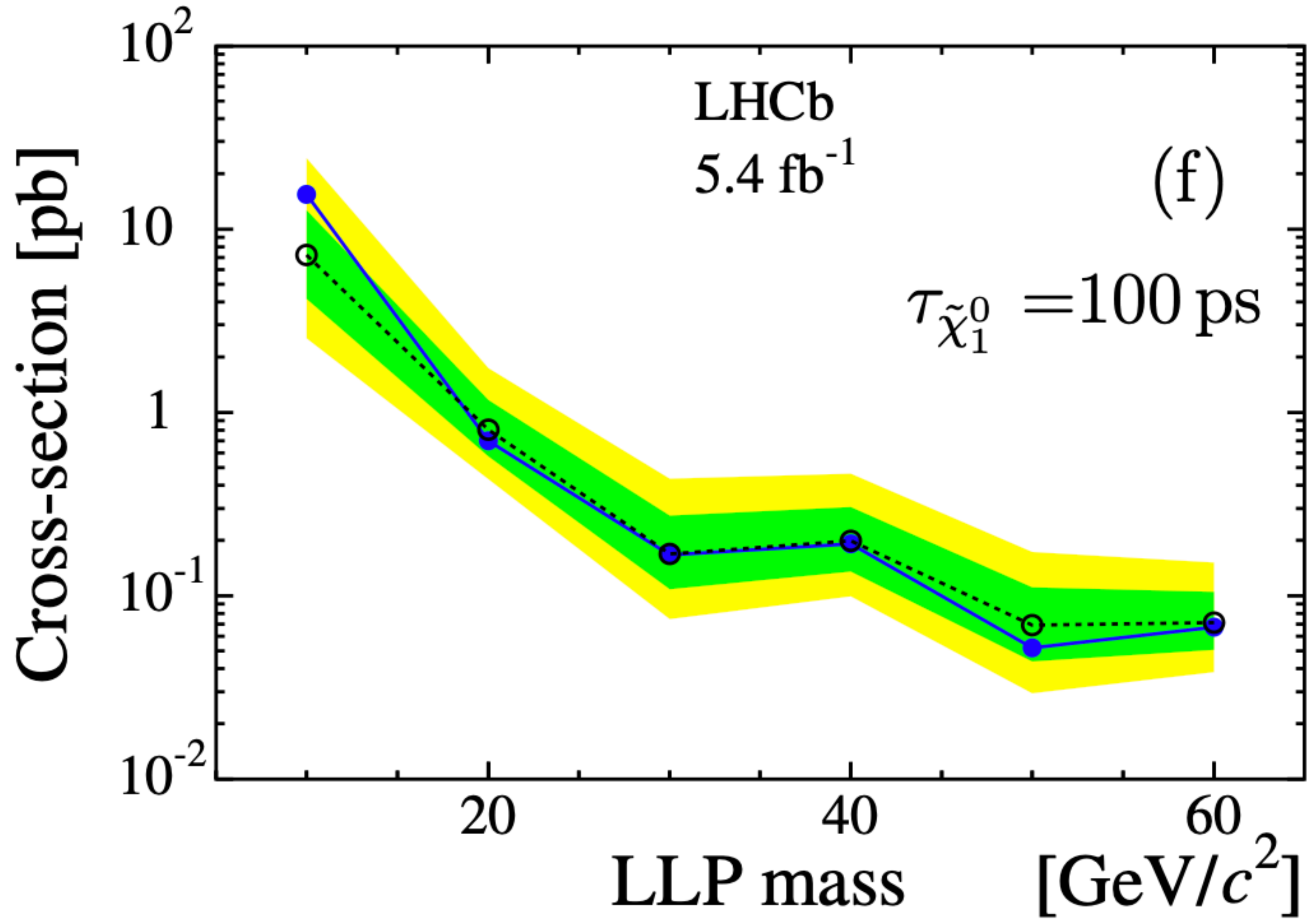


Tested lifetimes from 20 ps to 200 ps

Mass from 5 to 60 GeV

Eur. Phys. J. C82 (2022) 373



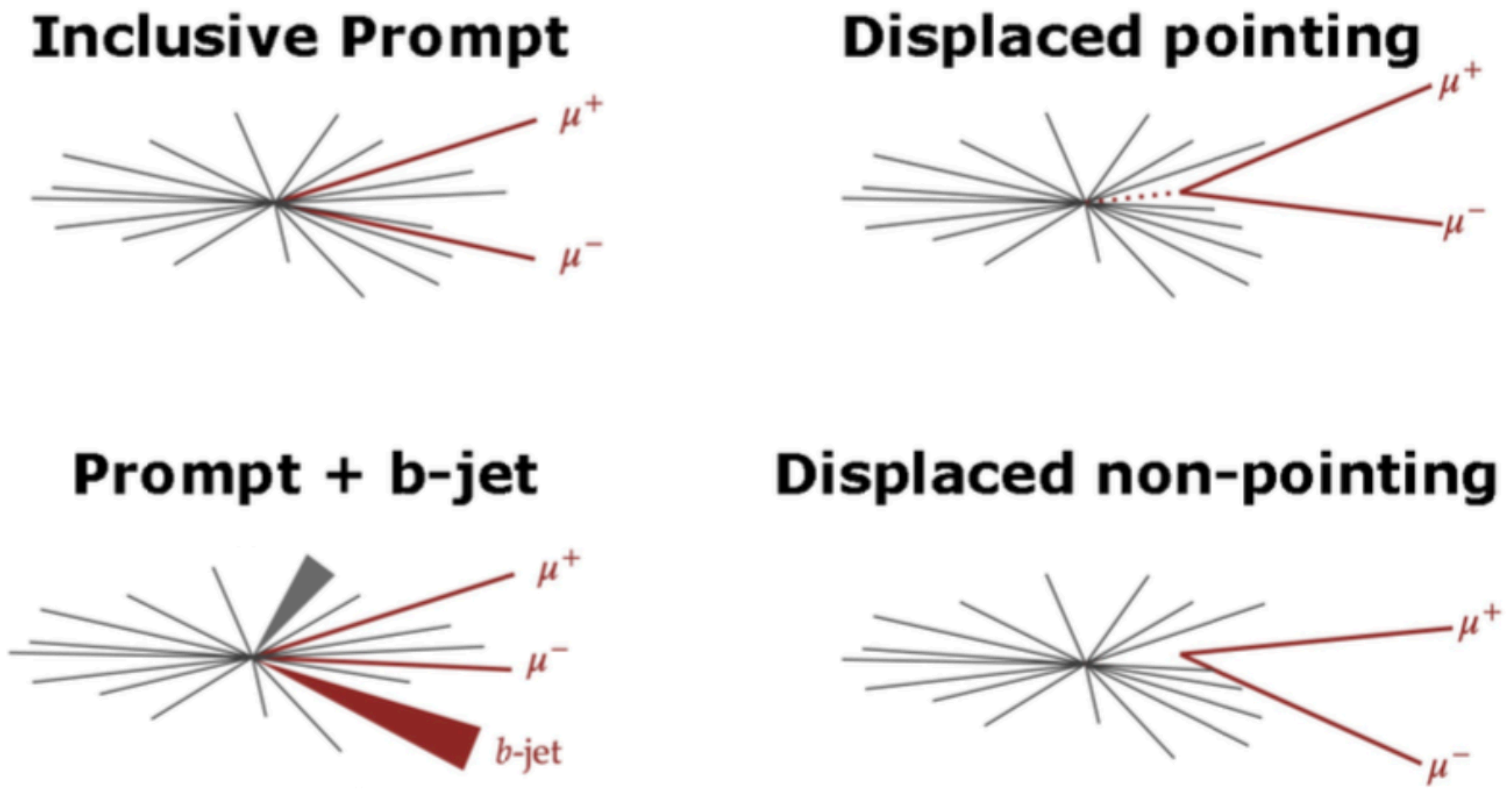


95% CL upper limits

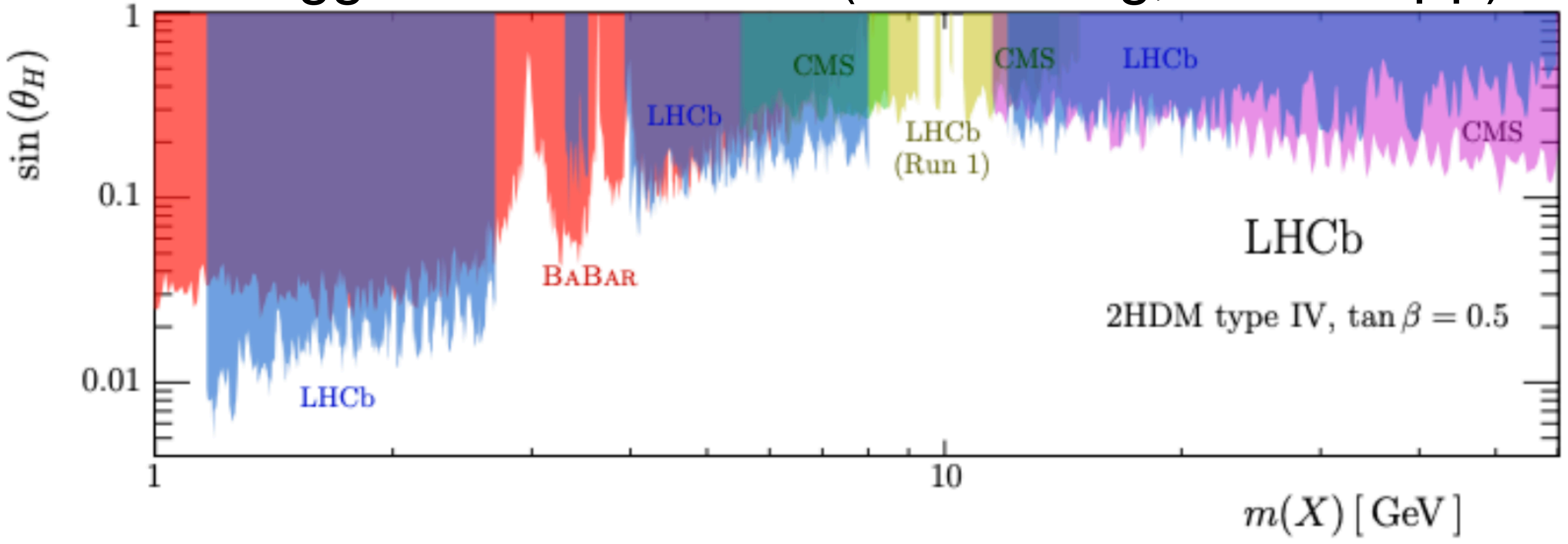
Light Higgs bosons

Higgs to dimuons

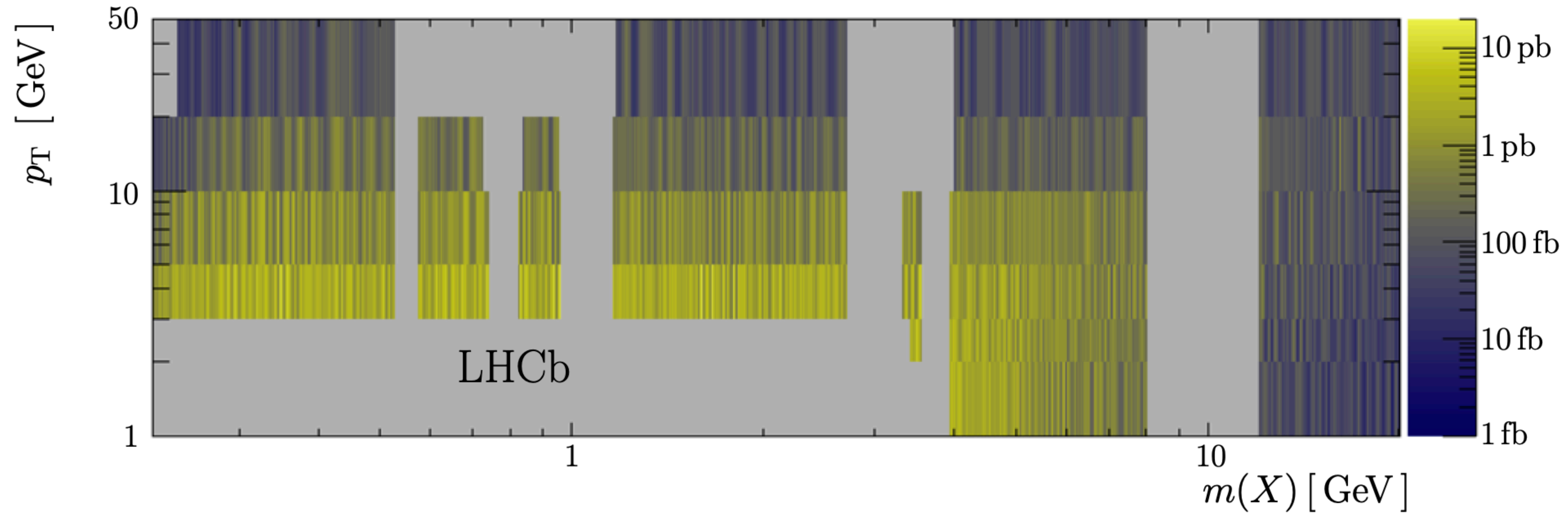
JHEP 10 (2020) 156

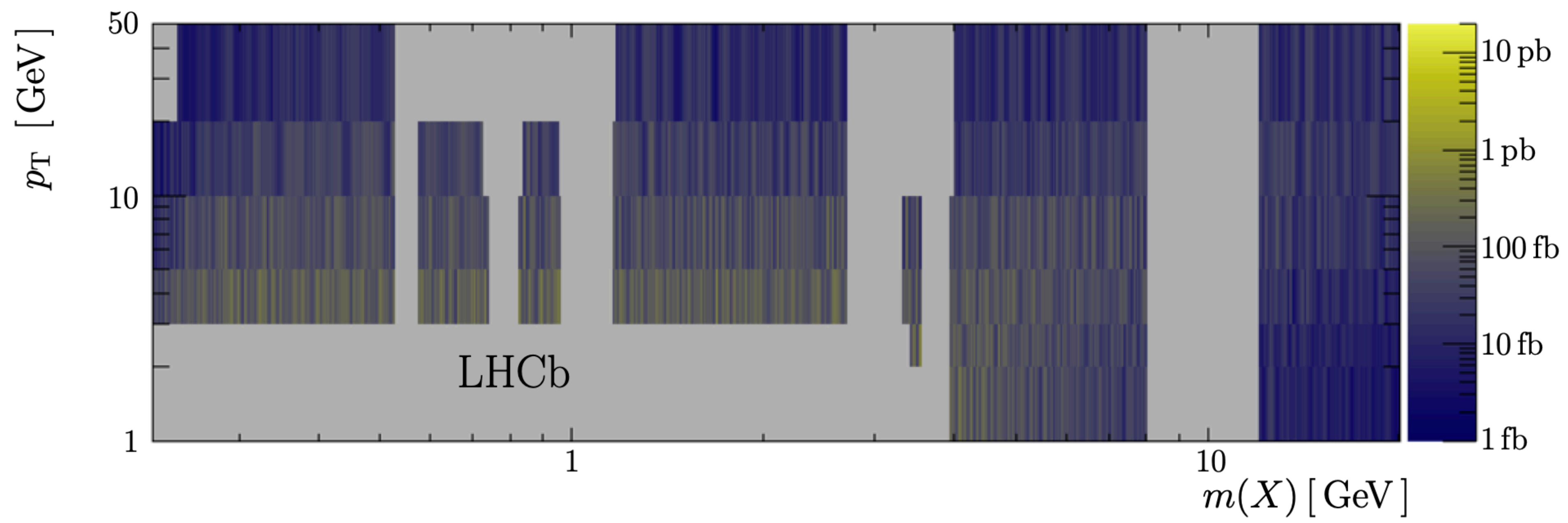


2 Higgs Doublet Model (H-X mixing, with X→μμ)



Inclusive prompt 90% CL upper limits

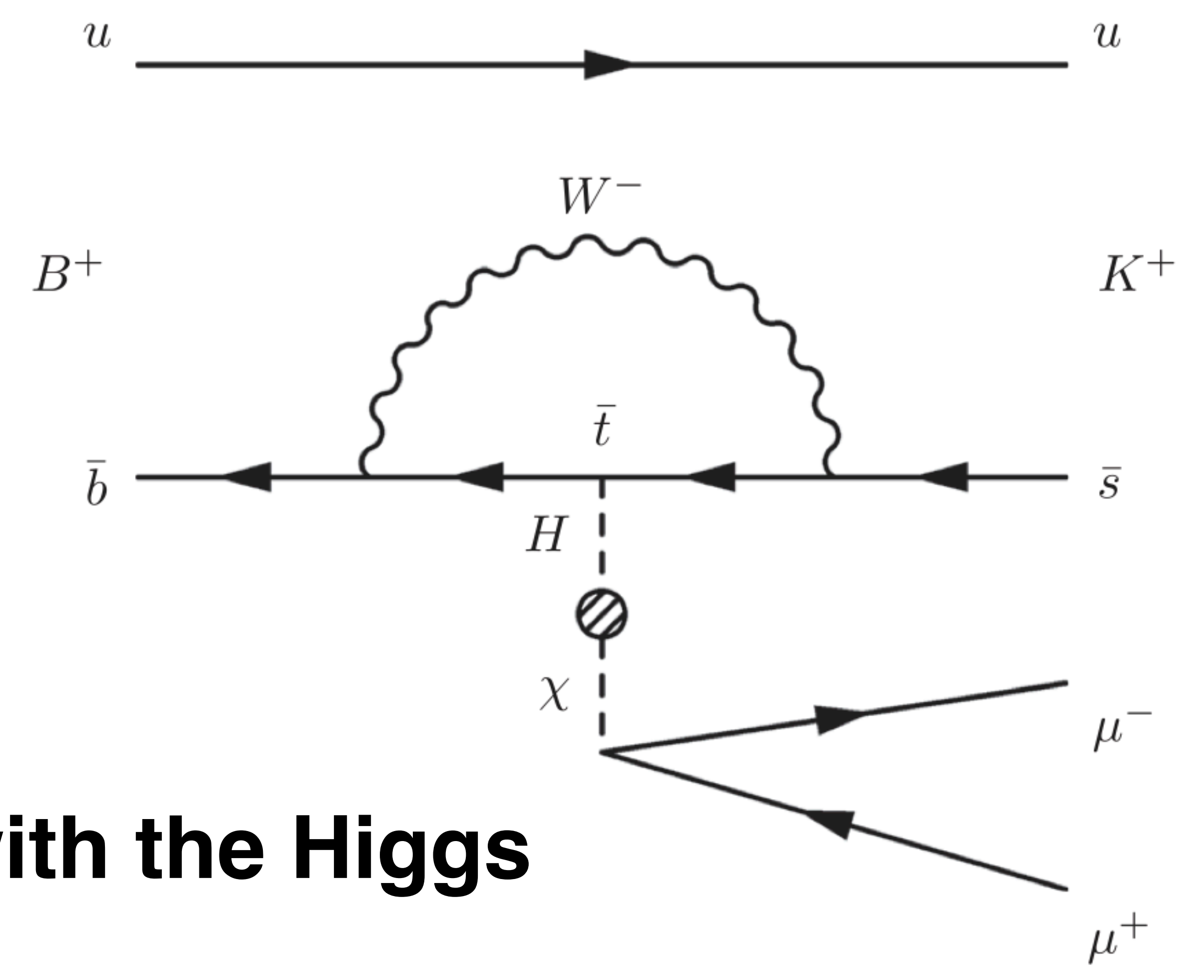




Prompt + b-jet 90% CL upper limits

Searches with B decays

Hidden sector bosons

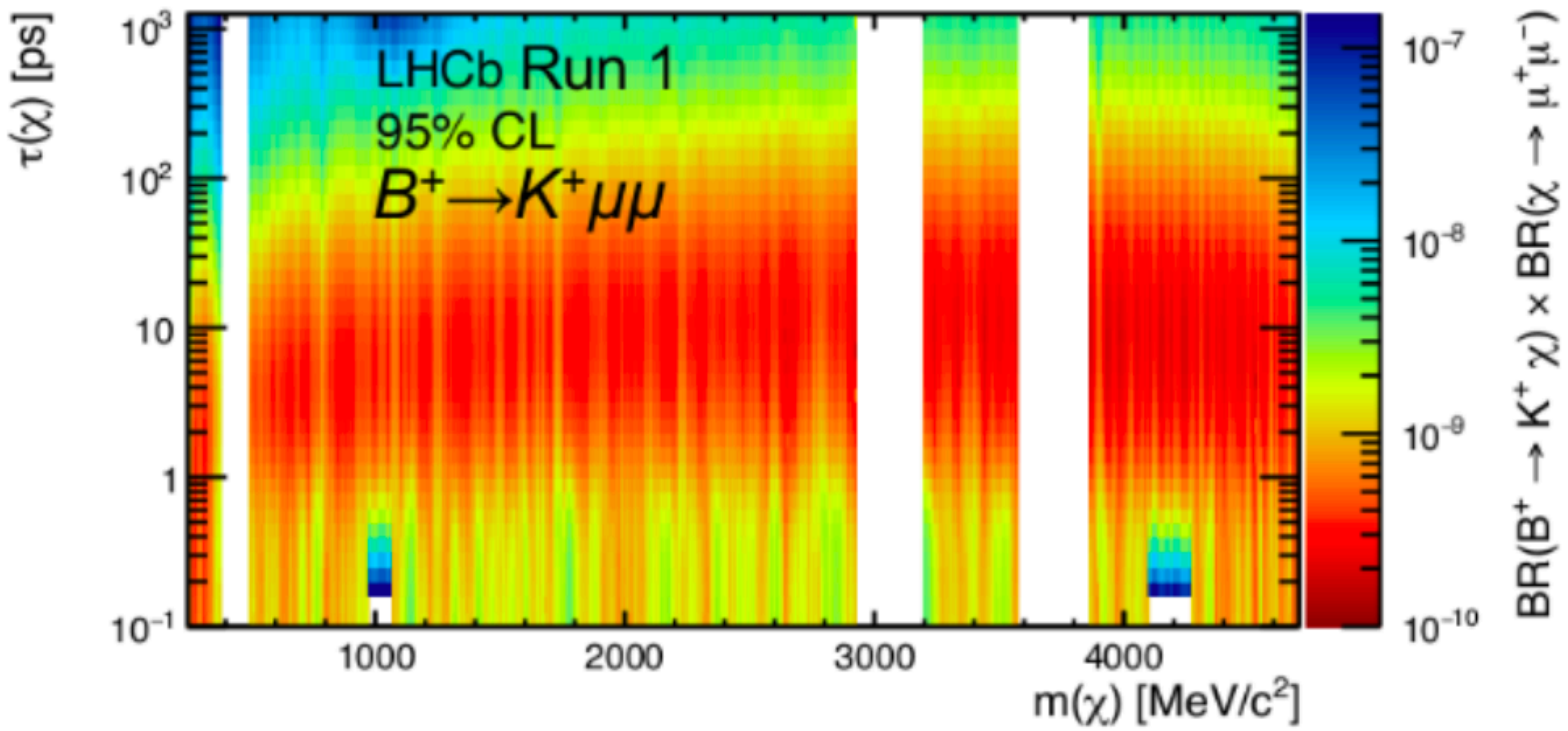


Mixing with the Higgs

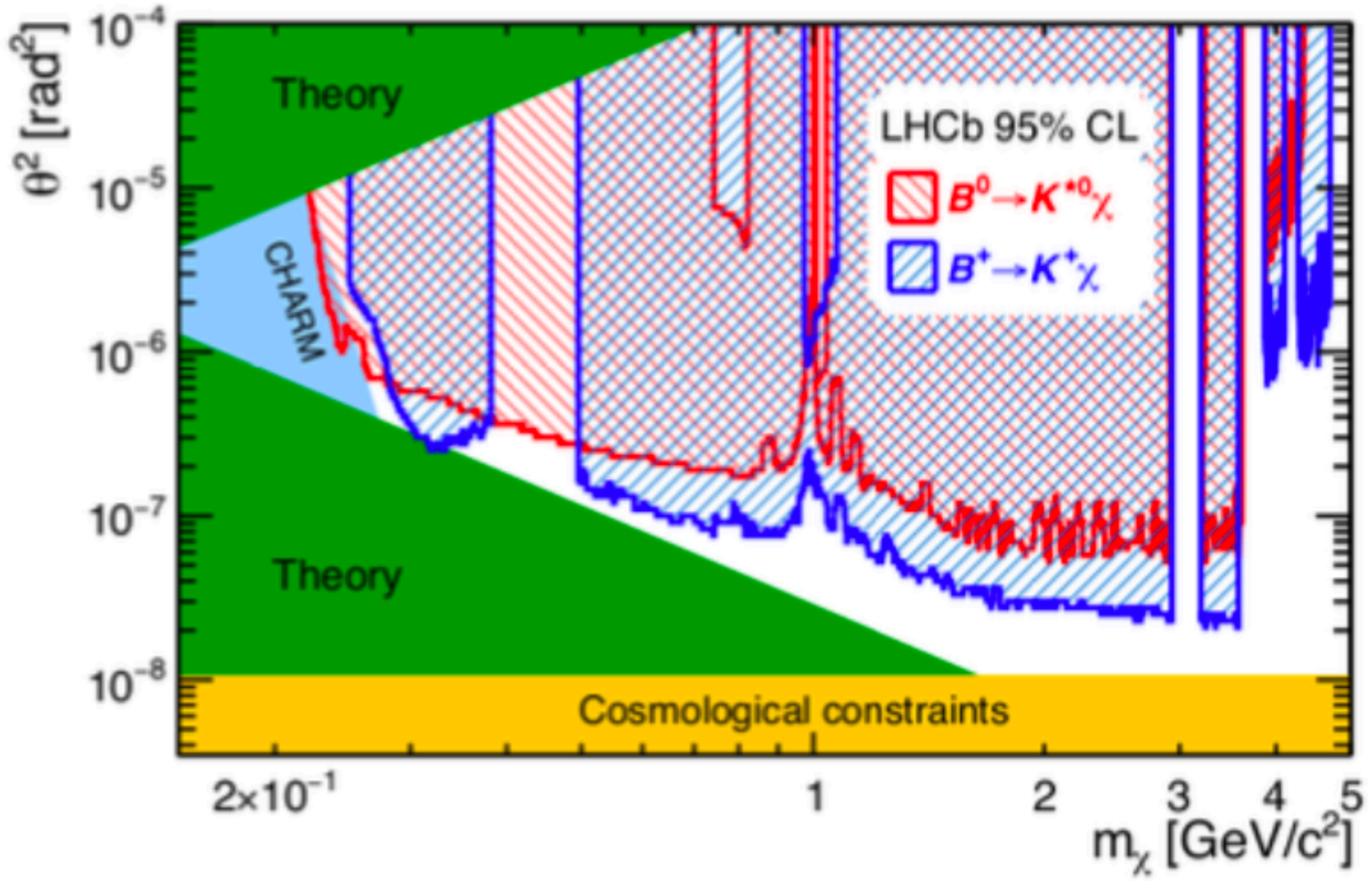
$$B^+ \to K^+\chi(\mu^+\mu^-)$$

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

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



Inflaton model



Conclusions

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

Thanks for your attention!

Backup

Open questions

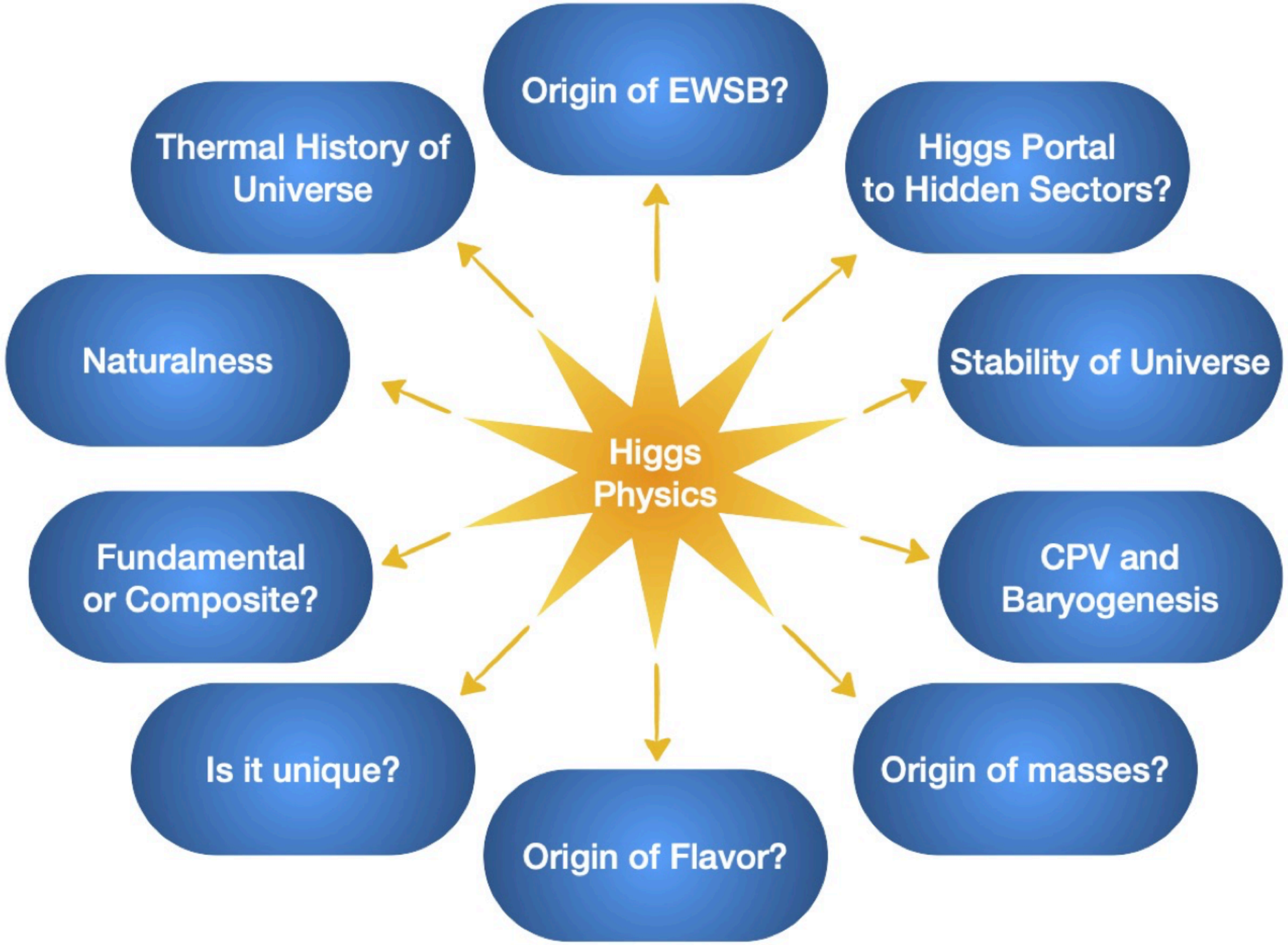
- The **Higgs field gives mass to the particles**, therefore **Higgs Physics is connected to most of open questions in fundamental Physics**

- We have the experimental proof that **neutrinos have mass: how the Higgs field can generate it? The Standard Model cannot predict it!**

- We have the experimental proof that **Dark Matter (or some unexpected gravitational effect…) exists**: **the Standard Model cannot explain it!**

- **The Standard Model and the Quantum Field Theory cannot explain the gravitational mass of General Relativity: the Higgs field should have a role!**

Snowmass forum report on Muon Colliders: https://doi.org/10.48550/arXiv.2209.01318



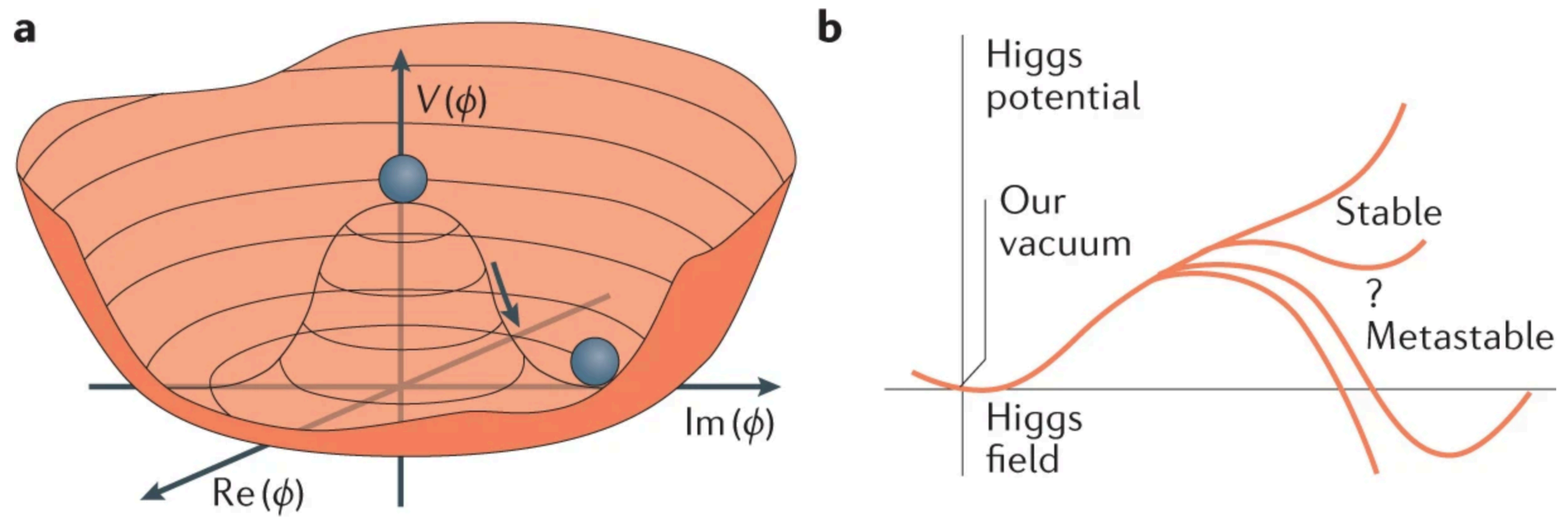
Higgs field

- The Higgs boson has been discovered, but **the Higgs field, responsible of the Electroweak Symmetry Breaking and the generation of particle masses, is not measured yet!**

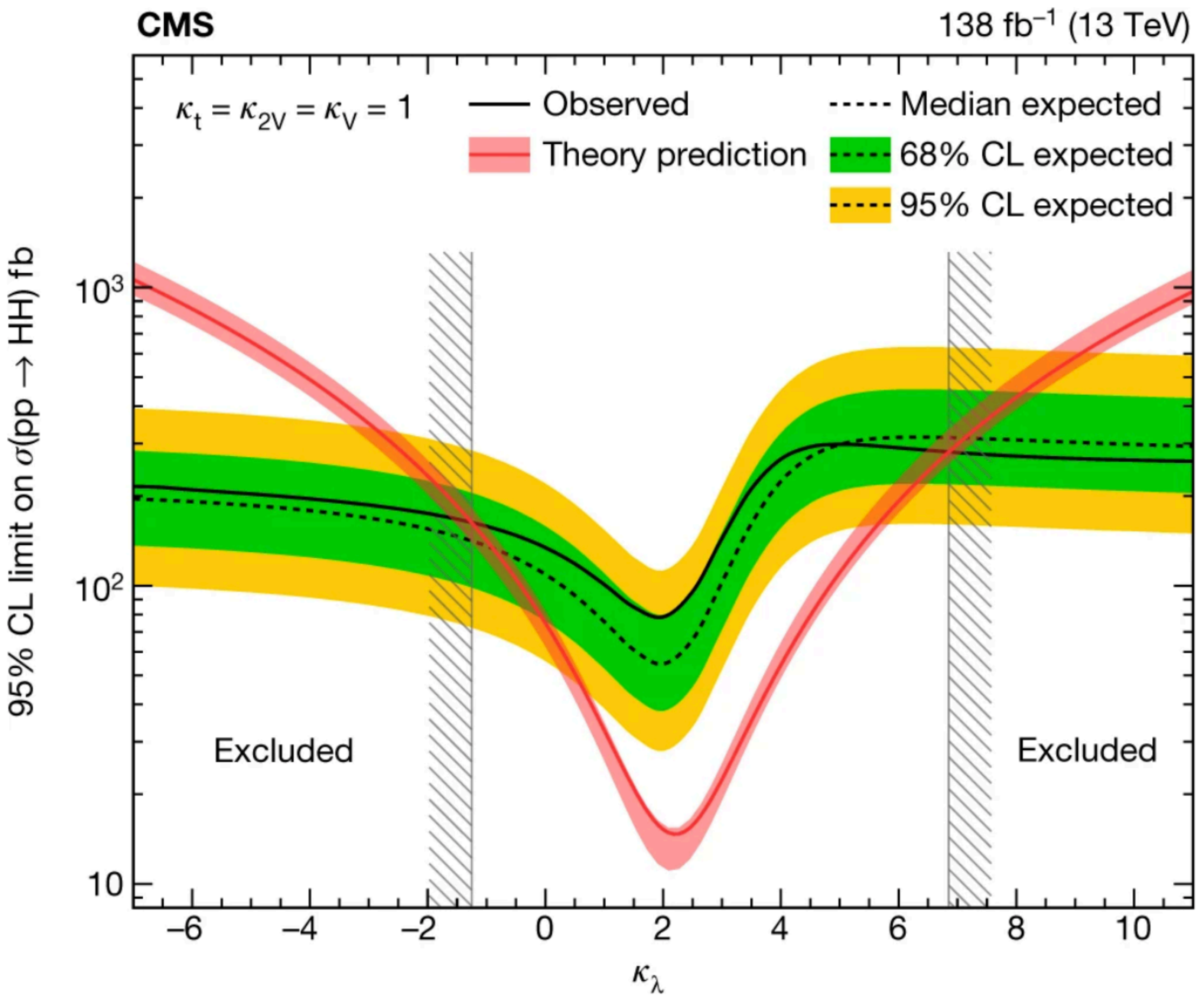
- It can be determined by measuring **the production of HH and HHH events**

$$V(\phi) = \frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4$$

Nature Reviews Physics volume 3, pages 608–624 (2021)



Nature volume 607, pages 60–68 (2022)



Limits on the trilinear coupling obtained by the CMS experiment ←

Higgs potential after symmetry breaking:

$$V(H) = \frac{1}{2}m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4}\lambda_4 H^4,$$

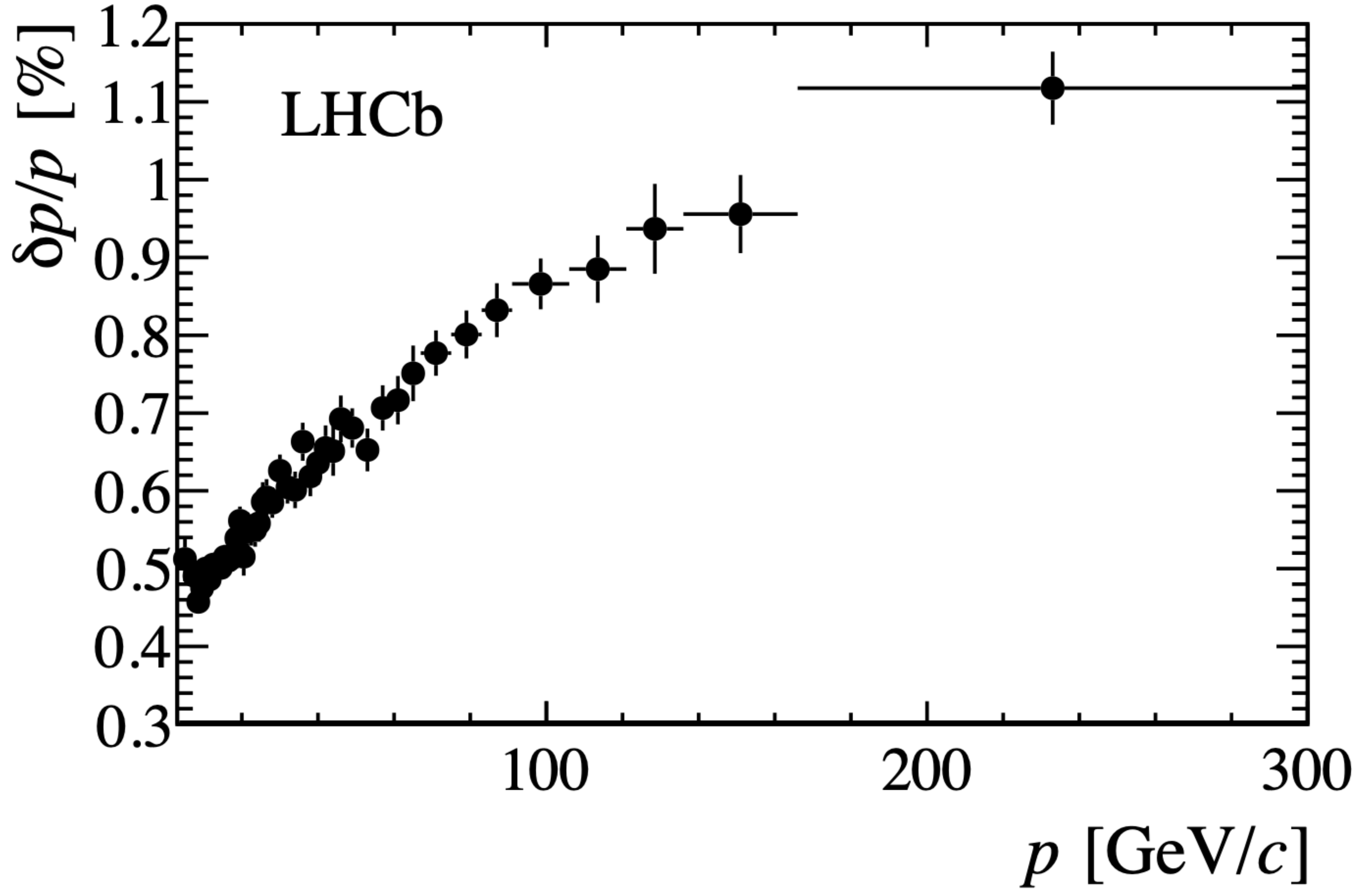
Standard Model self-couplings:

$$\lambda_3 = \lambda_4 = m_H^2/2v^2 \equiv \lambda_{SM}$$

It is not possible to measure all the terms of the Higgs field at the High Luminosity LHC: new accelerators are needed!

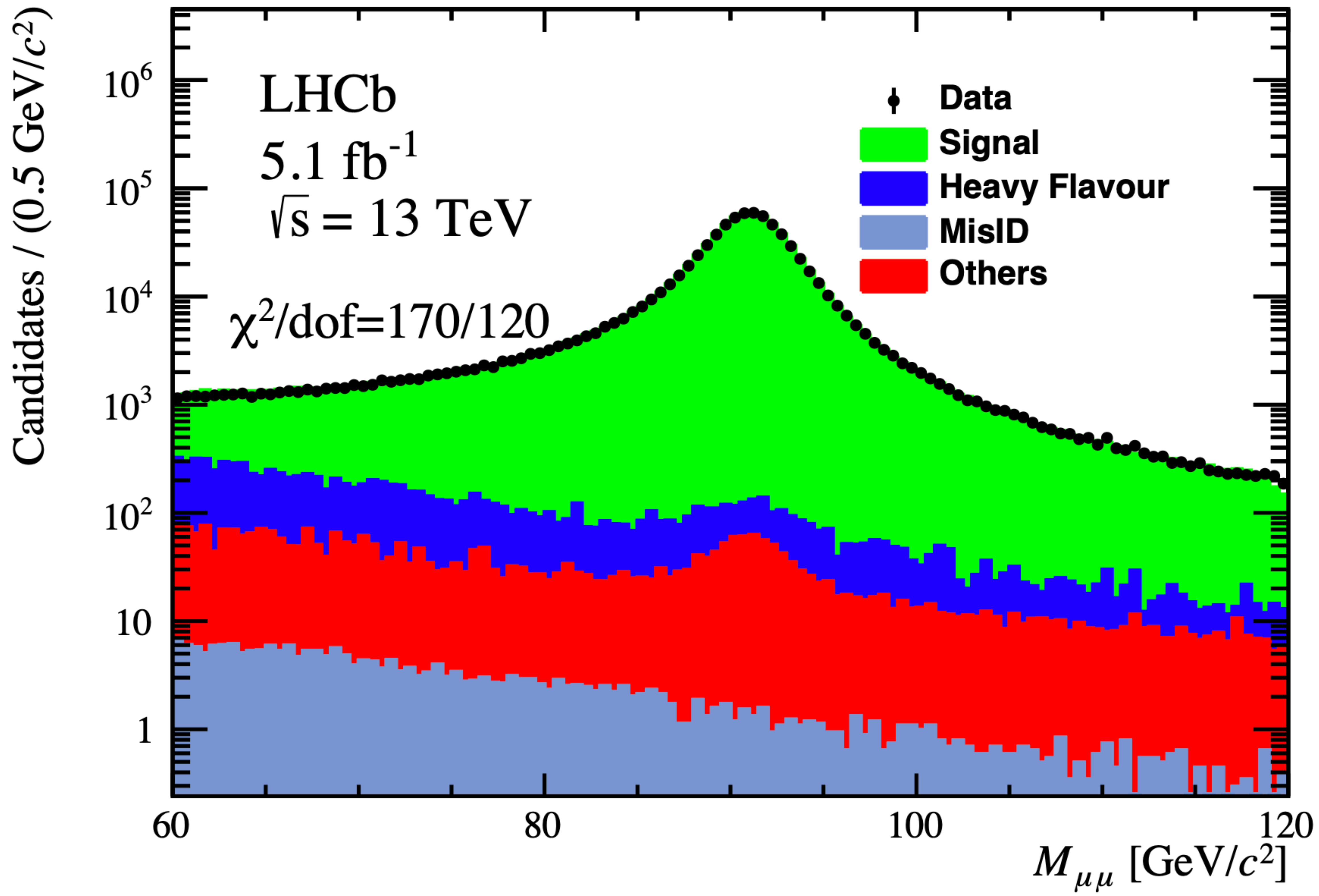
Muons at LHCb

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



Relative momentum resolution versus momentum for long tracks in data obtained using J/ψ→μμ decays

JHEP 07 (2022) 26

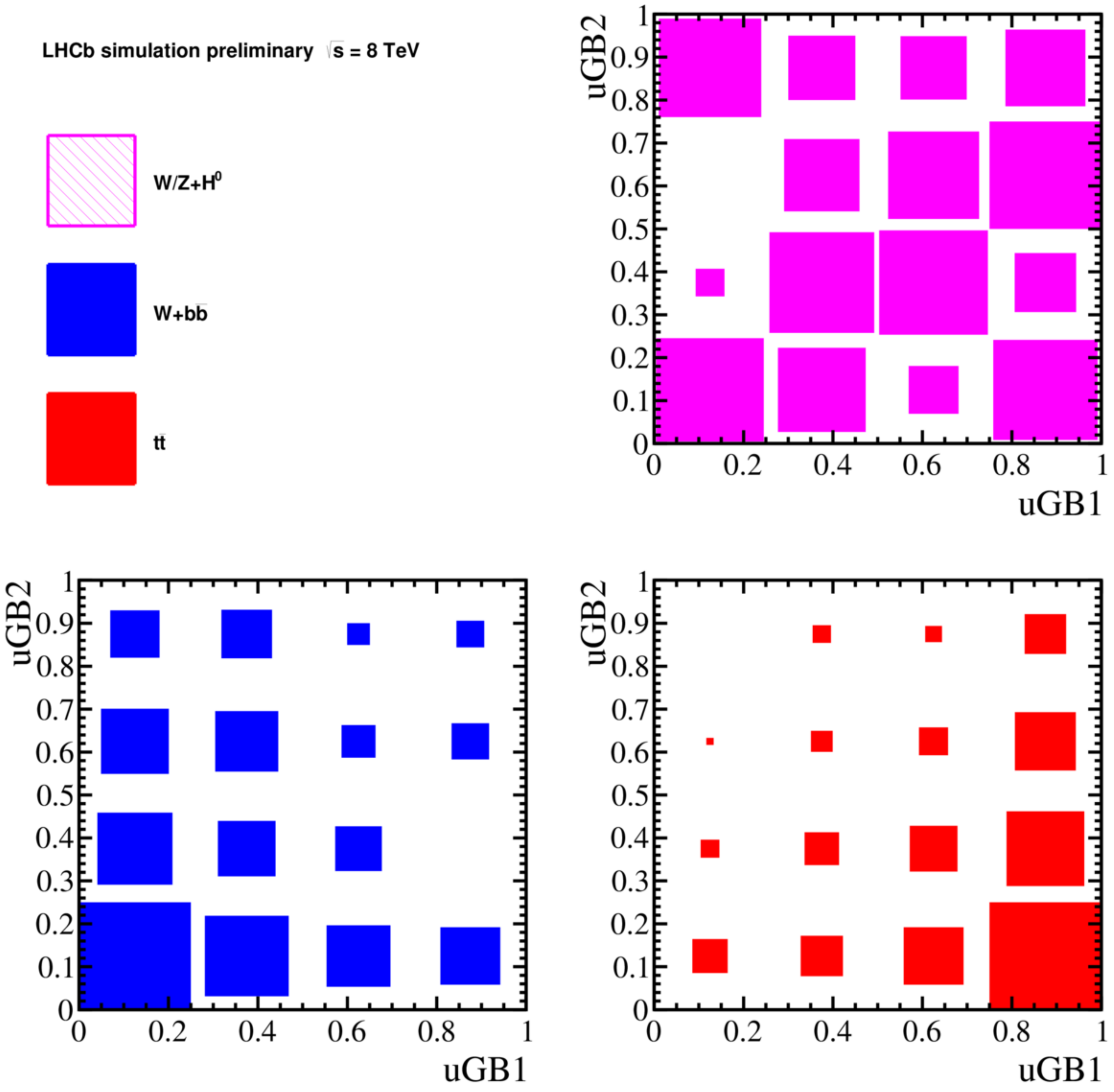


Z→μμ invariant mass peak

Excellent muon performance from low to high momentum

W/Z+H production

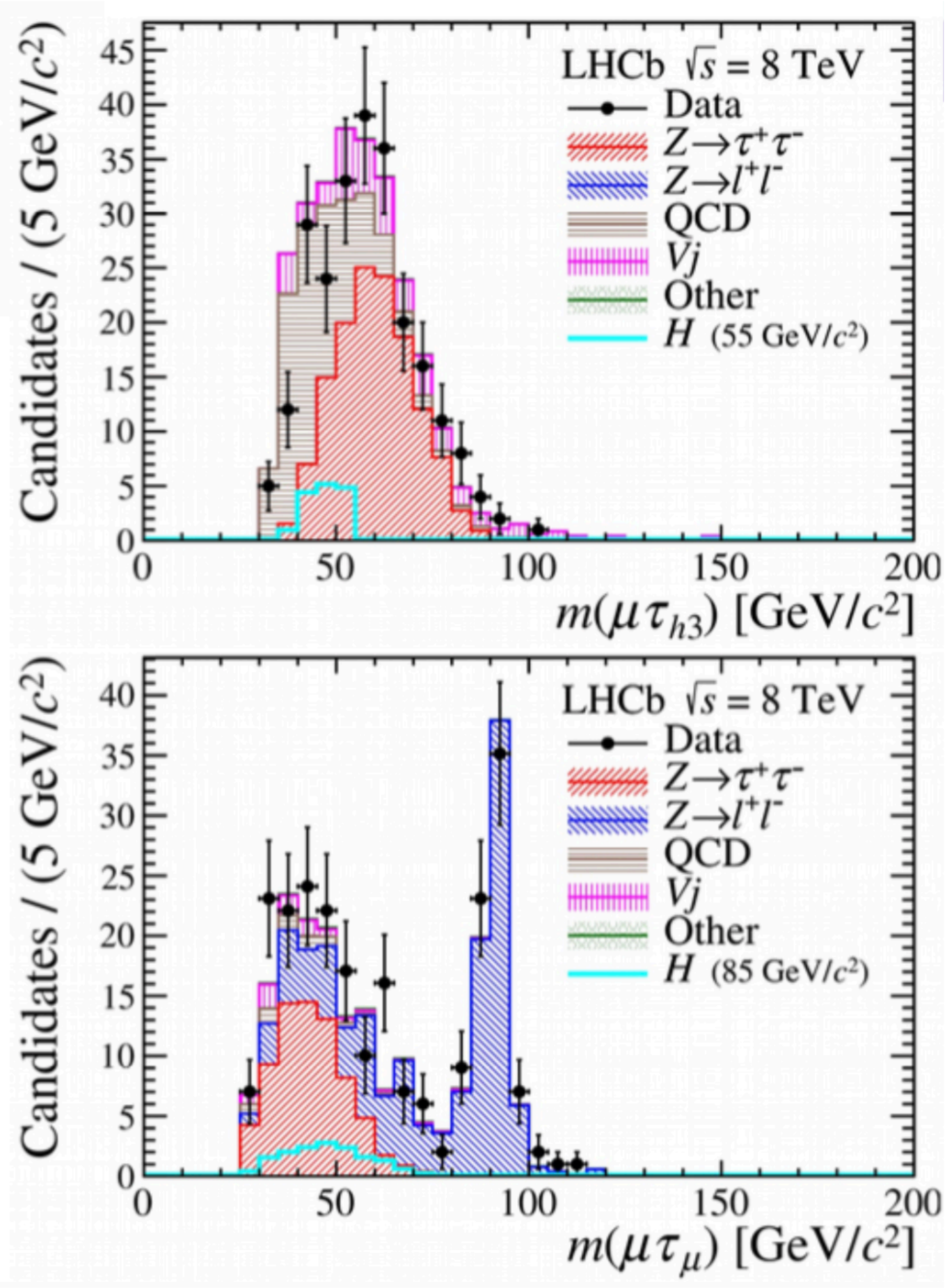
- The other backgrounds are **W+b$\bar{b}$/c$\bar{c}$ and top**
- A multivariate method (**uniform gradient boost, uGB**) has been used to separate the backgrounds from the signal
- Inputs are 12 kinematic variables of jets and leptons
- **Two uGBs are trained in order to be uncorrelated with the dijet 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

Lepton flavour violating Higgs decays

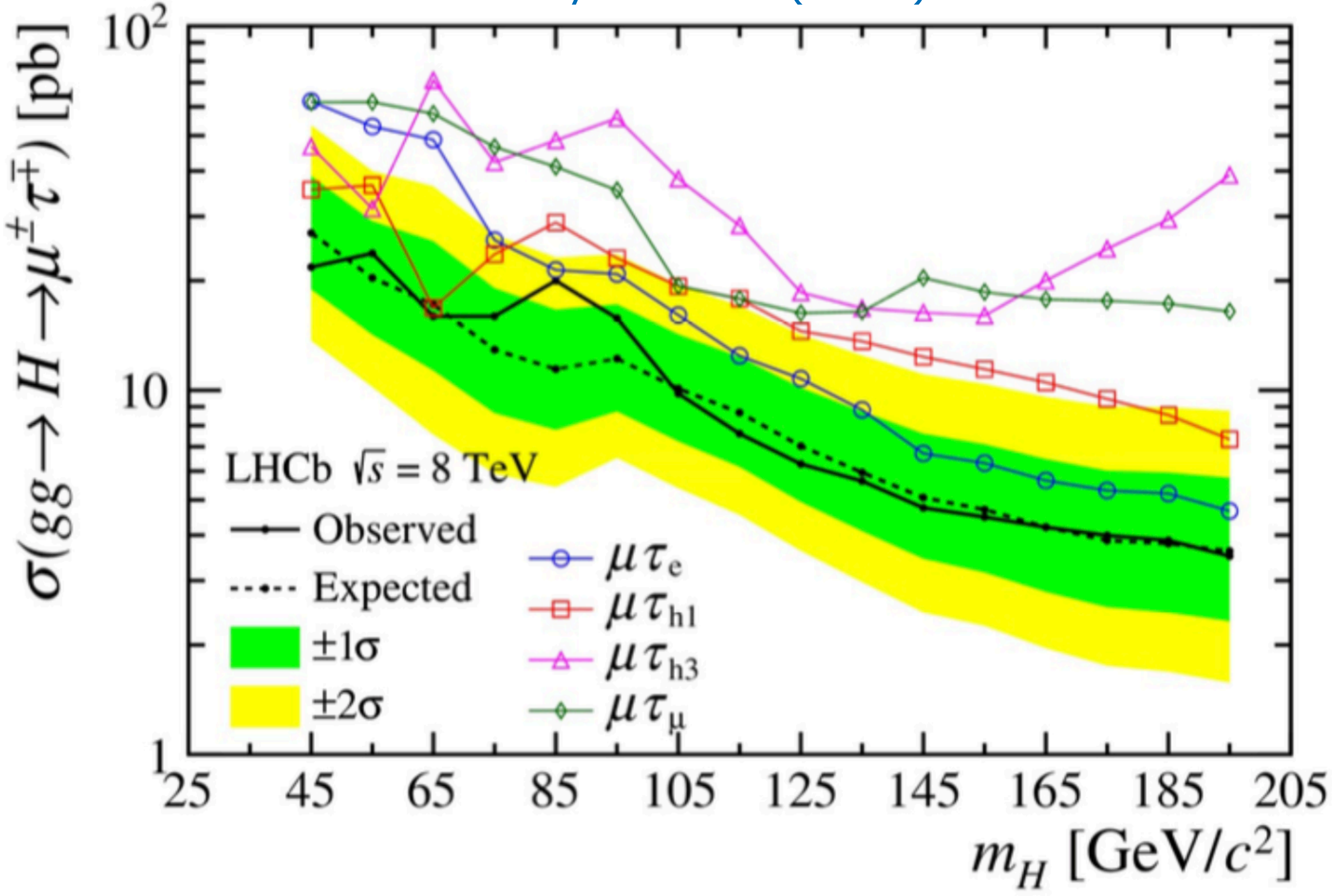
Search for H→μτ



Tau reconstructed in different channels:

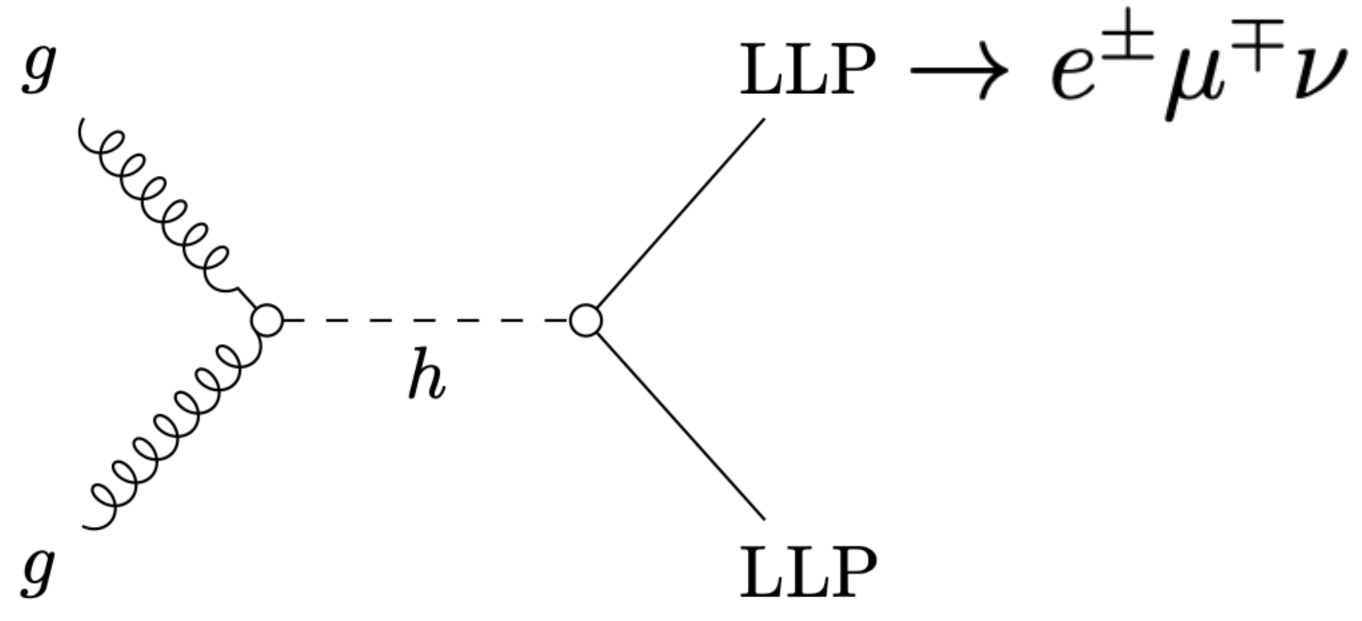
- muon
- electron
- hadron
- 3-hadron

Eur. Phys. J. C78 (2018) 1008



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

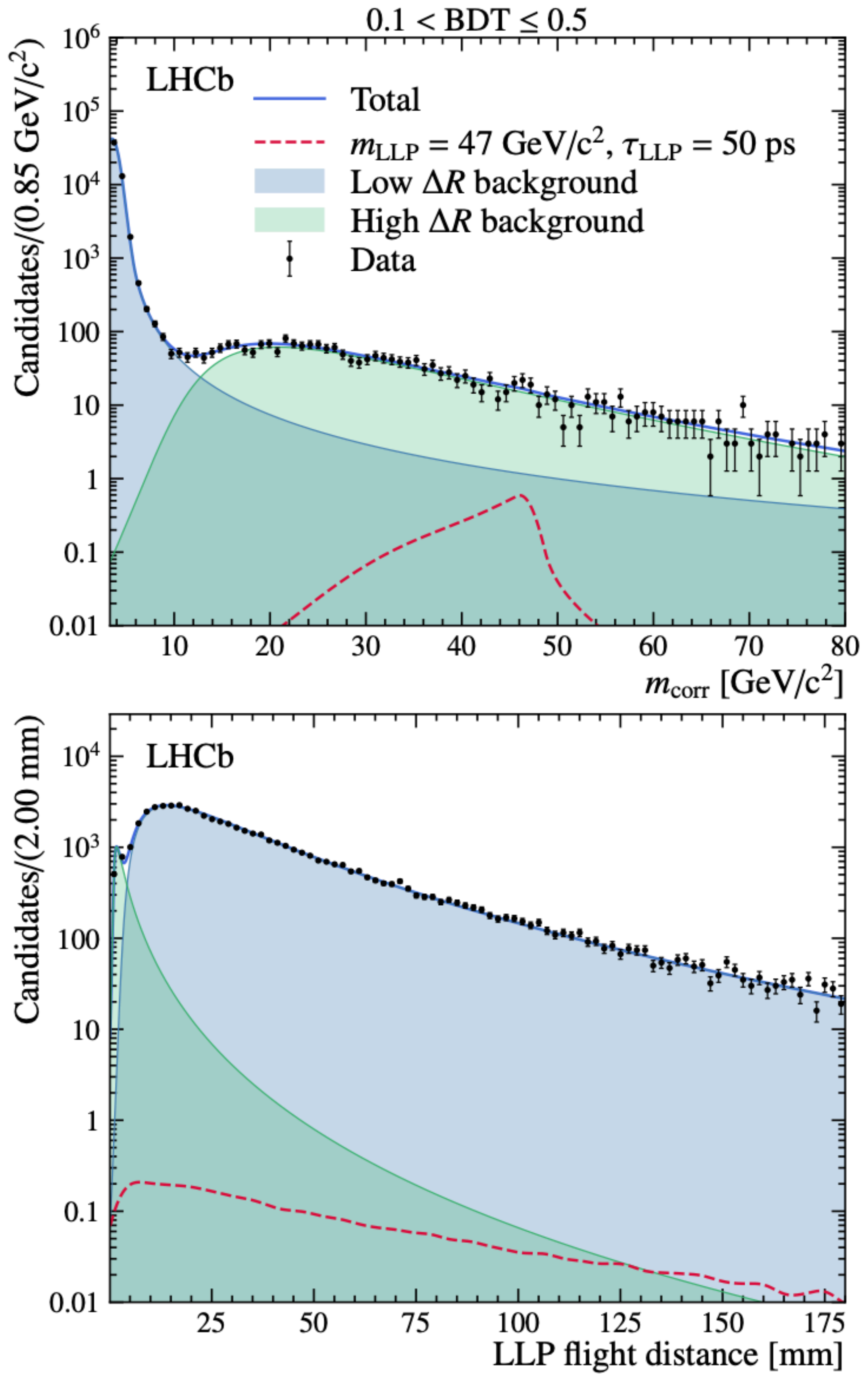
LLP decaying semileptonically



Lepton flavour violating LLP decay

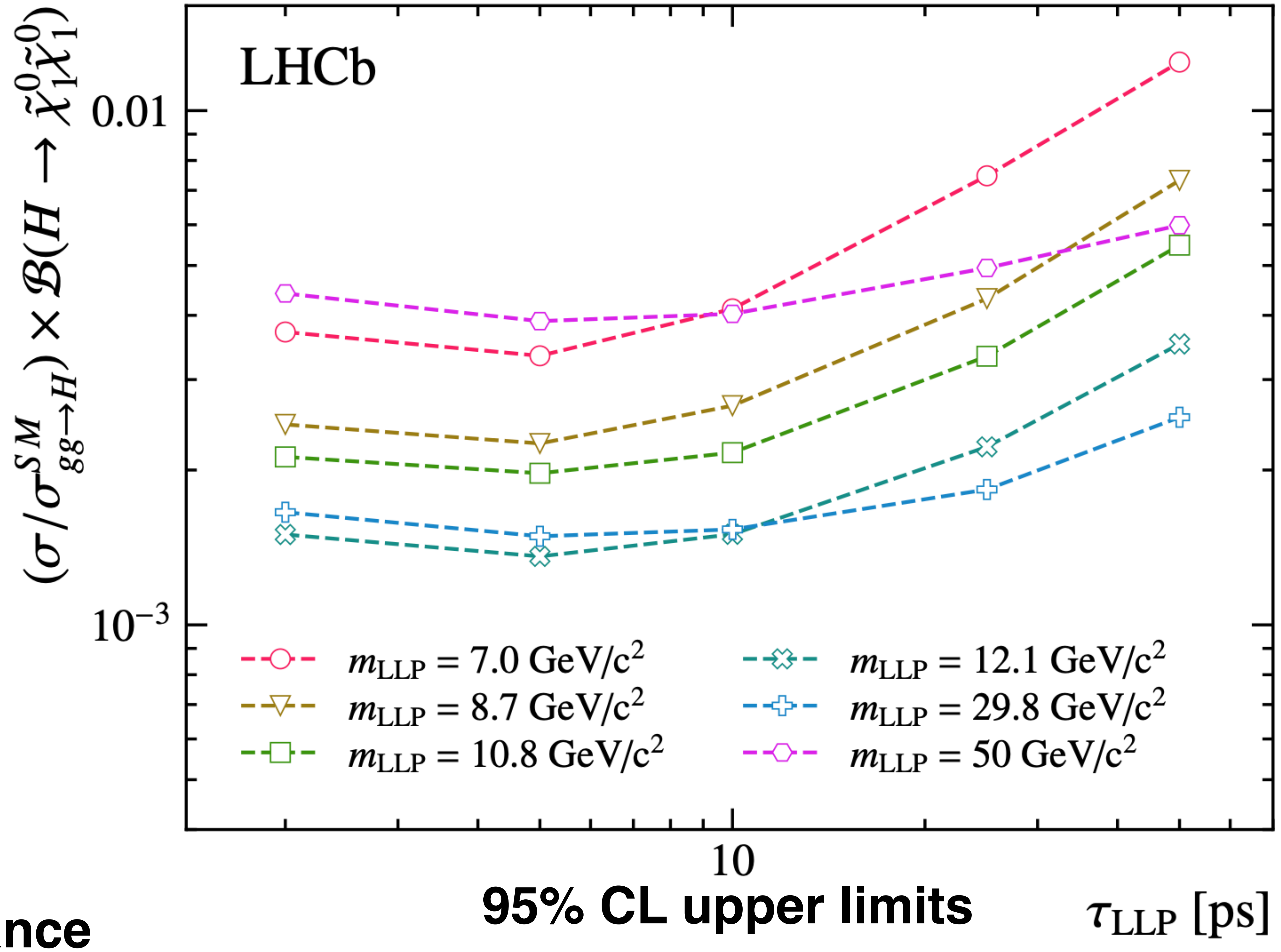
Signature: electron-muon pair

Eur. Phys. J. C81 (2021) 261



Fit to LLP mass and flight distance

Mass from 7 to 50 GeV

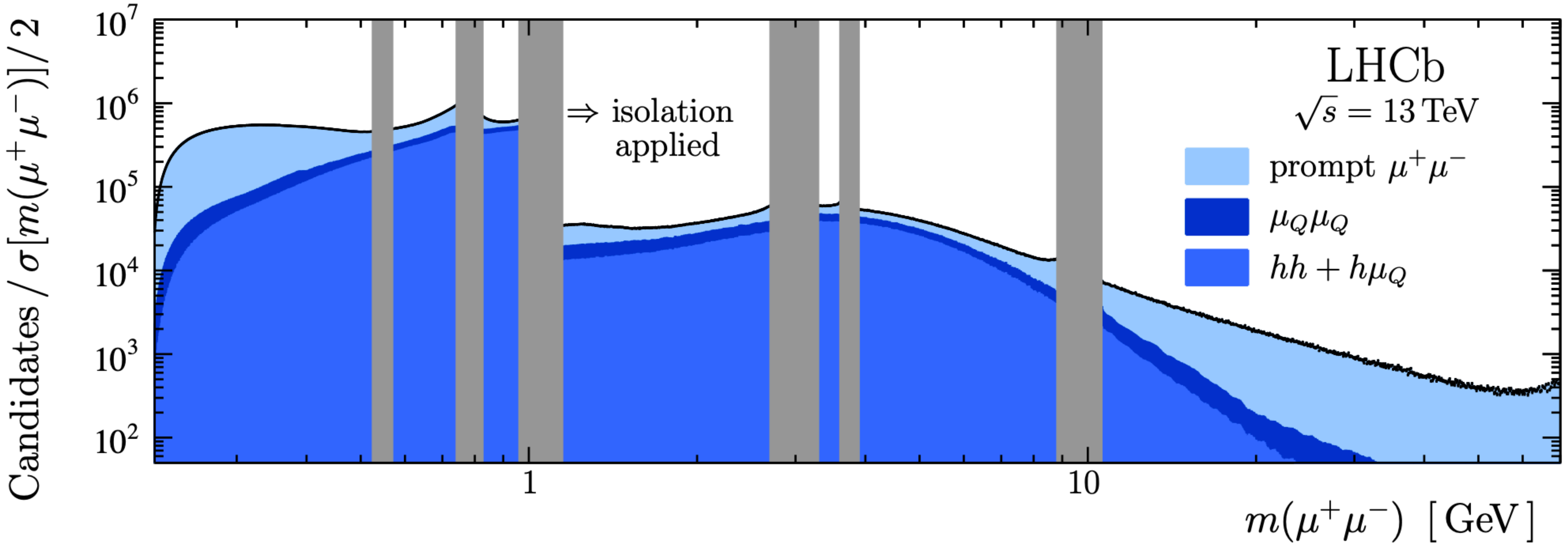


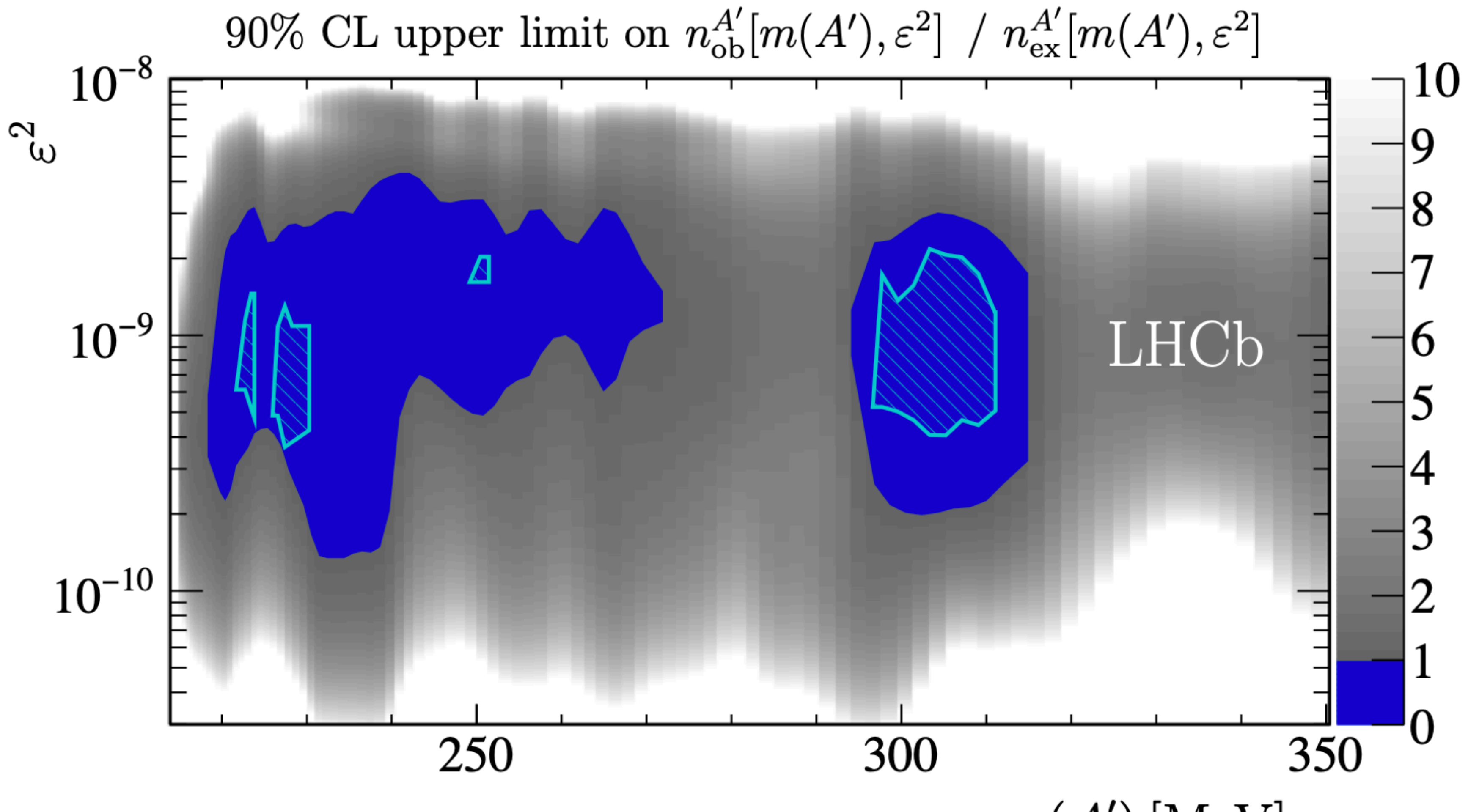
95% CL upper limits

Dimuon searches

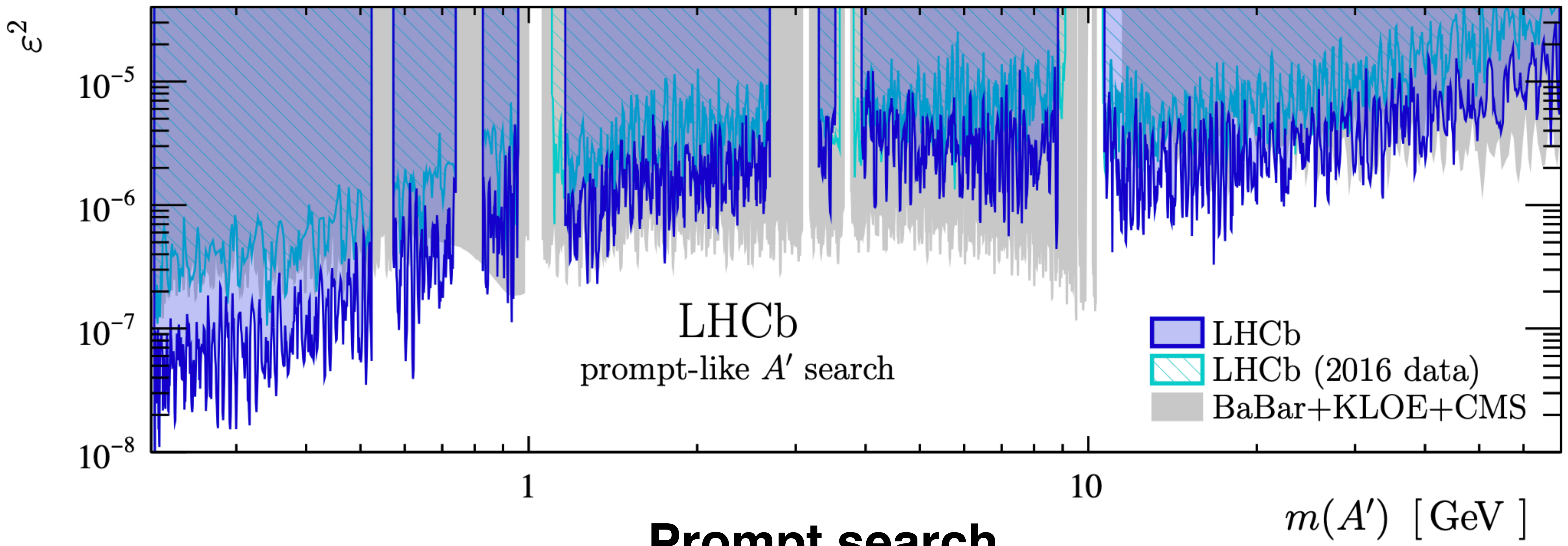
- **Since Run 2 we have dedicated trigger lines for dimuon searches**
- We have used them to put the most stringent constraints on dark photons in the mass range [214, 740] MeV and [10.6, 30] GeV

PHYS. REV. LETT. 124 (2020) 041801





Displaced search



Prompt search