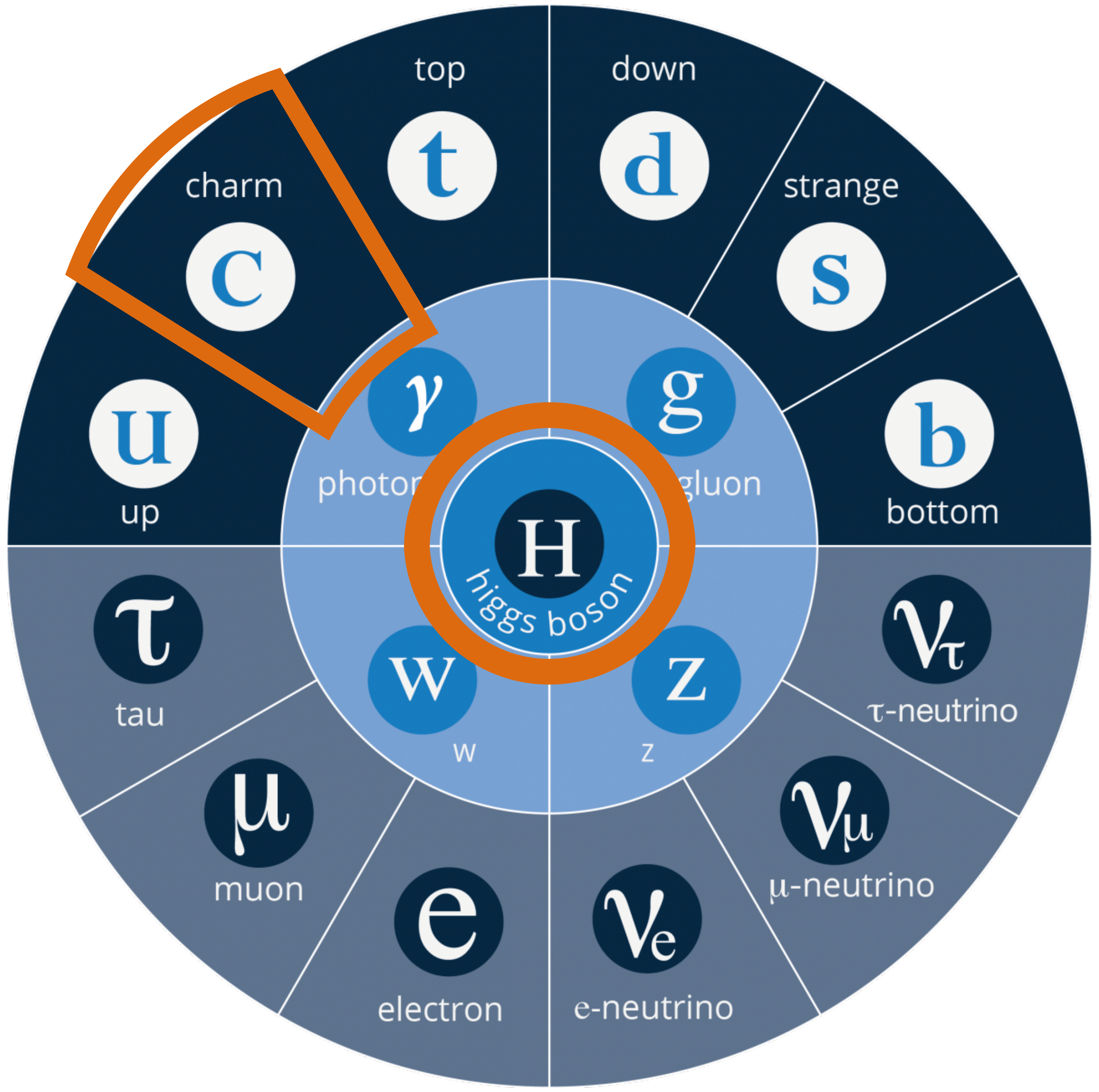
Charming the Higgs boson:
The search for H→cc

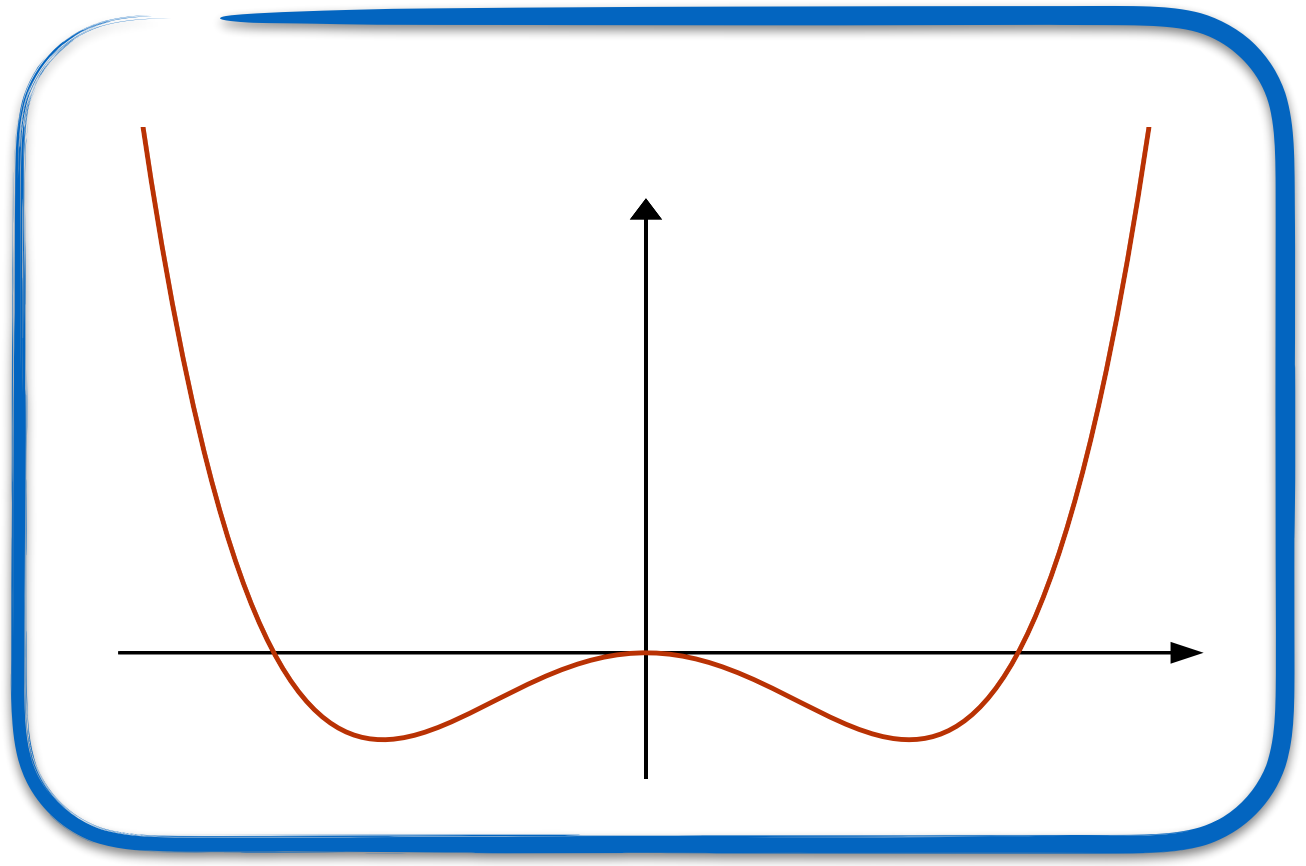


NNV subatomic physics session, Lunteren, 01.11.19

Marko Stamenkovic

Higgs boson: the keystone of the Standard Model

A sketch of the Standard Model Lagrangian density:



$$\mathcal{L}_{\mathrm{SM}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$
$$+ i\bar{\psi}\not{D}\psi$$

Higgs interactions

$$+ |D_\mu \phi|^2 - \mu^2(\phi^\dagger\phi) - \lambda(\phi^\dagger\phi)^2$$ → **Higgs mechanism**

$$+ y_{ij}\psi_i\phi\psi_j + \mathrm{h.c.}$$ → **Yukawa terms**

Higgs boson: the keystone of the Standard Model

A sketch of the Standard Model Lagrangian density:

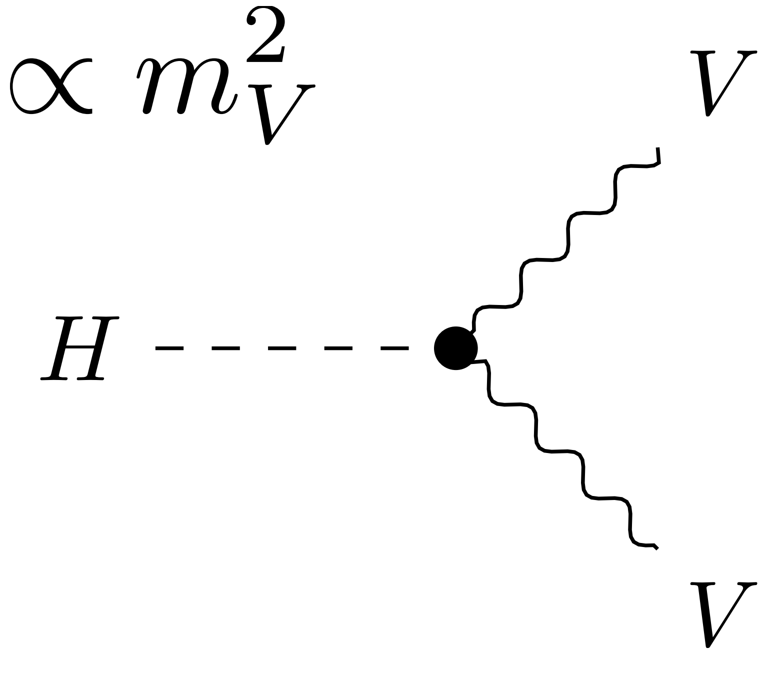
$$
\begin{aligned}
\mathcal{L}_{\mathrm{SM}} = & -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \\
& + i\bar{\psi}\not{D}\psi \\
& + |D_\mu\phi|^2 - \mu^2(\phi^\dagger\phi) - \lambda(\phi^\dagger\phi)^2 \\
& + y_{ij}\psi_i\phi\psi_j + \mathrm{h.c.}
\end{aligned}
$$

→ **Higgs mechanism**

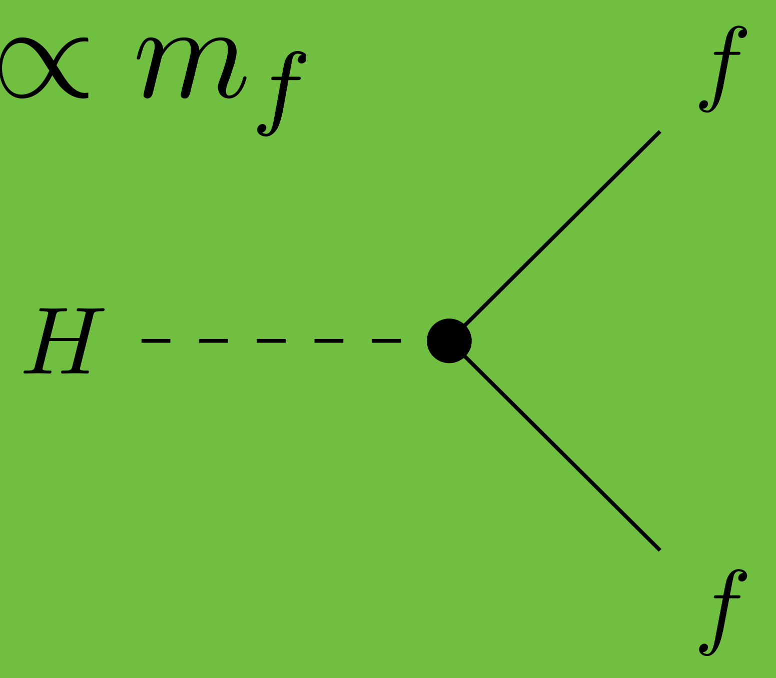
→ **Yukawa terms**

This talk

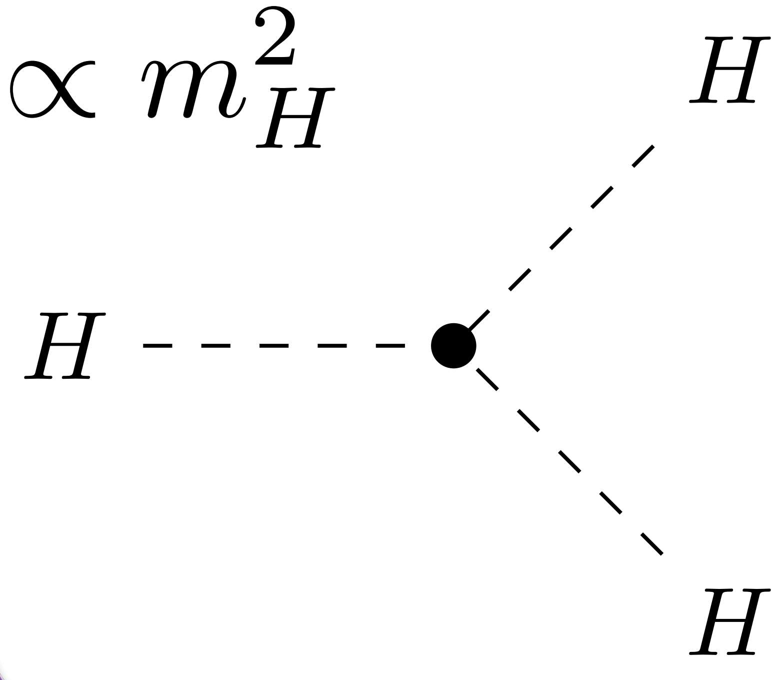
$\propto m_V^2$



$\propto m_f$

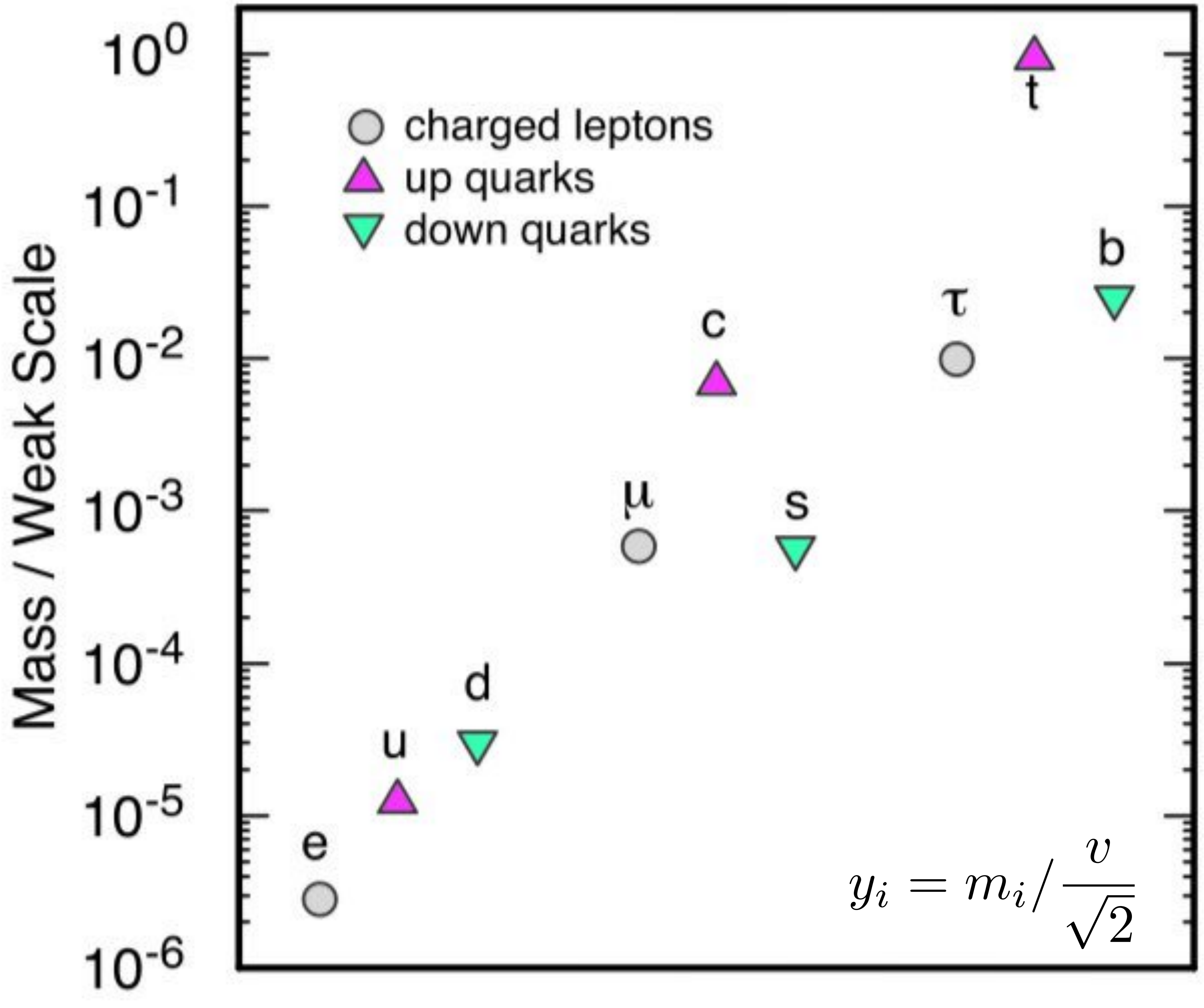


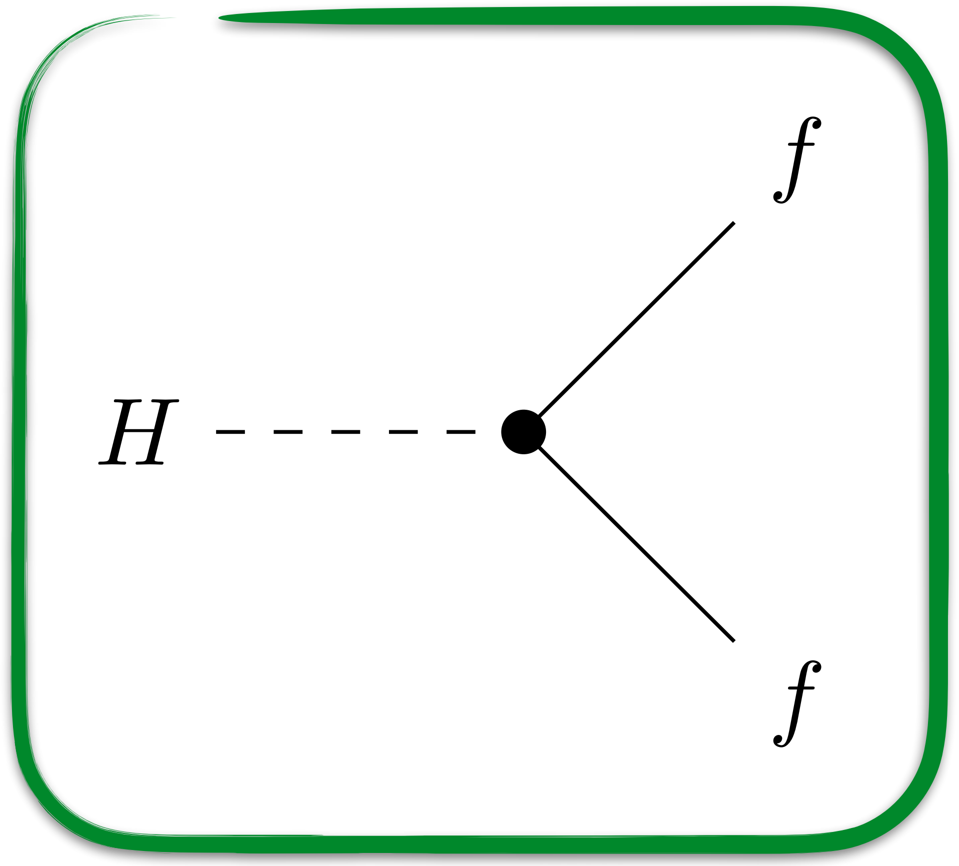
$\propto m_H^2$



Higgs boson decay to a pair of fermions

arXiv:0905.3187





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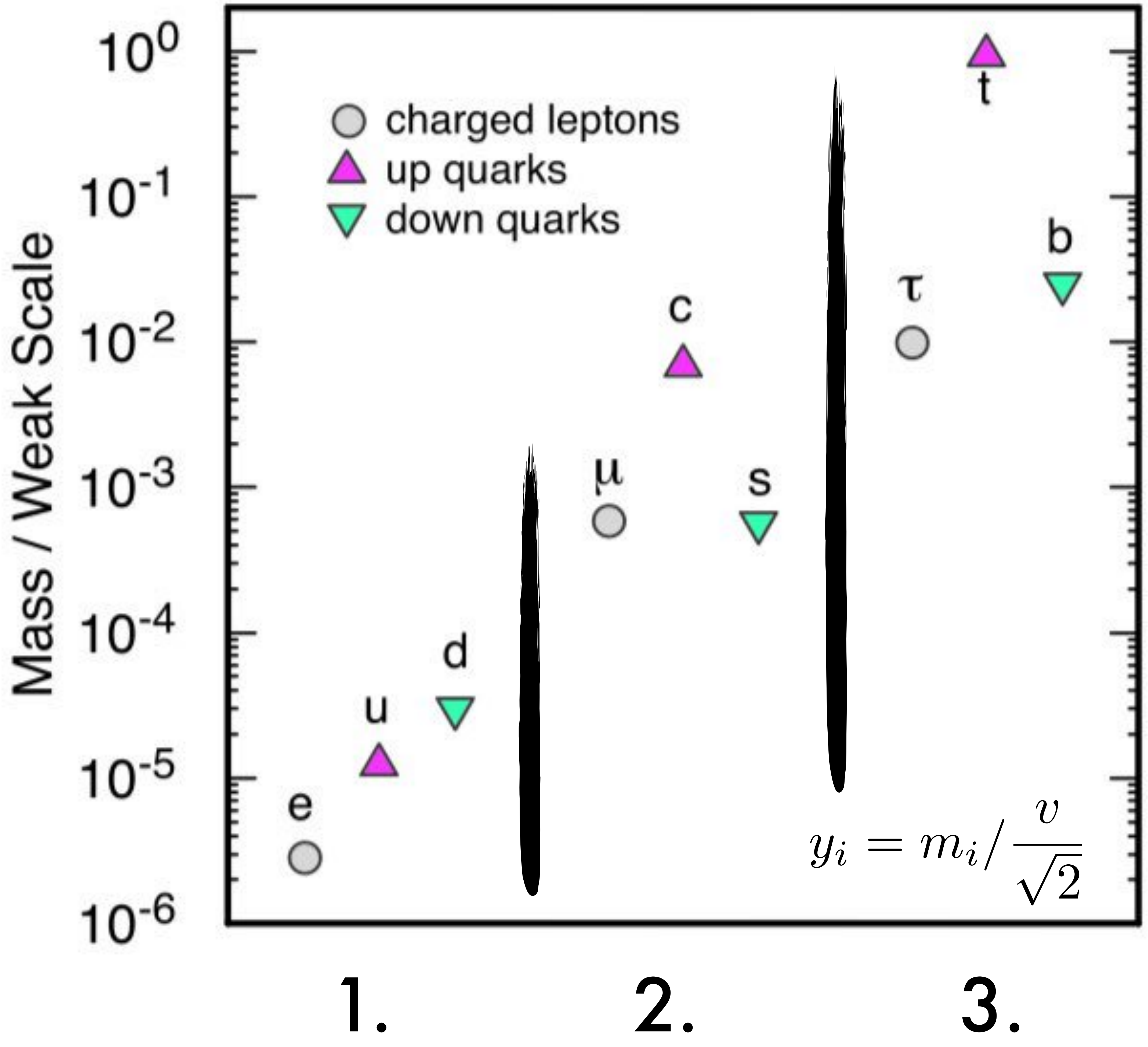

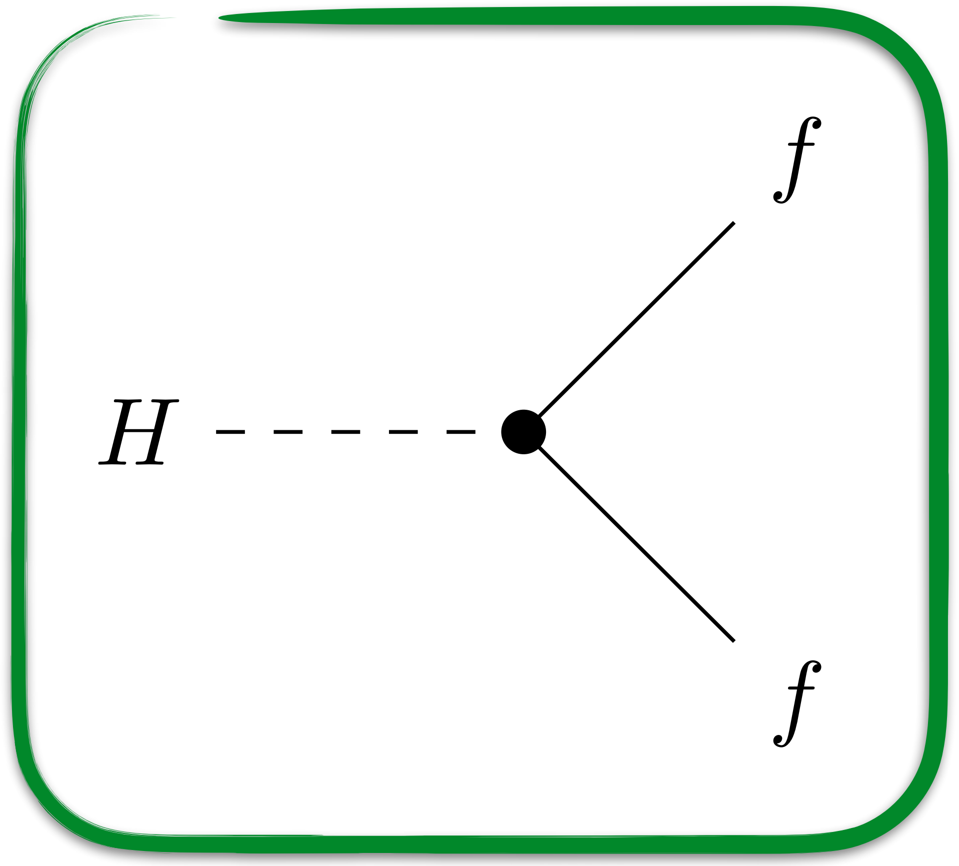

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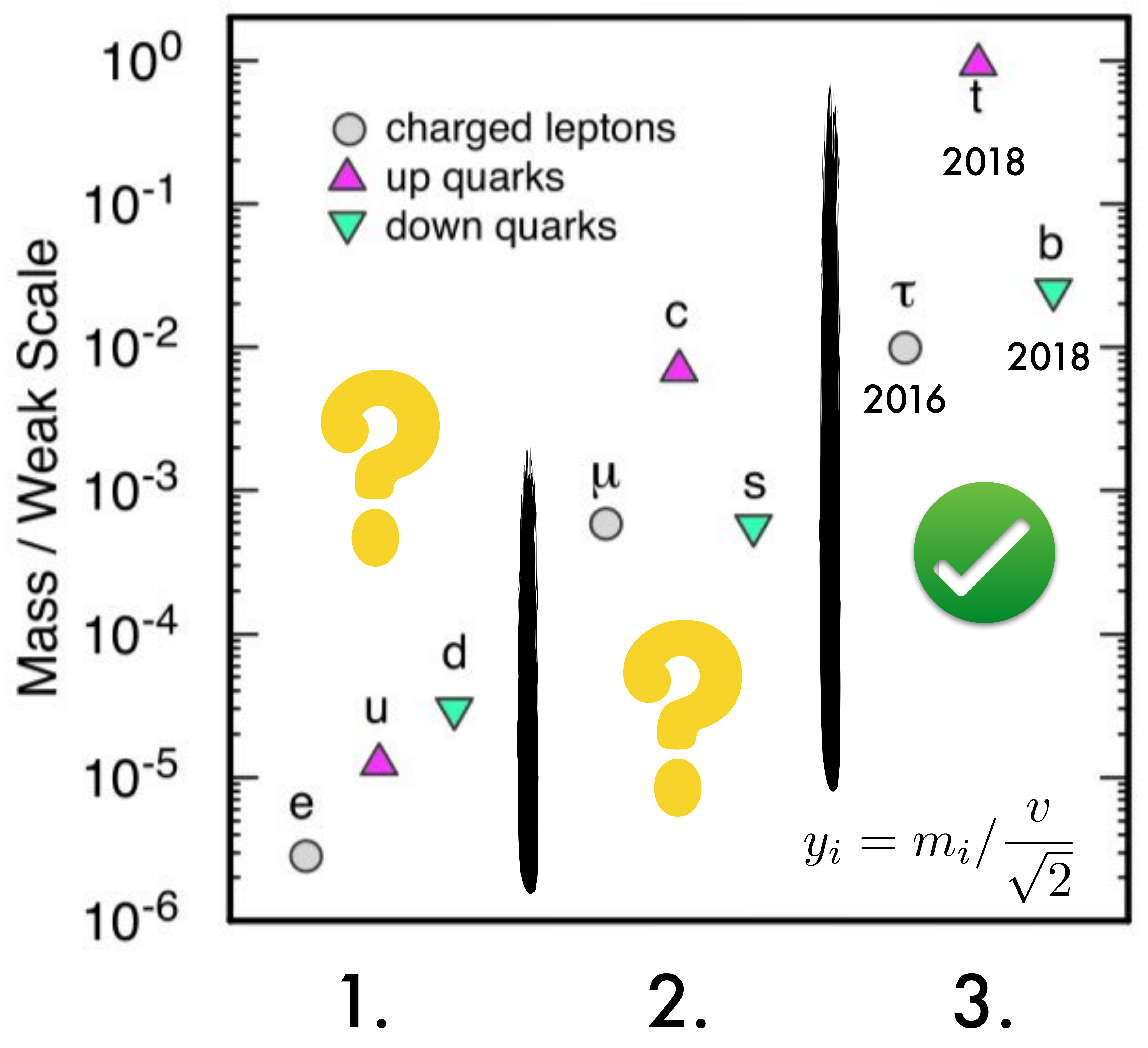

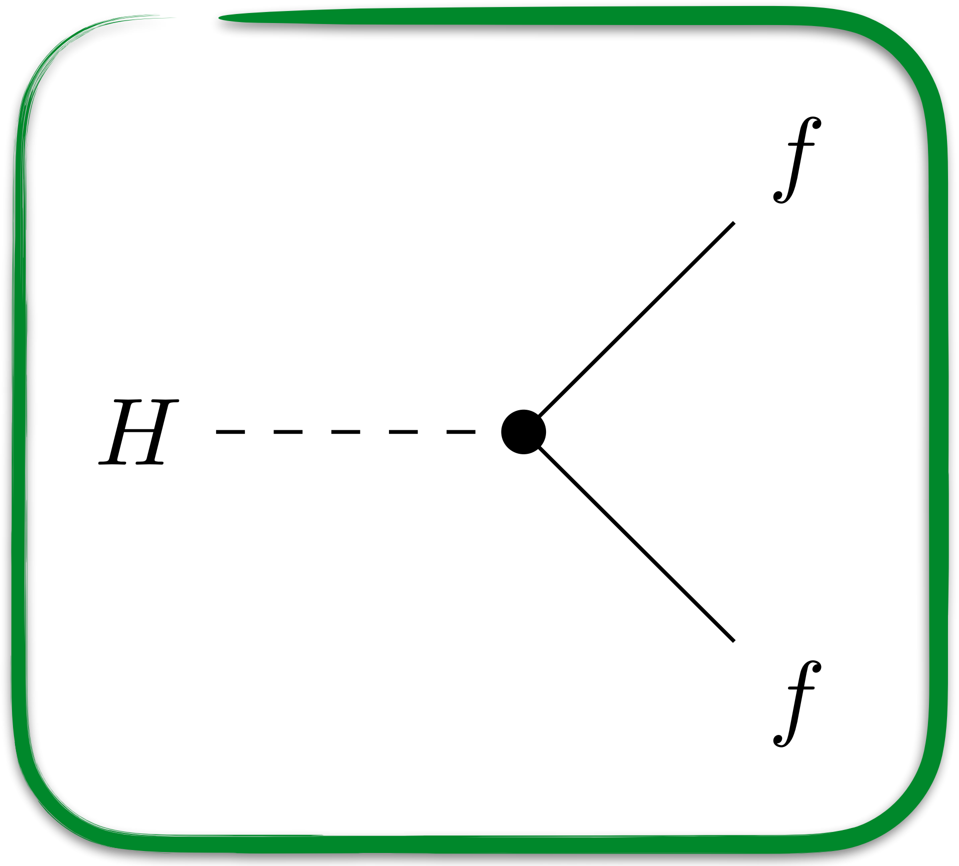

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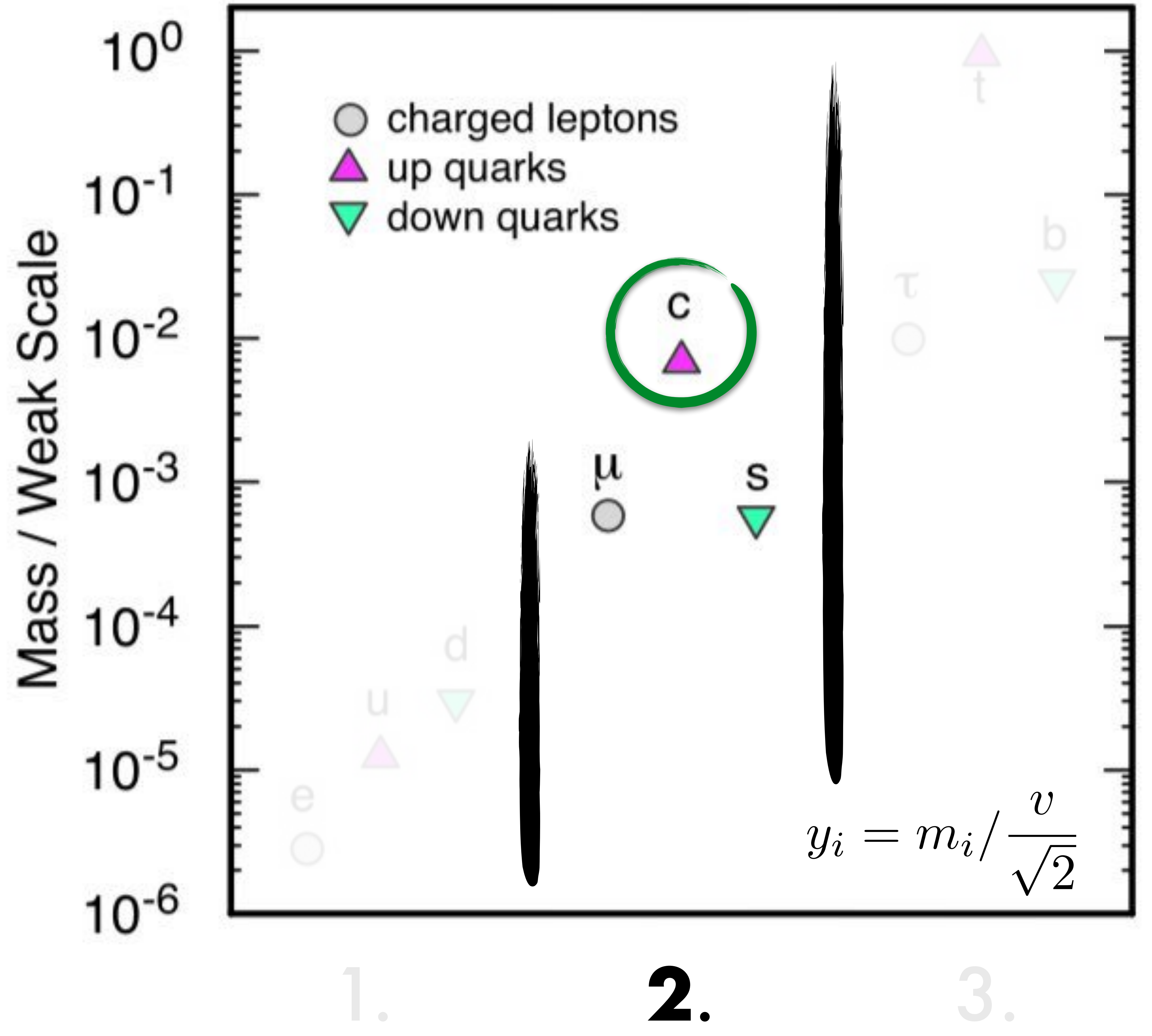
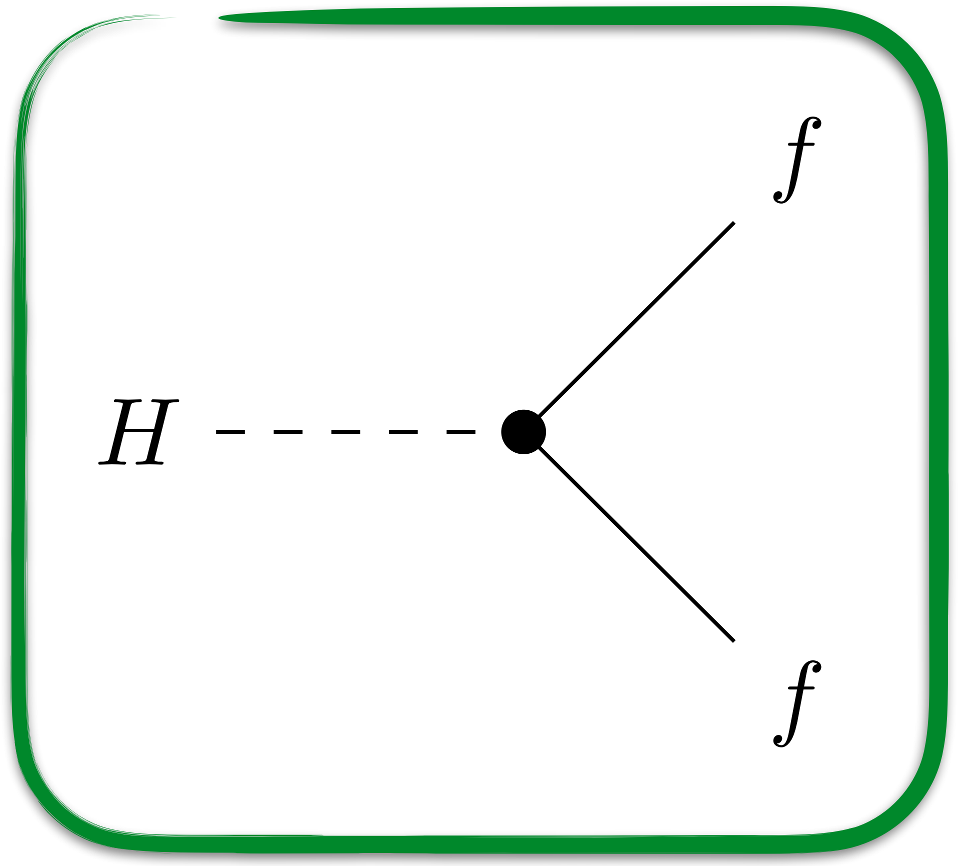
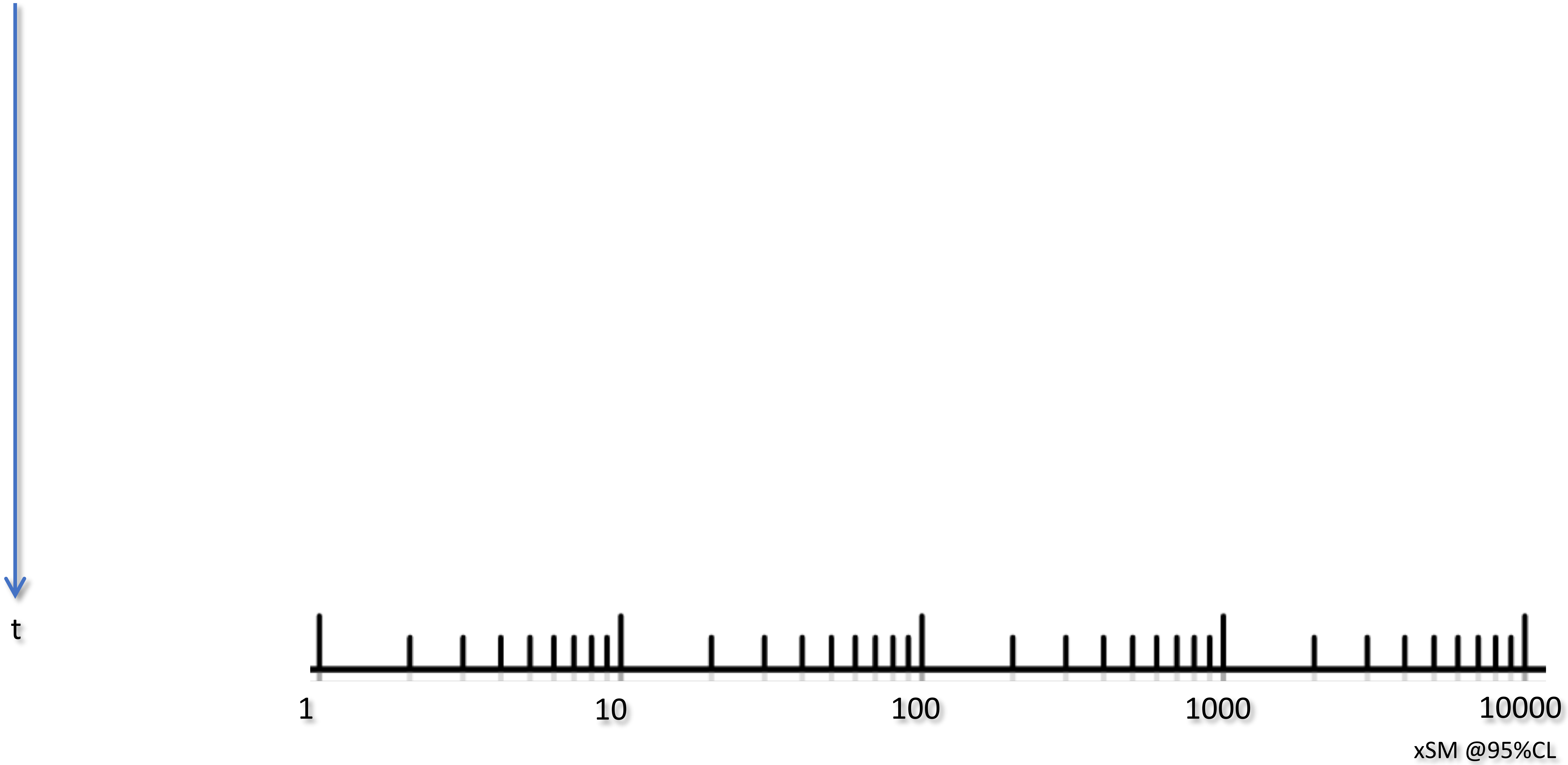




H→cc : **direct probe** of Higgs coupling to **2nd generation**!

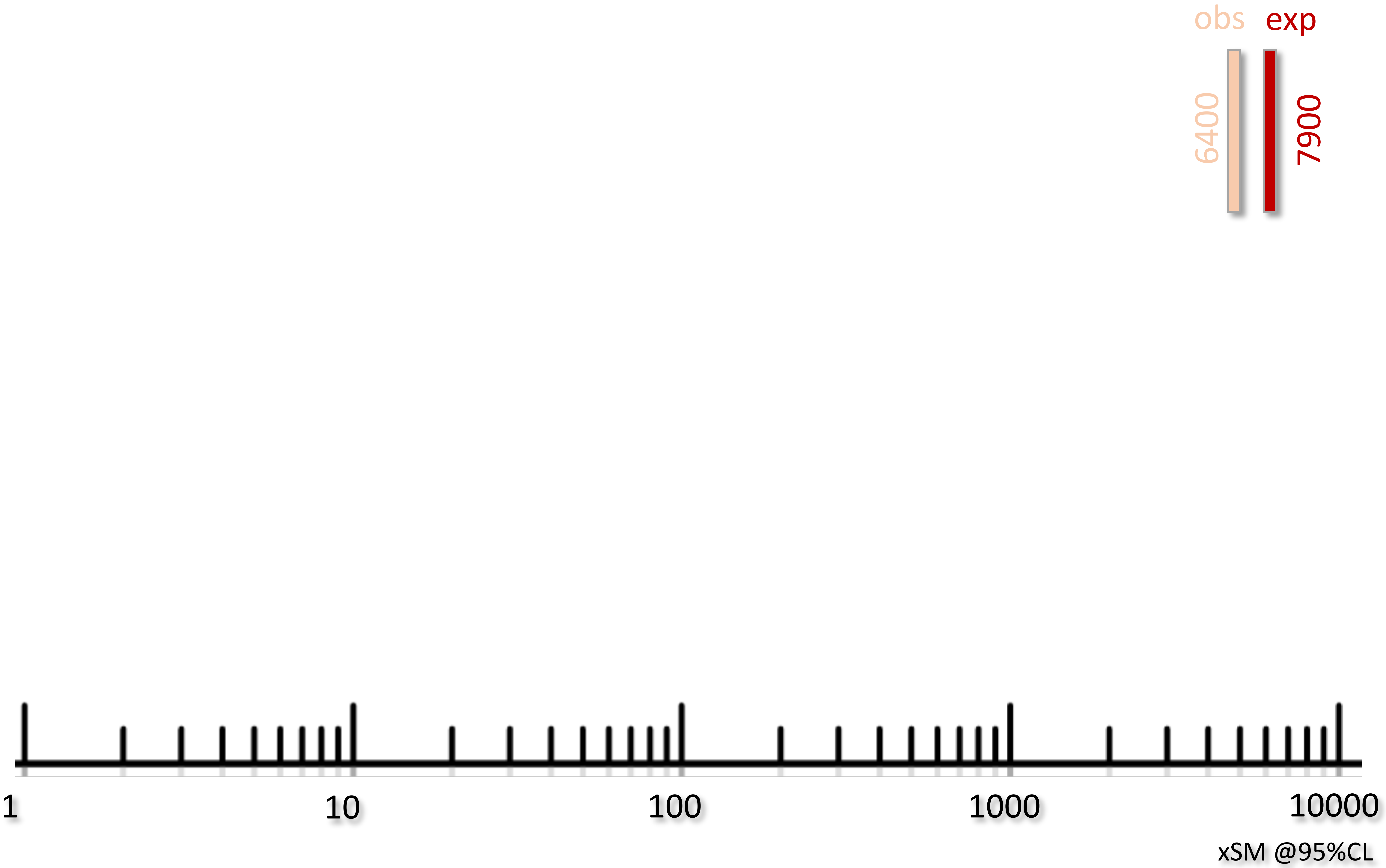
Sensitivity timeline: H → cc



Sensitivity timeline: H → cc

2016: LHCb
LHCb-CONF-2016-006

t

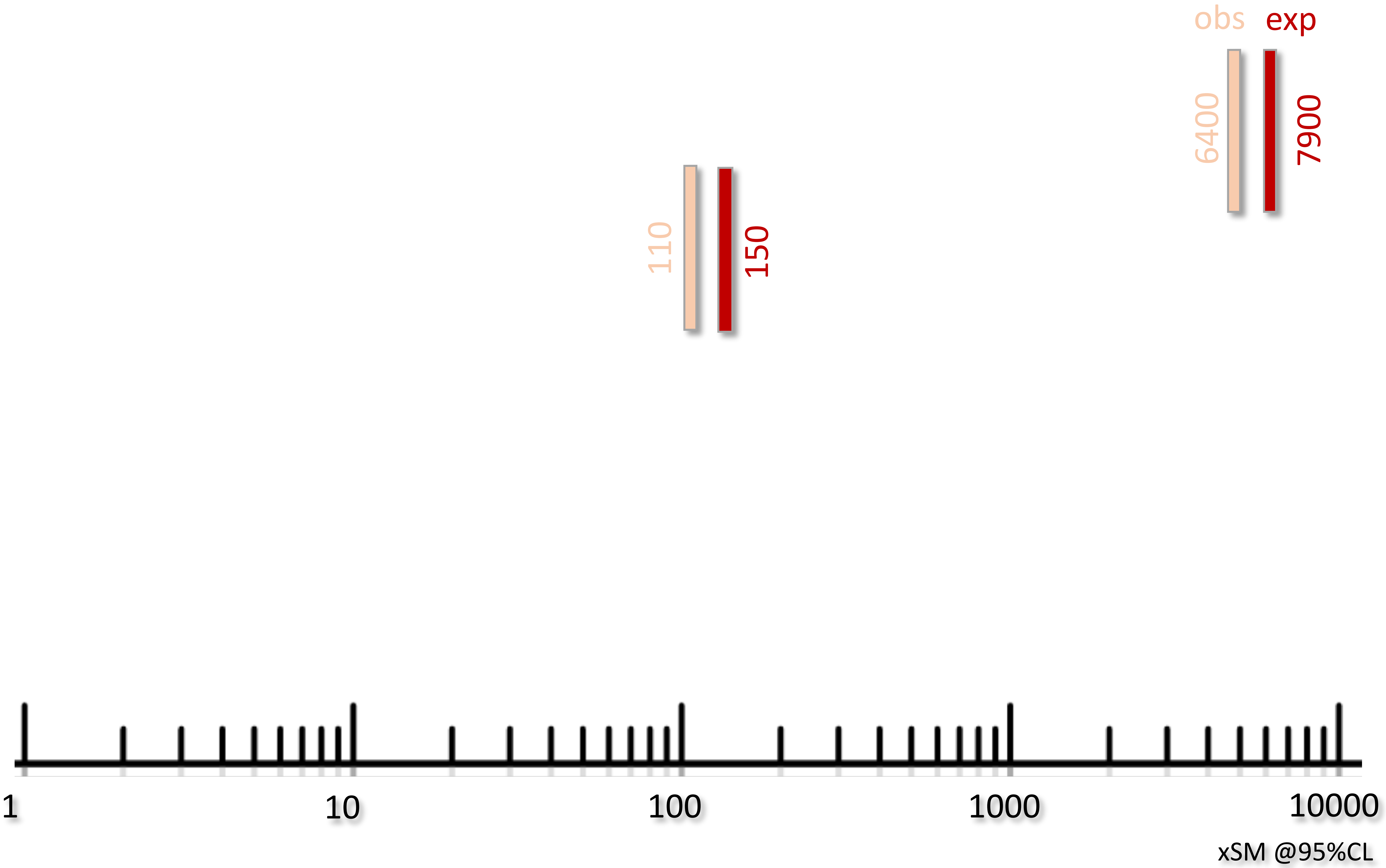


Sensitivity timeline: H → cc

2016: LHCb
LHCb-CONF-2016-006

2018: ATLAS
arXiv:1802.04329

t

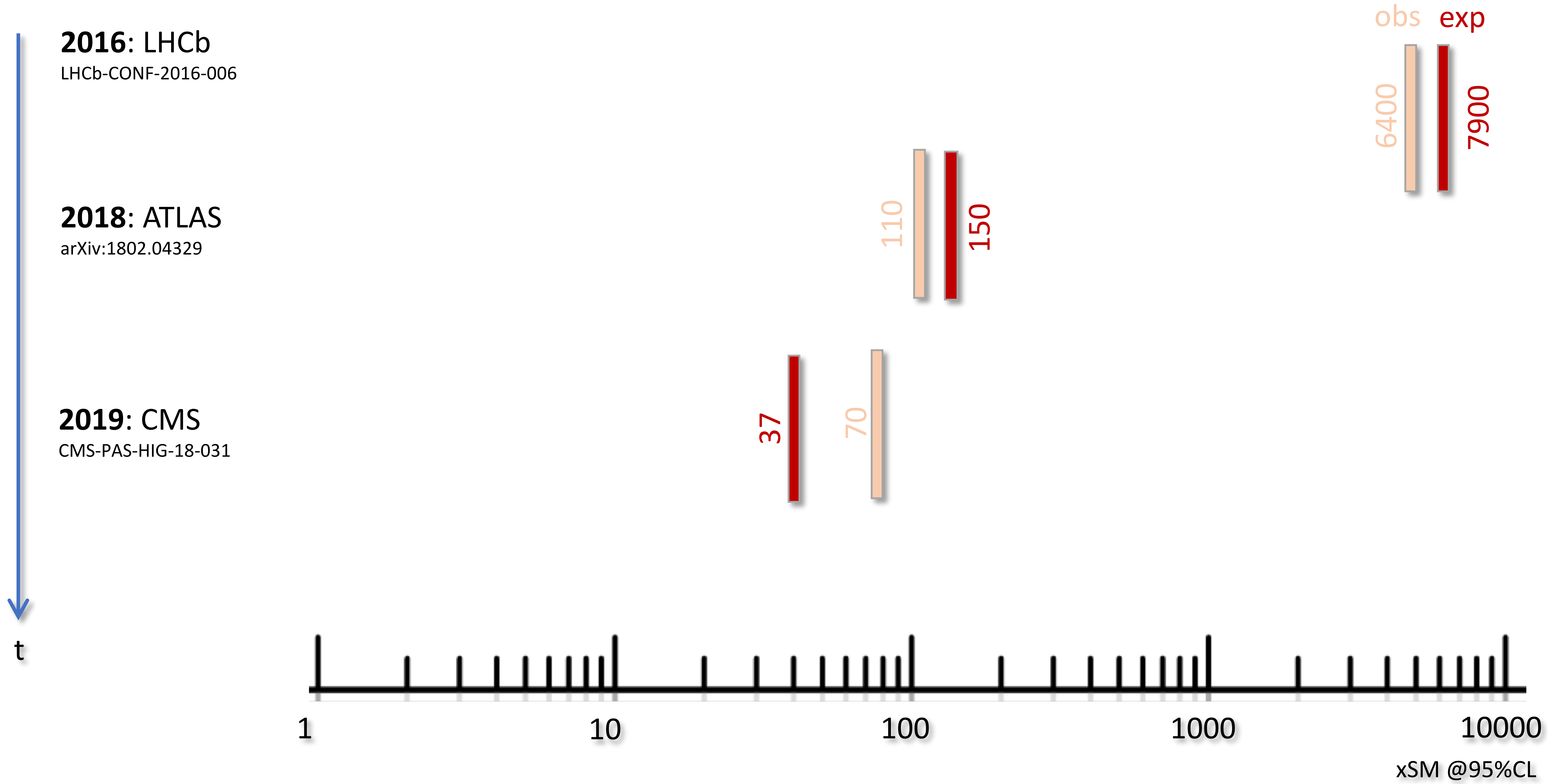


Sensitivity timeline: H → cc

2016: LHCb
LHCb-CONF-2016-006

2018: ATLAS
arXiv:1802.04329

2019: CMS
CMS-PAS-HIG-18-031



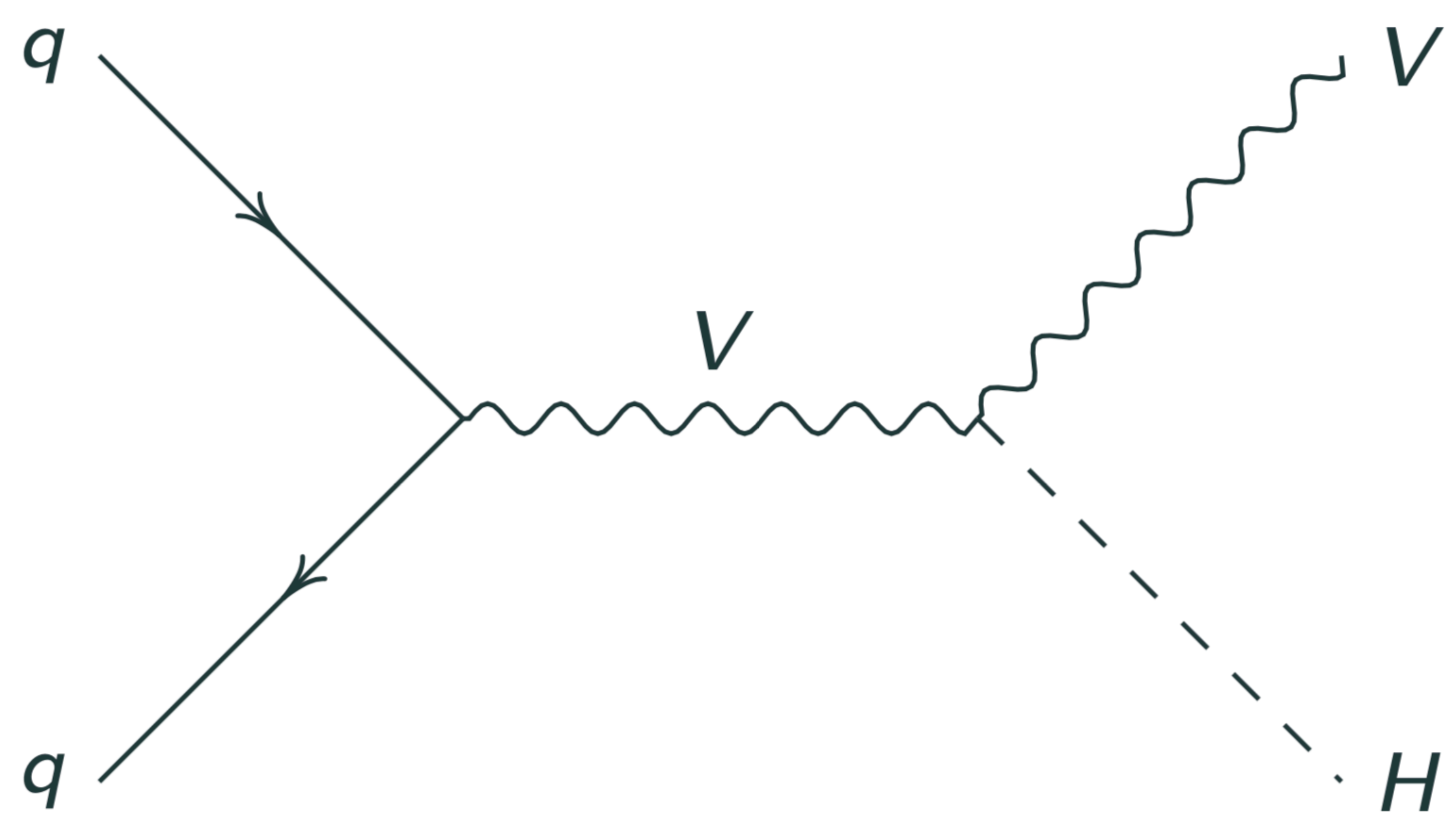
Challenging measurement

$\Updownarrow$

Technological improvements

How do we look for H→cc?

VH production mode:



How do we look for H→cc?

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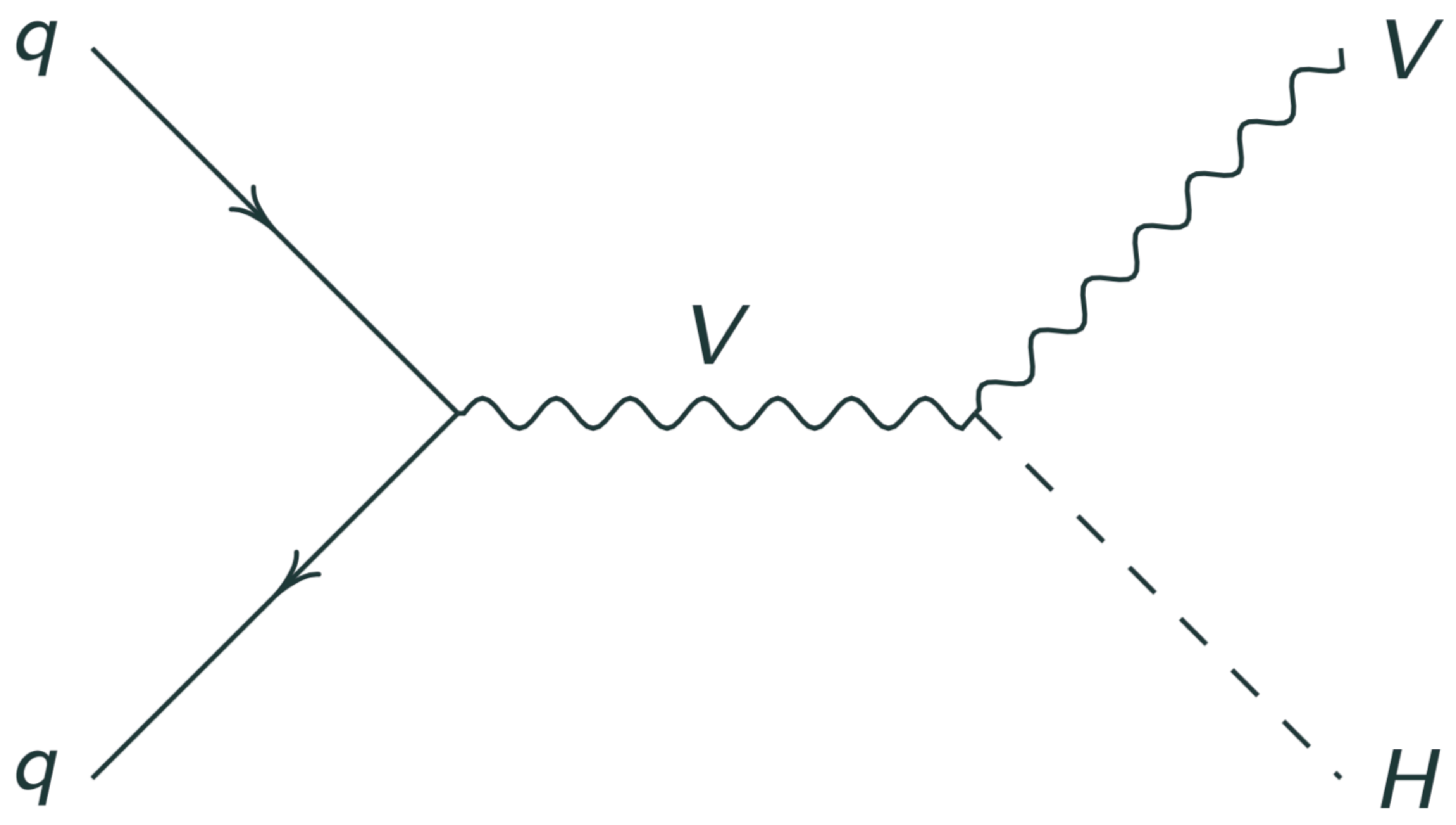
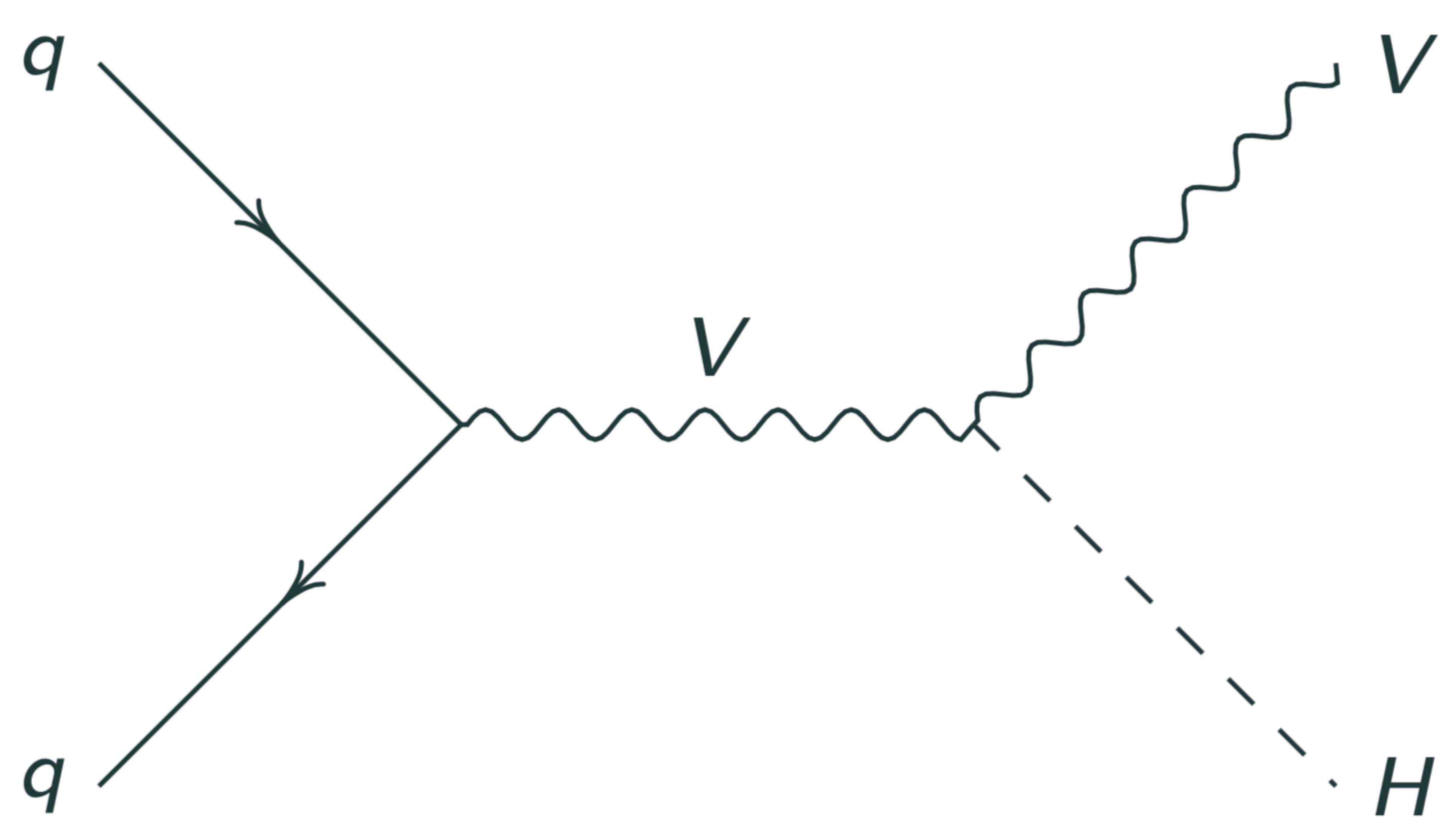


H decays to quarks:
H→bb, **H→cc**, …

How do we look for H→cc?

VH production mode:



V decays to leptons:
Z→νν, W→lν, Z→ll
(used for triggering and boost sensitivity)

H decays to quarks:
H→bb, **H→cc**, …

3 main channels:

0-lepton: Z→νν

1-lepton: W→lν

2-lepton: Z→ll


ATLAS
EXPERIMENT
Run: 309440
Event: 990753168
2016-09-27 14:35:10 CEST

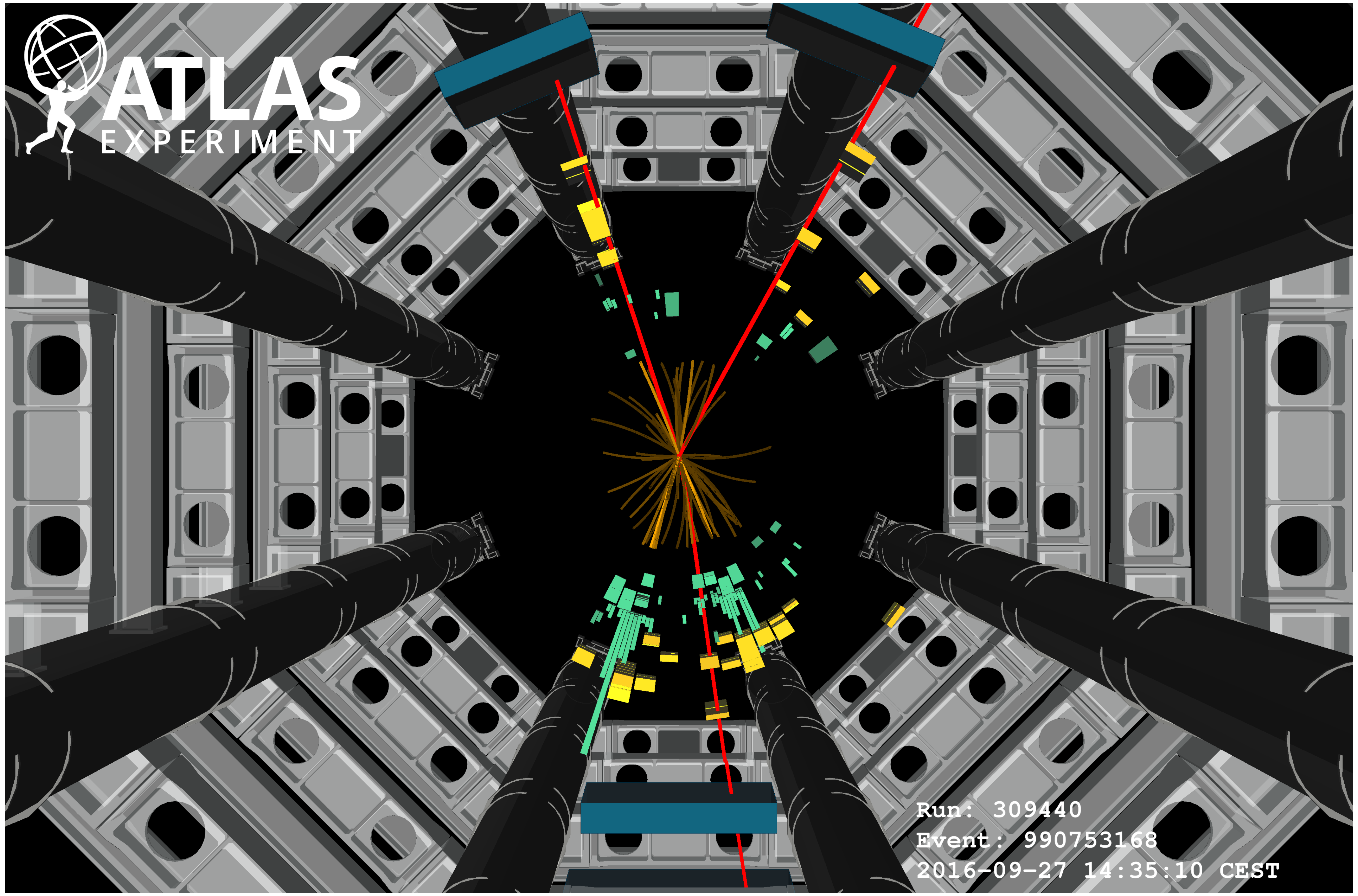
Analysis strategy

Final states: V(ll)H(cc)

- Leptons for triggering
  - → 1/2 leptons channels
    - Charged e/μ
  - → 0 lepton channels
    - Missing energy

Main challenges:

- High background of c-jet pair production at hadron colliders
- Low branching fraction of H→cc
- Background modelling
- H→bb background
- Charm tagging
- Higgs mass resolution



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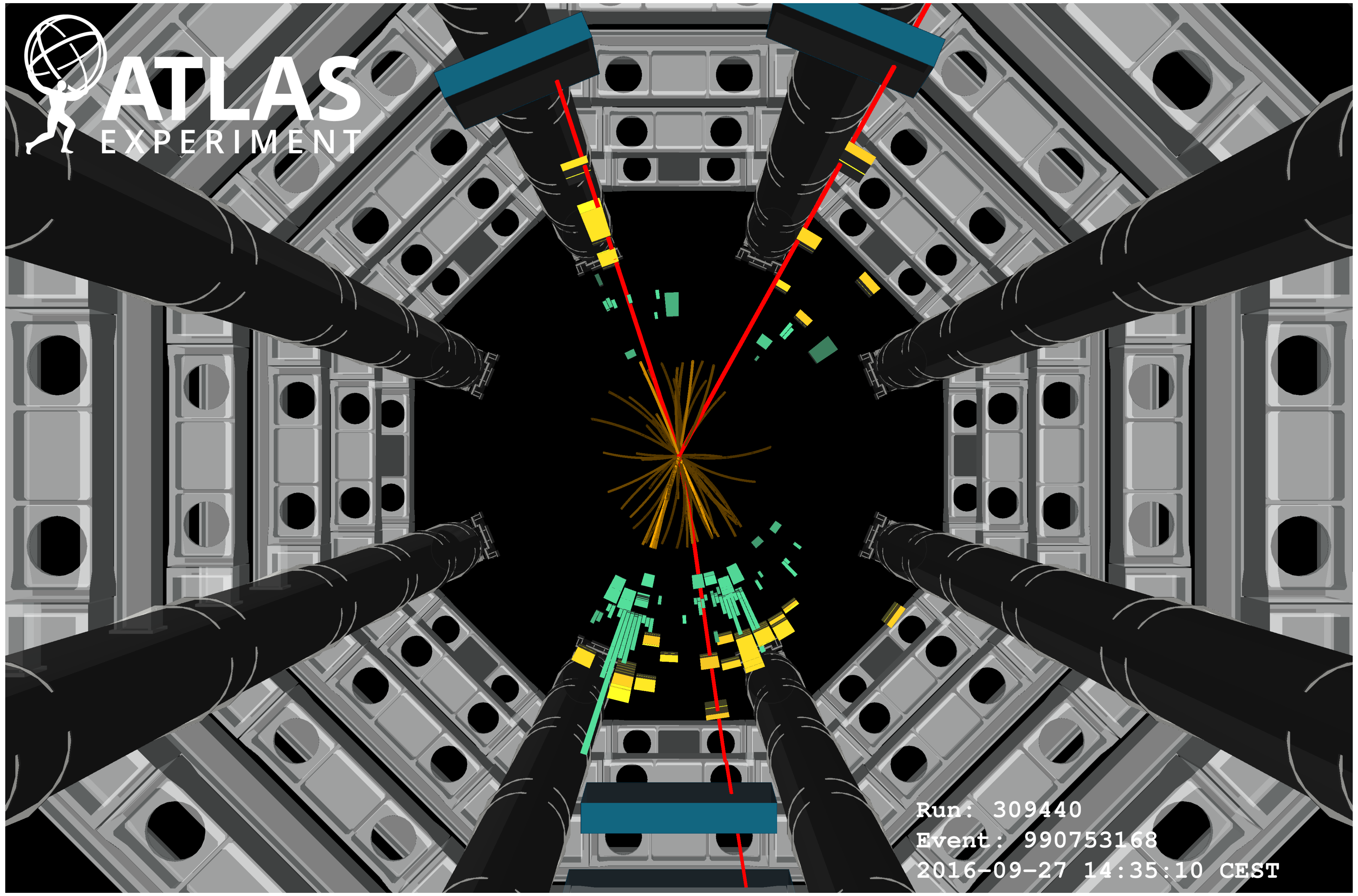
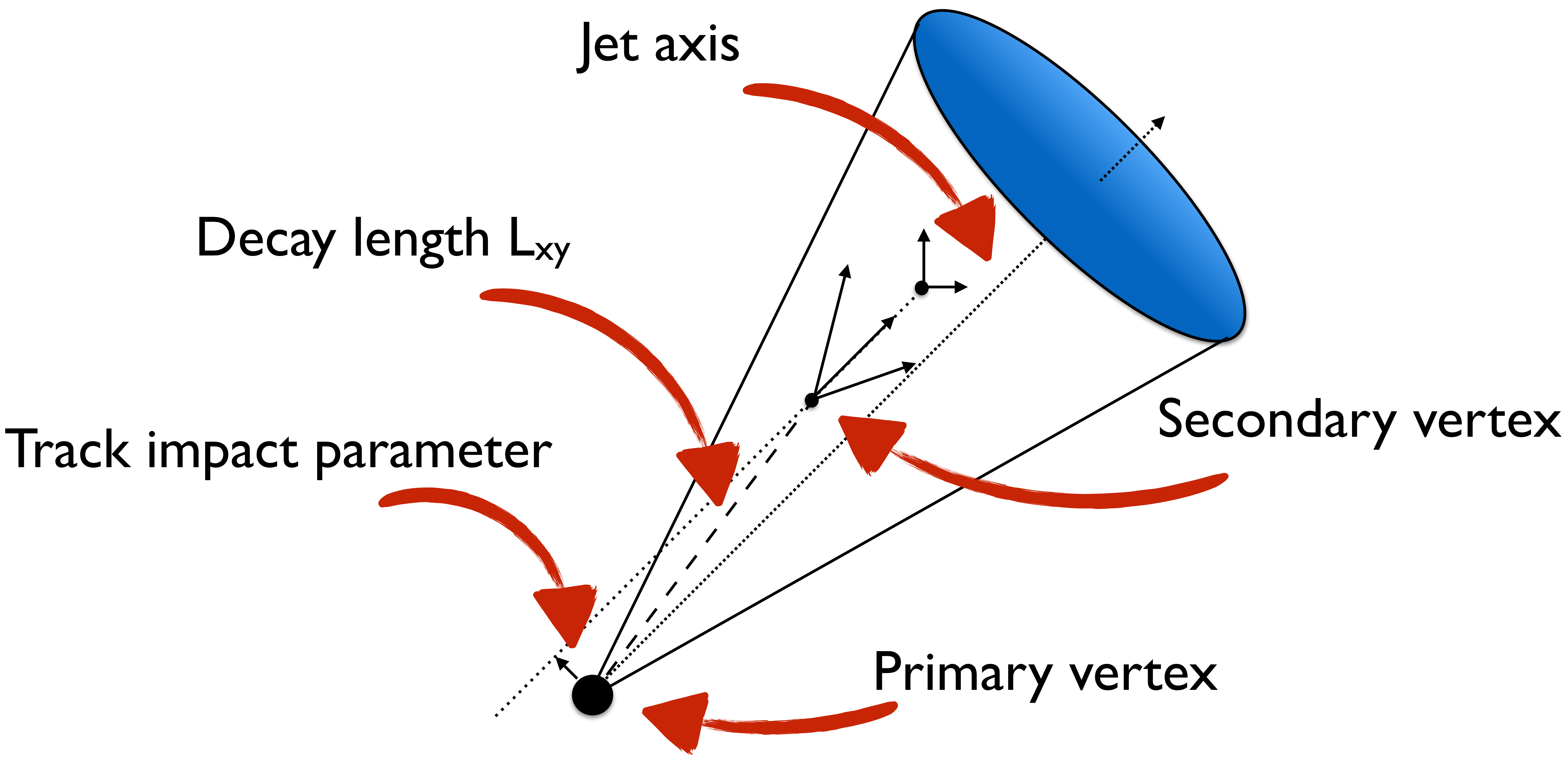
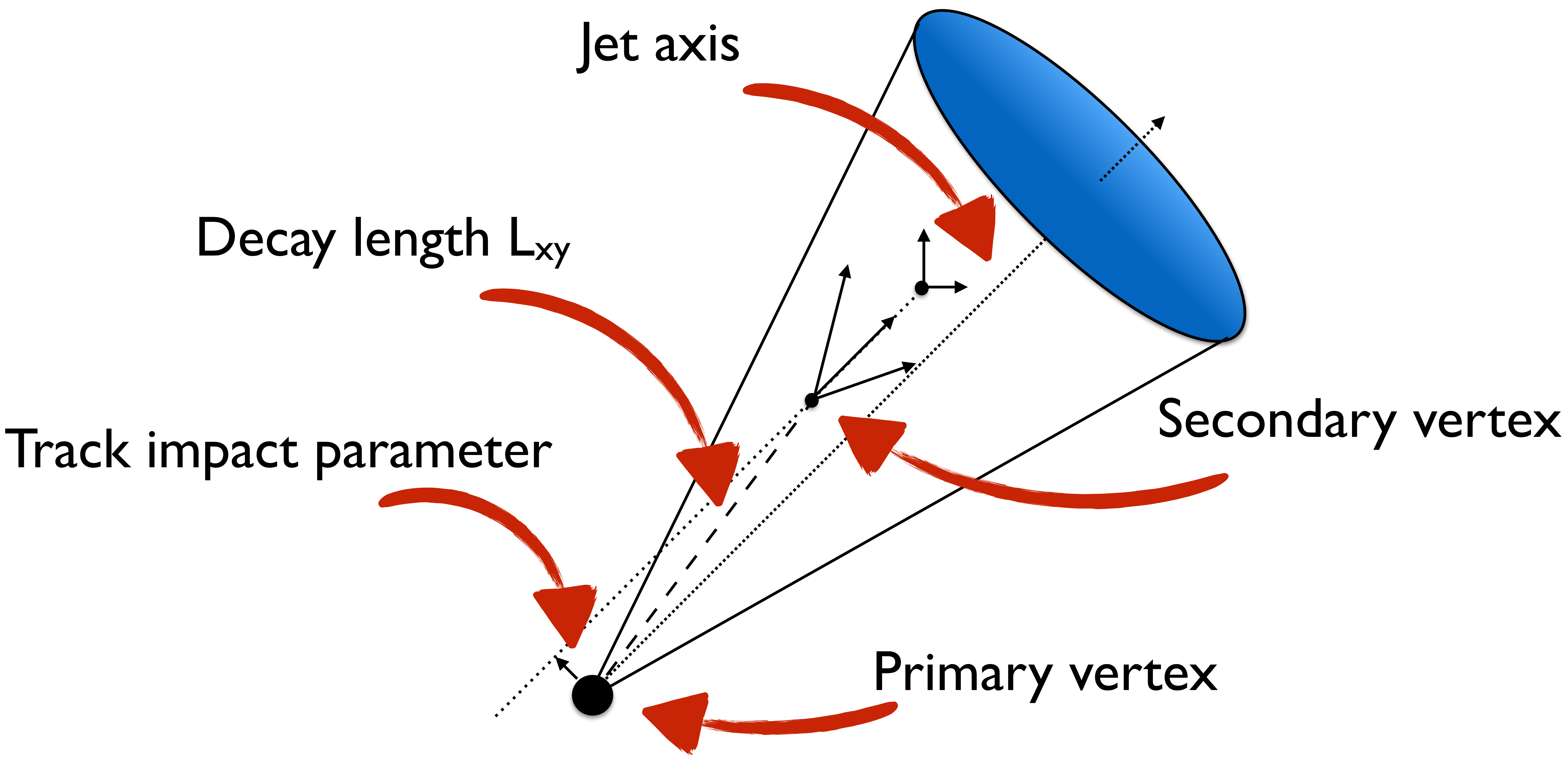


Flavour tagging in a nutshell



Flavour tagging in a nutshell



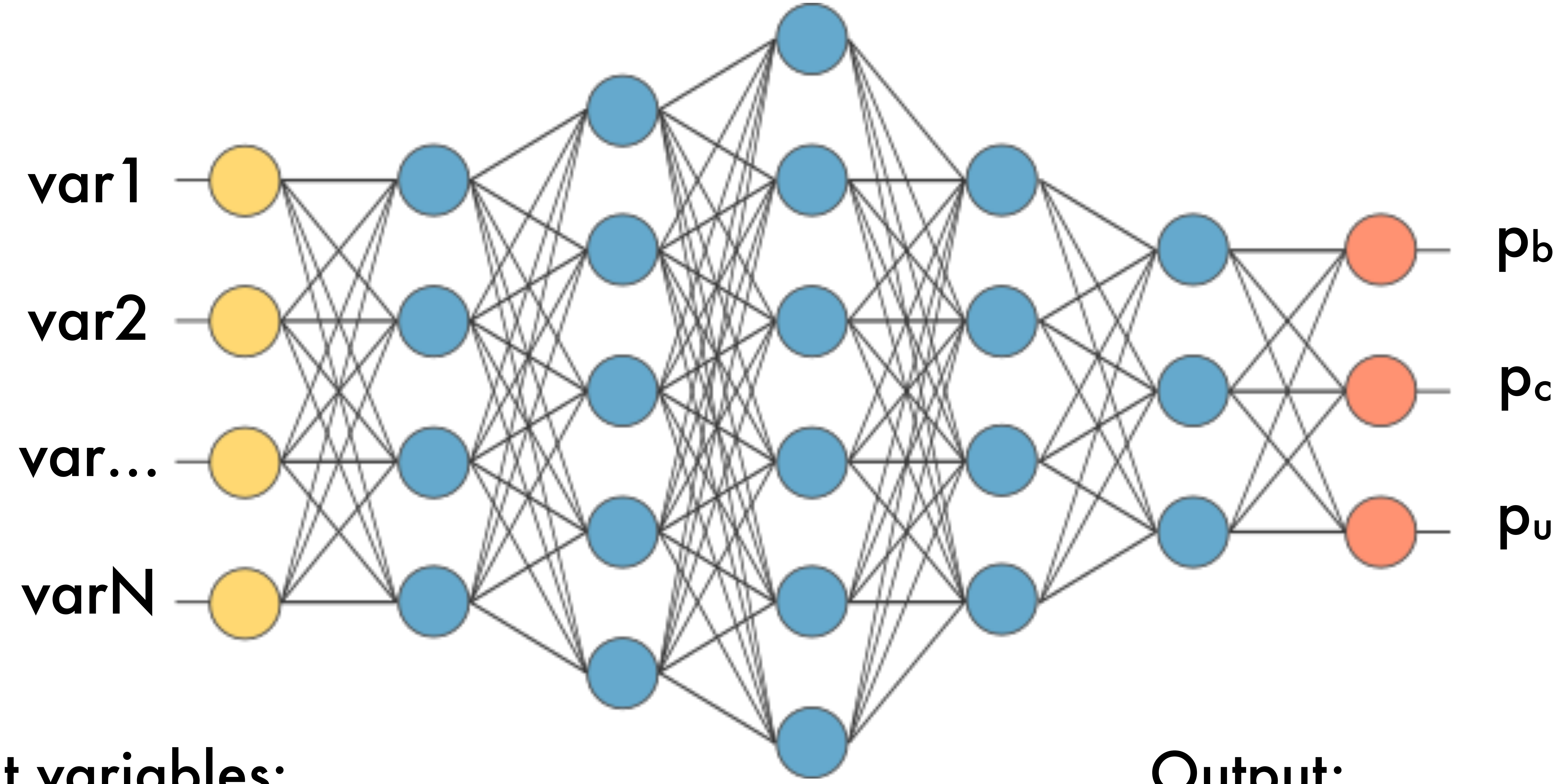
b-hadrons
Mass ~ 5 GeV
τ ~ 1.5 ps
$c\tau$ ~ 450μm
<L_{xy}>@70GeV ~ 6mm

c-hadrons
Mass ~ 2 GeV
τ ~ 0.4 ps
$c\tau$ ~ 120μm
<L_{xy}>@70GeV ~ 1.5mm

light-hadrons (esp. $\pi^{\pm}$, K)
Mass ~ 0.5 GeV
τ >> ps
$c\tau$ >> μm
SV due to radiations

Challenge: c-jets are physically "in-between" b-jets and light-jets

Flavour tagging in 2019@ATLAS



Input variables:

- Kinematics
- Lifetime, impact parameter
- Secondary vertices
- Invariant masses

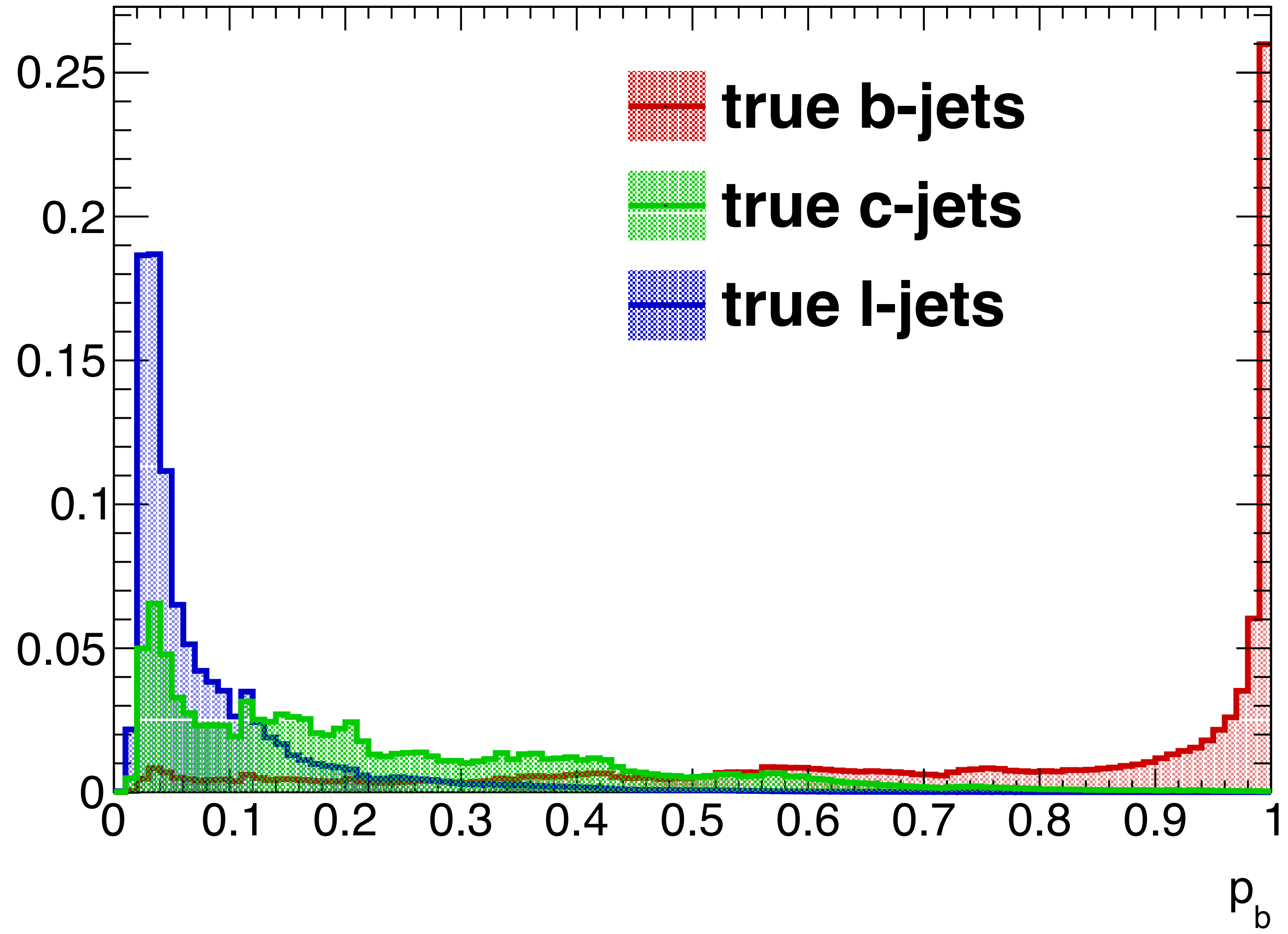
Output:

- Probabilities of being b-, c- and light-jets (p_u)
- $p_b + p_c + p_u = 1$

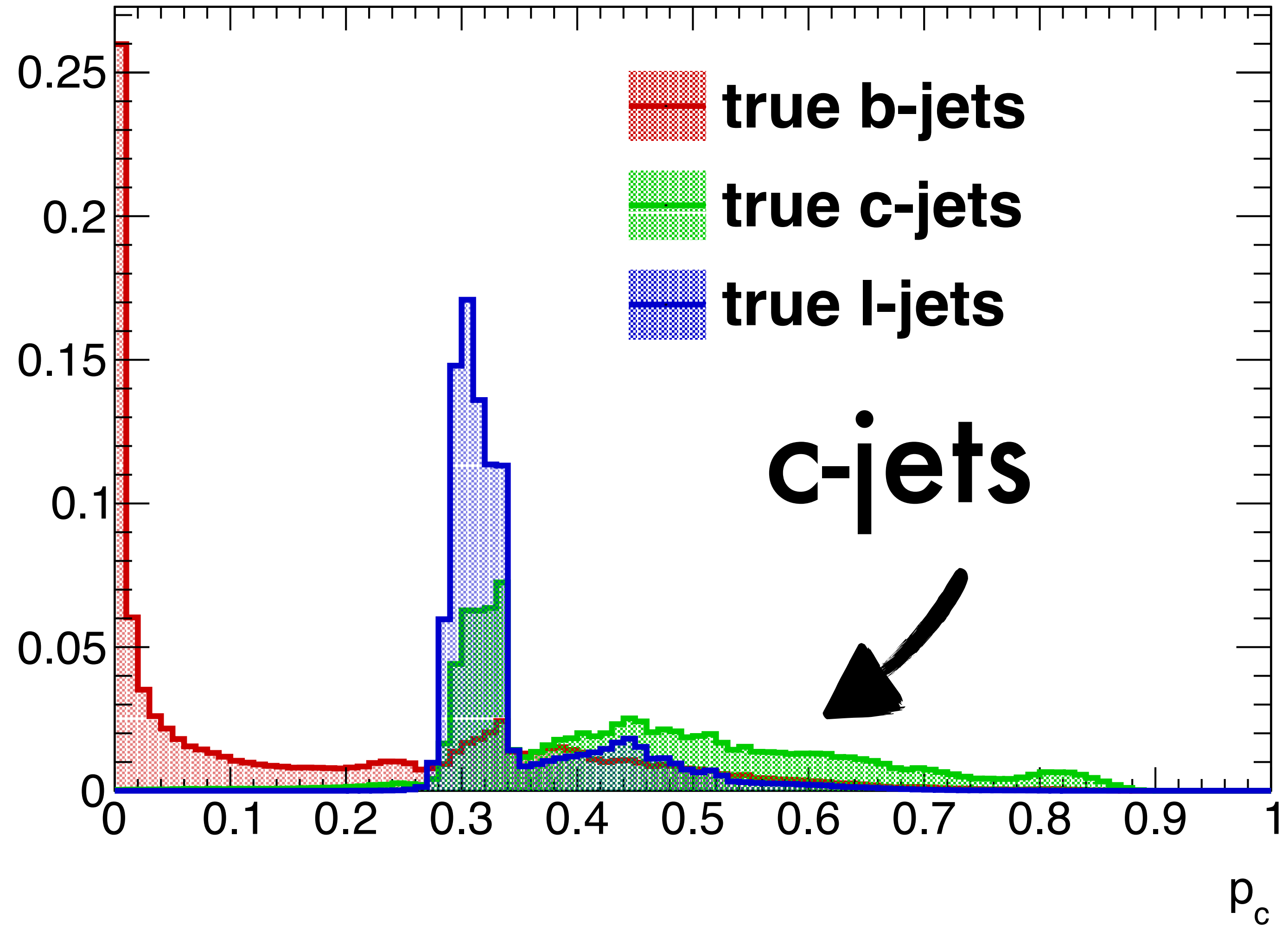
Flavour tagging in 2019@ATLAS

ATLAS simulation
Preliminary results

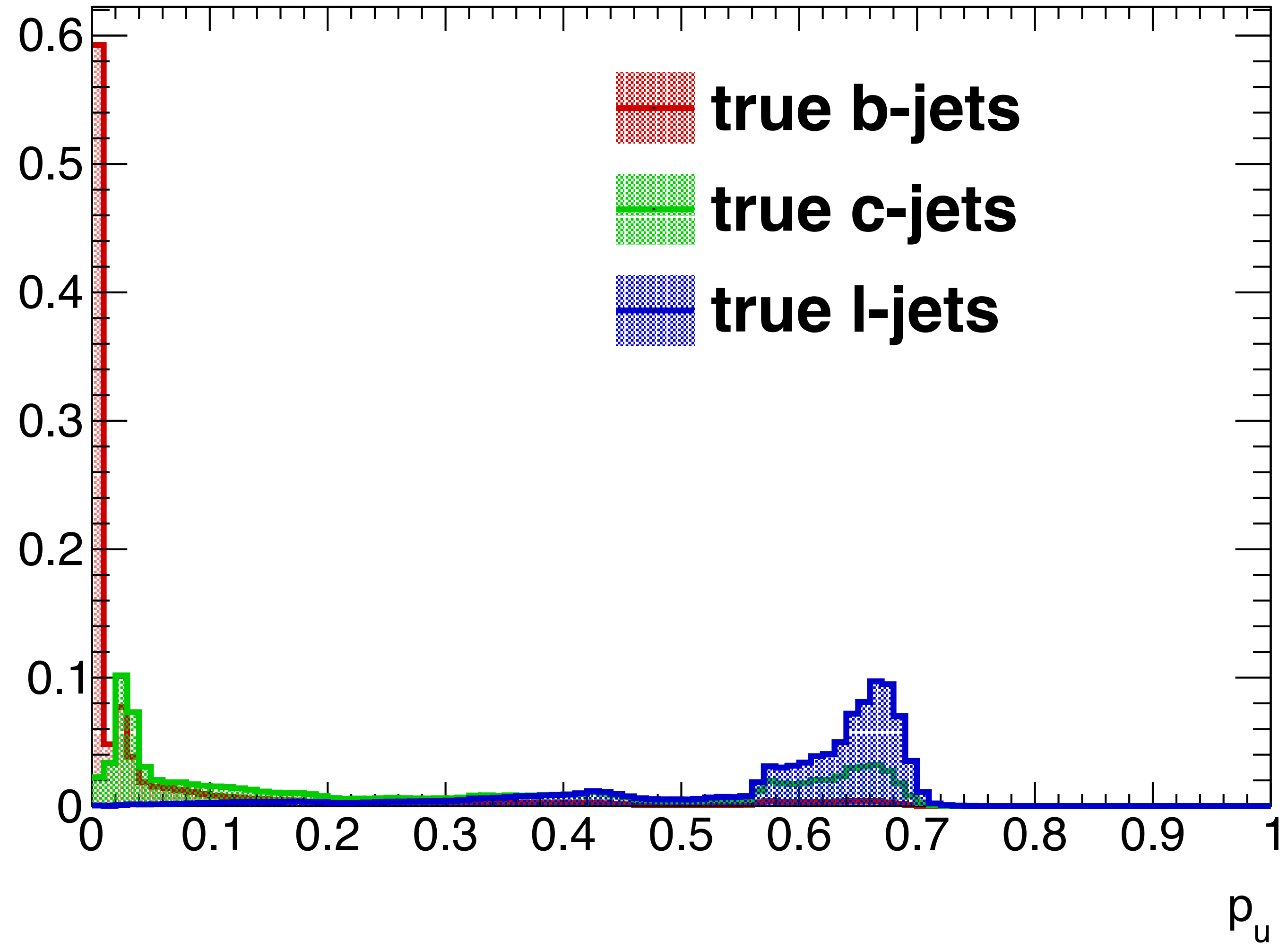
P(b-jet)



P(c-jet)



P(light-jet)



Flavour tagging performance:

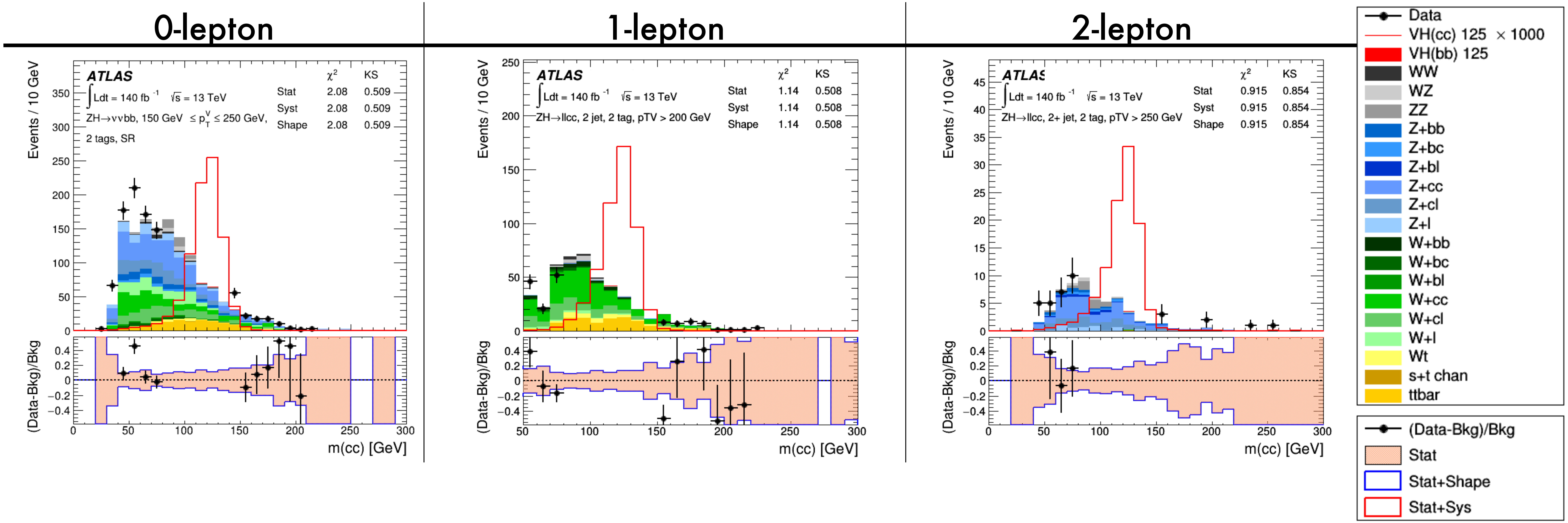
	c-tagger
c-jets	27%
b-jets	8%
light-jets	1,6%

	b-tagger
b-jets	70%
c-jets	11%
light-jets	0,2%

Preliminary results

Preliminary full Run 2 results

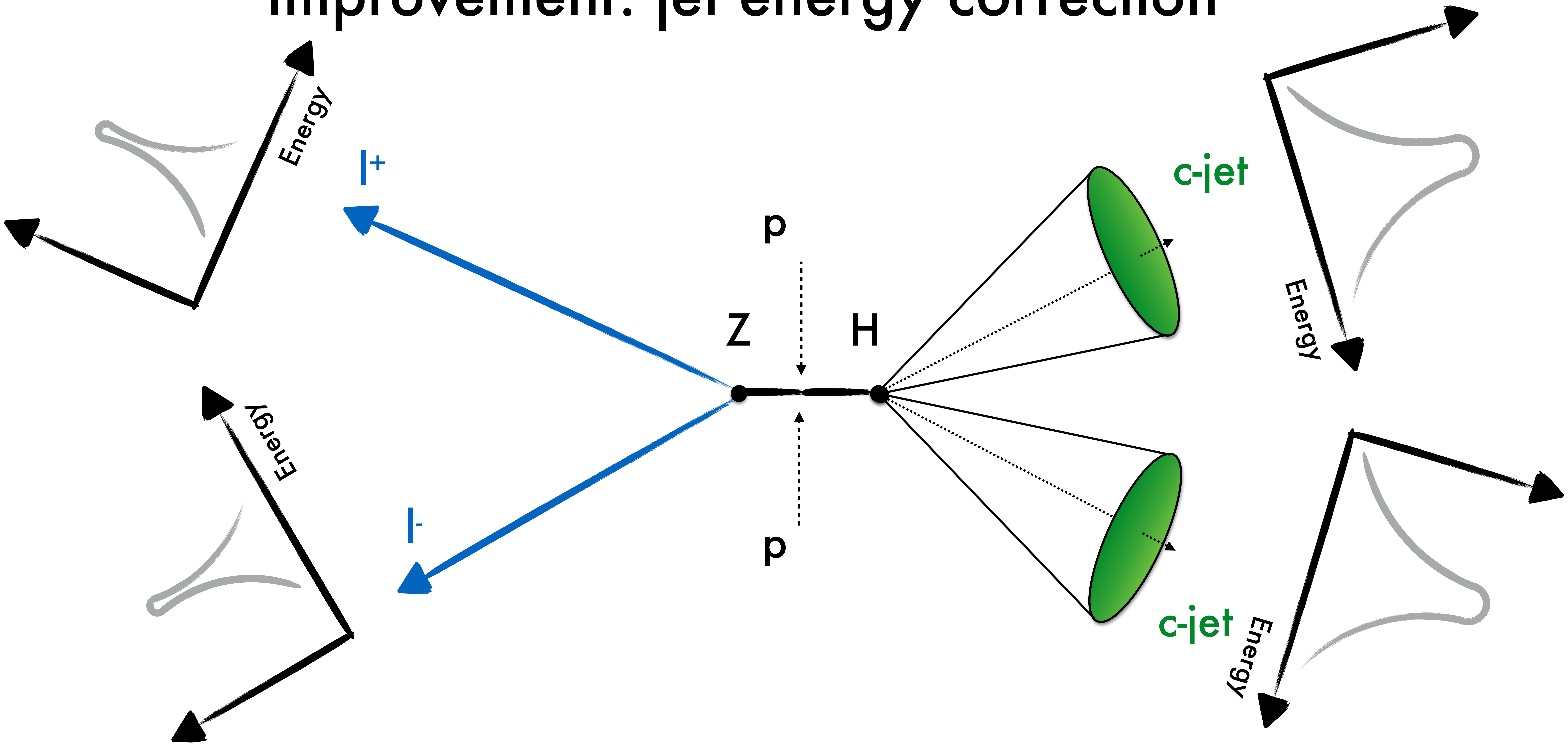
Signal and diboson blinded
Pre-fit



Invariant mass distribution of the Higgs candidate

- Dominated by large backgrounds: Z + 2 c-jets, W + 2 c-jets, top-antitop
- VH(cc) signal peak around 125 GeV

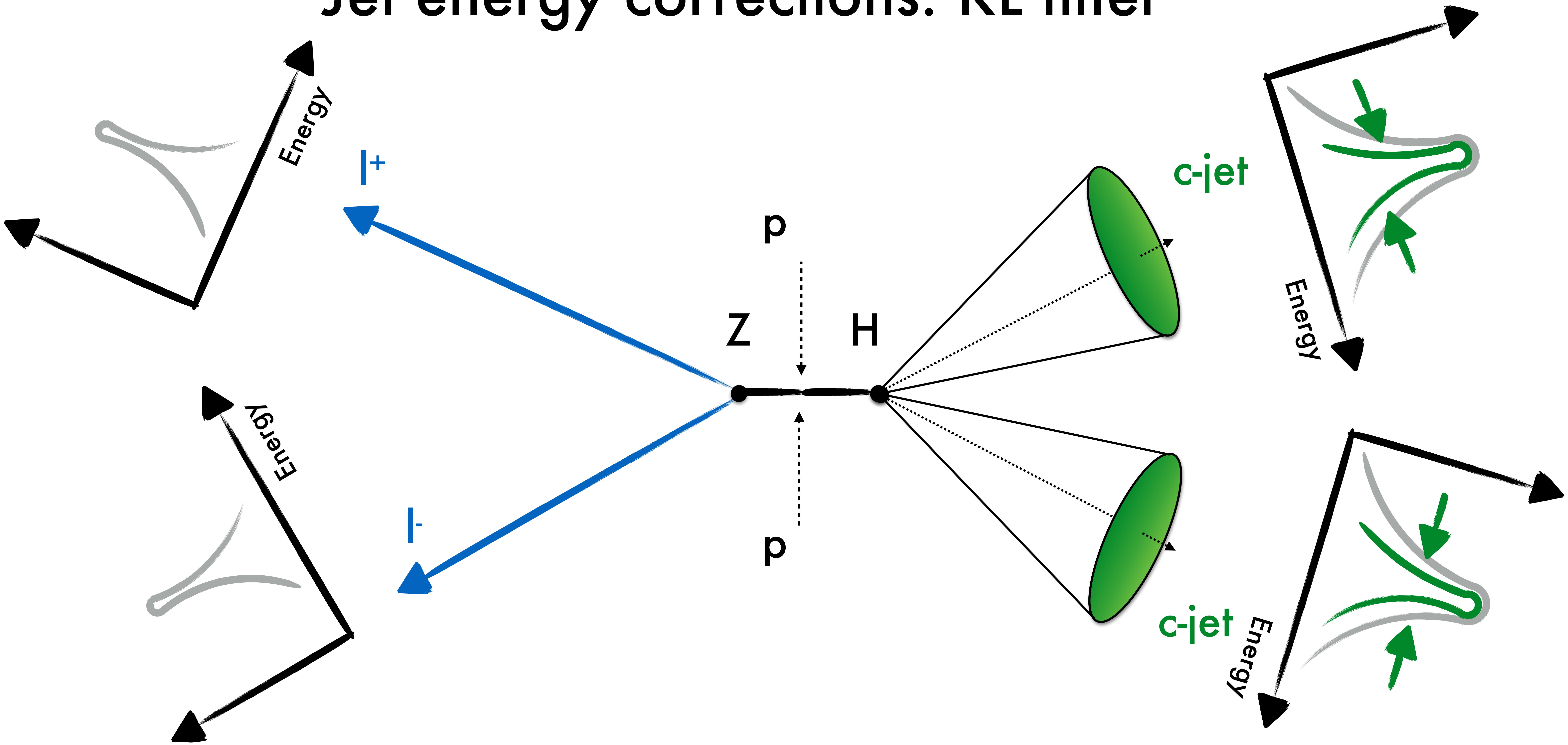
Improvement: jet energy correction



2-lepton channel:

- Jet energy resolution: 10%
- Leptons energy resolution: 1%

Jet energy corrections: KL fitter



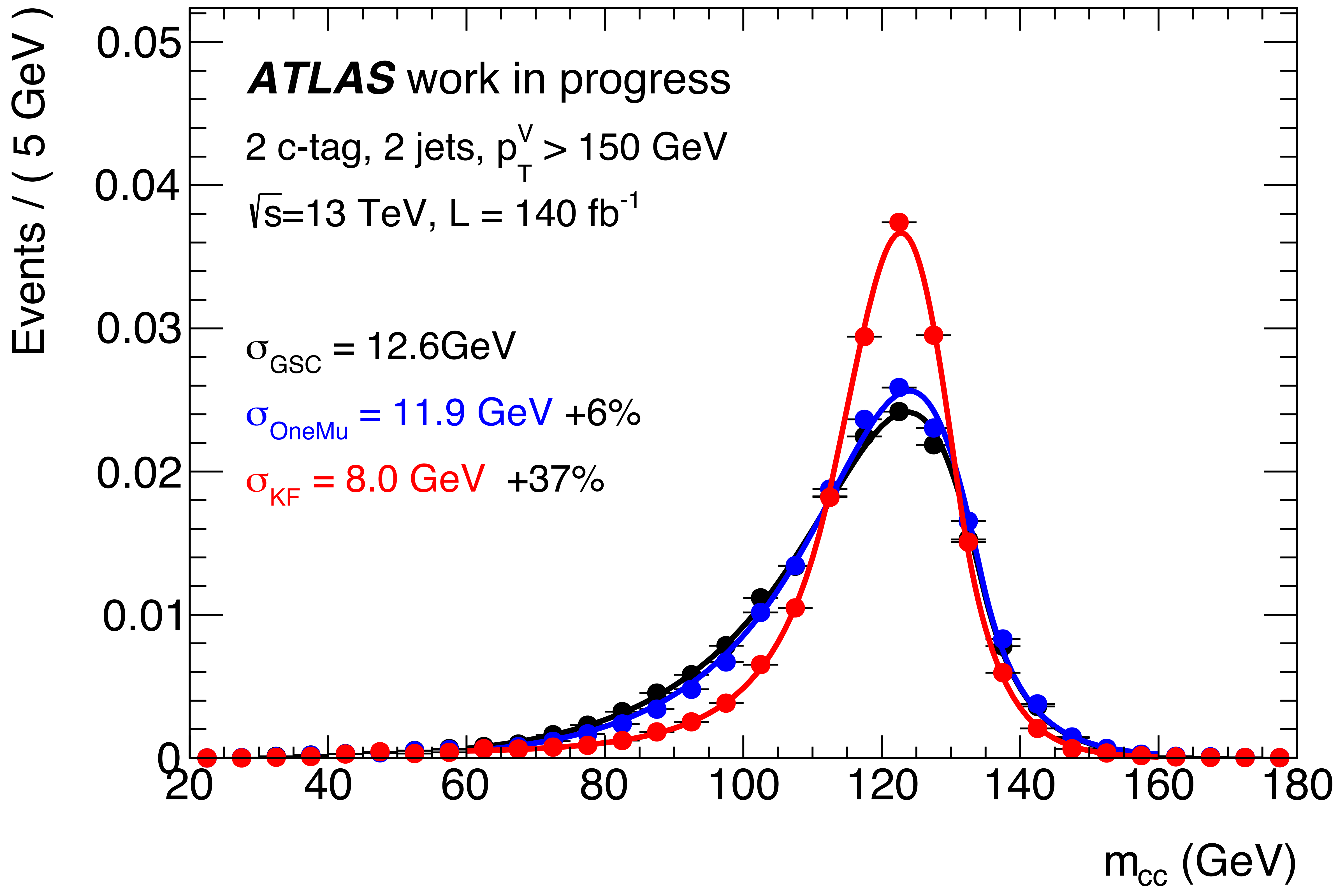
Kinematic Likelihood fitter (KL fitter):

- Fit event topology exploiting balance of p_T VH system
- Exploit leptons energy resolution to correct jet energy

→ Direct consequence: improvement in Higgs m(cc) resolution

VH(cc) 2-lepton mass resolution

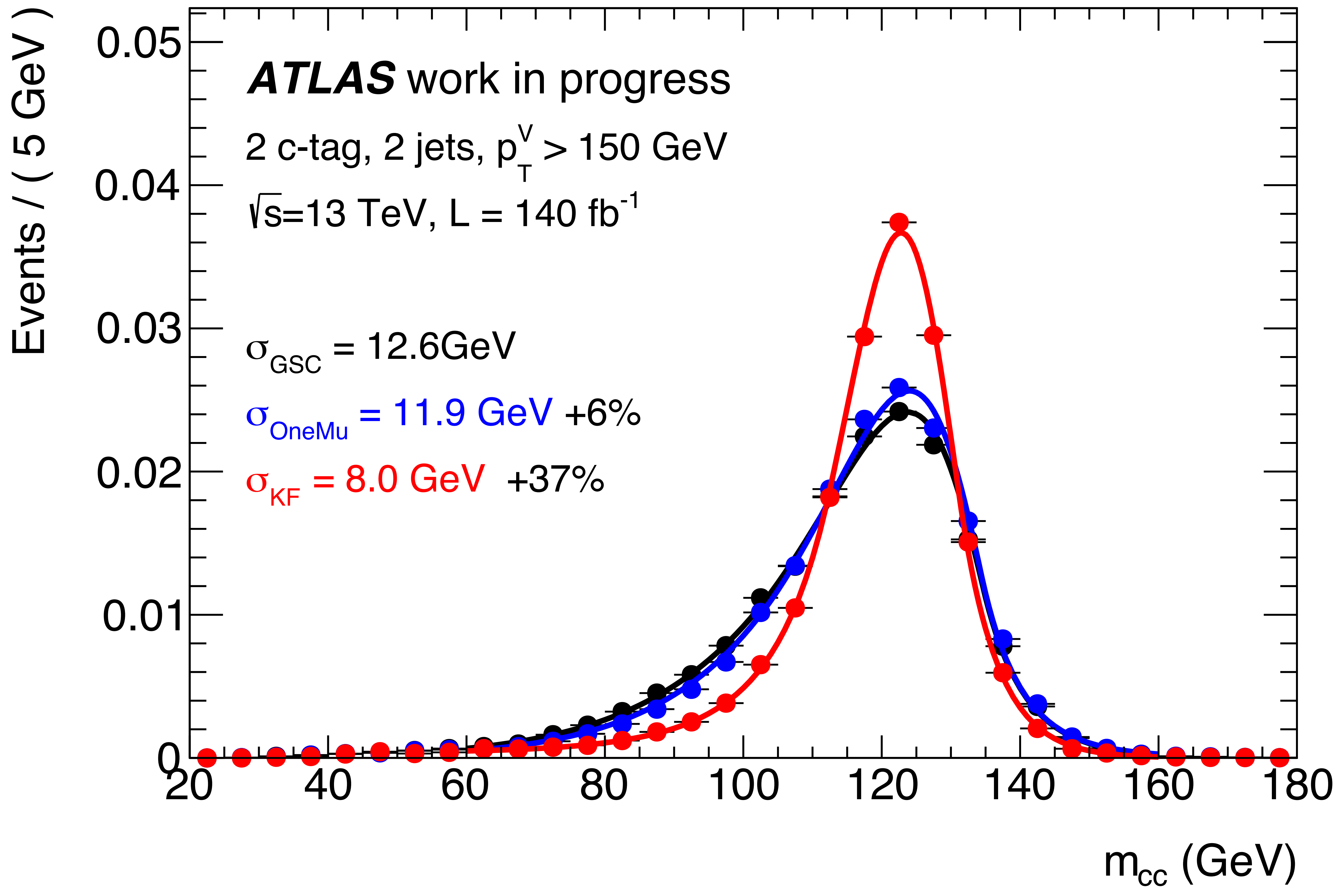
2 c-tag
2 jets
pTV > 150 GeV
qqZH(cc)



Standard Jet Calibration : σ = 12.6 GeV

VH(cc) 2-lepton mass resolution

2 c-tag
2 jets
pTV > 150 GeV
qqZH(cc)



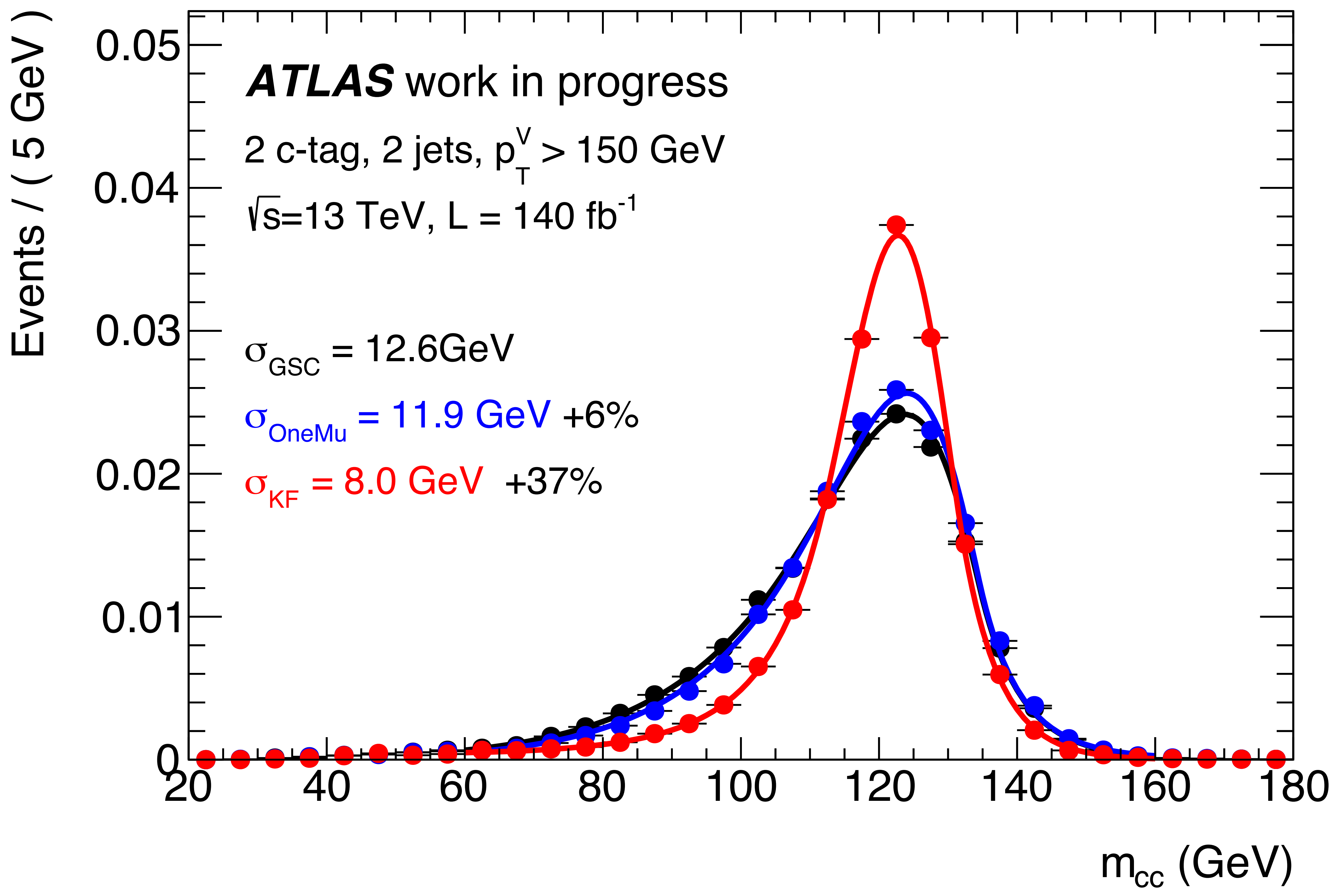
Standard Jet Calibration: σ = 12.6 GeV

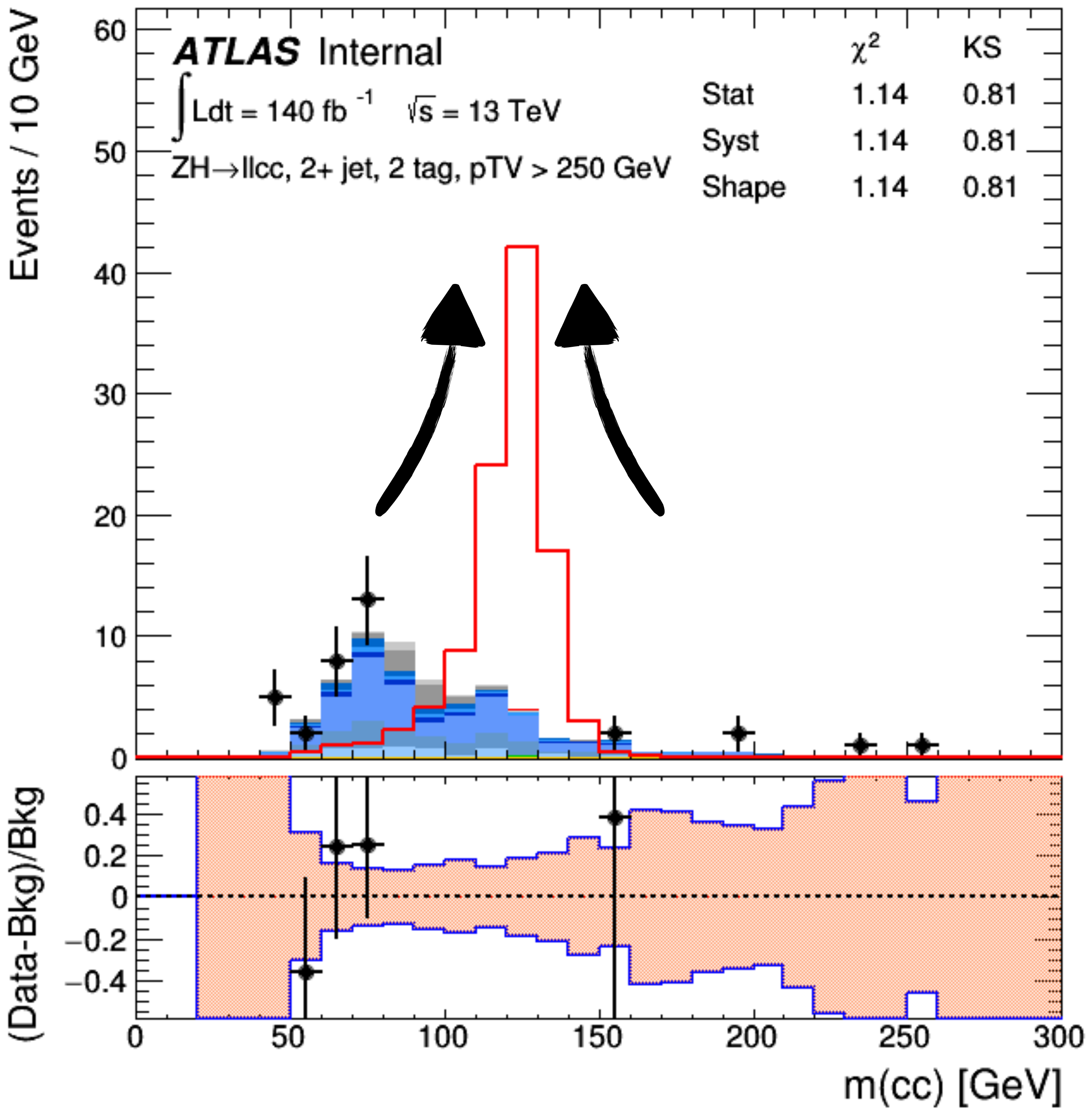
KL fitter σ_{KF} = 8.0 GeV

34% improvement on m(cc) resolution

VH(cc) mass resolution

2 c-tag
2 jets
pTV > 150 GeV
qqZH





Invariant mass resolution improvement: **x1.5**!

Sensitivity timeline: H → cc

2016: LHCb
LHCb-CONF-2016-006

2018: ATLAS
arXiv:1802.04329

2019: CMS
CMS-PAS-HIG-18-031

2020: ATLAS
ATLAS-CONF-2020-XXX

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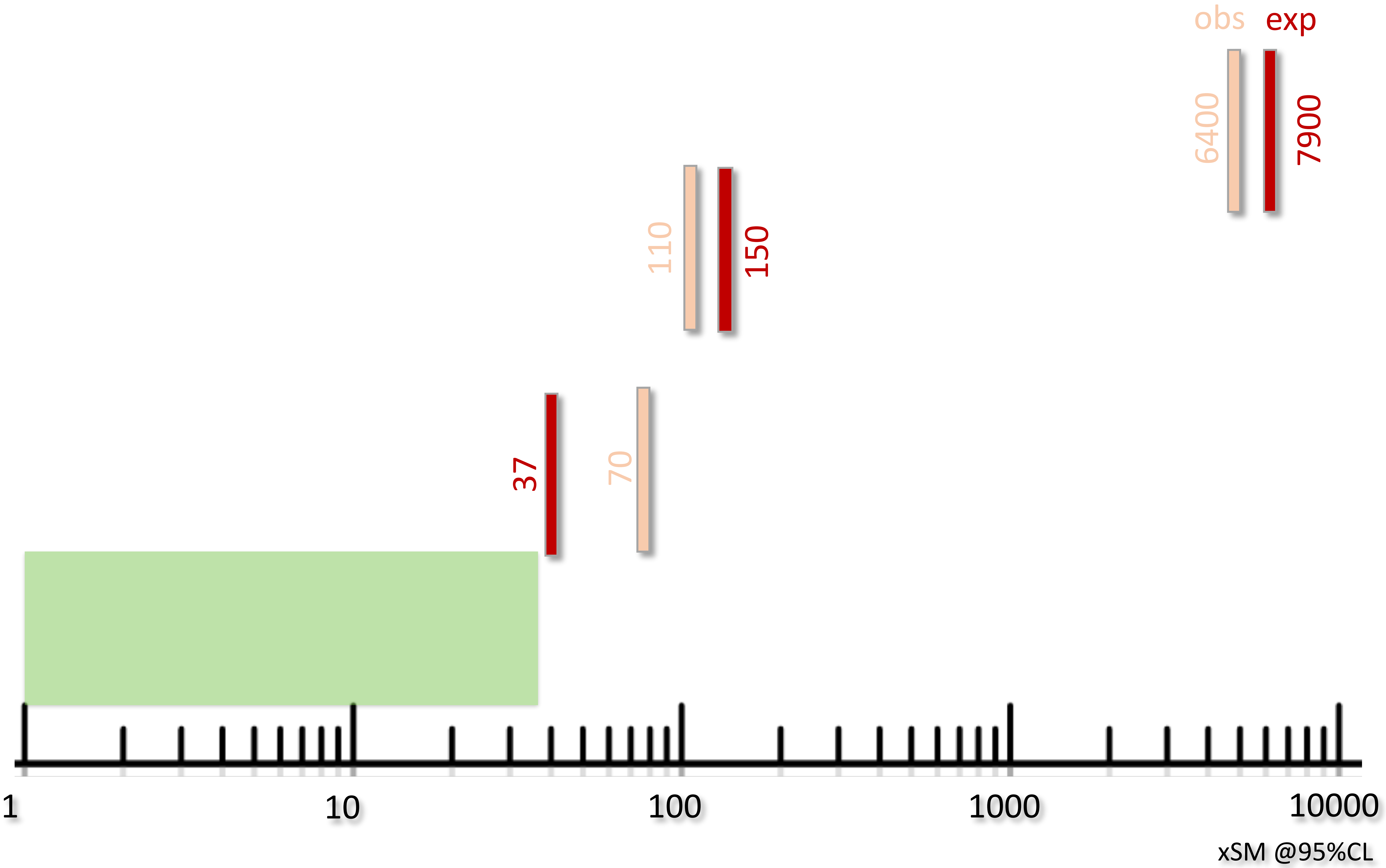
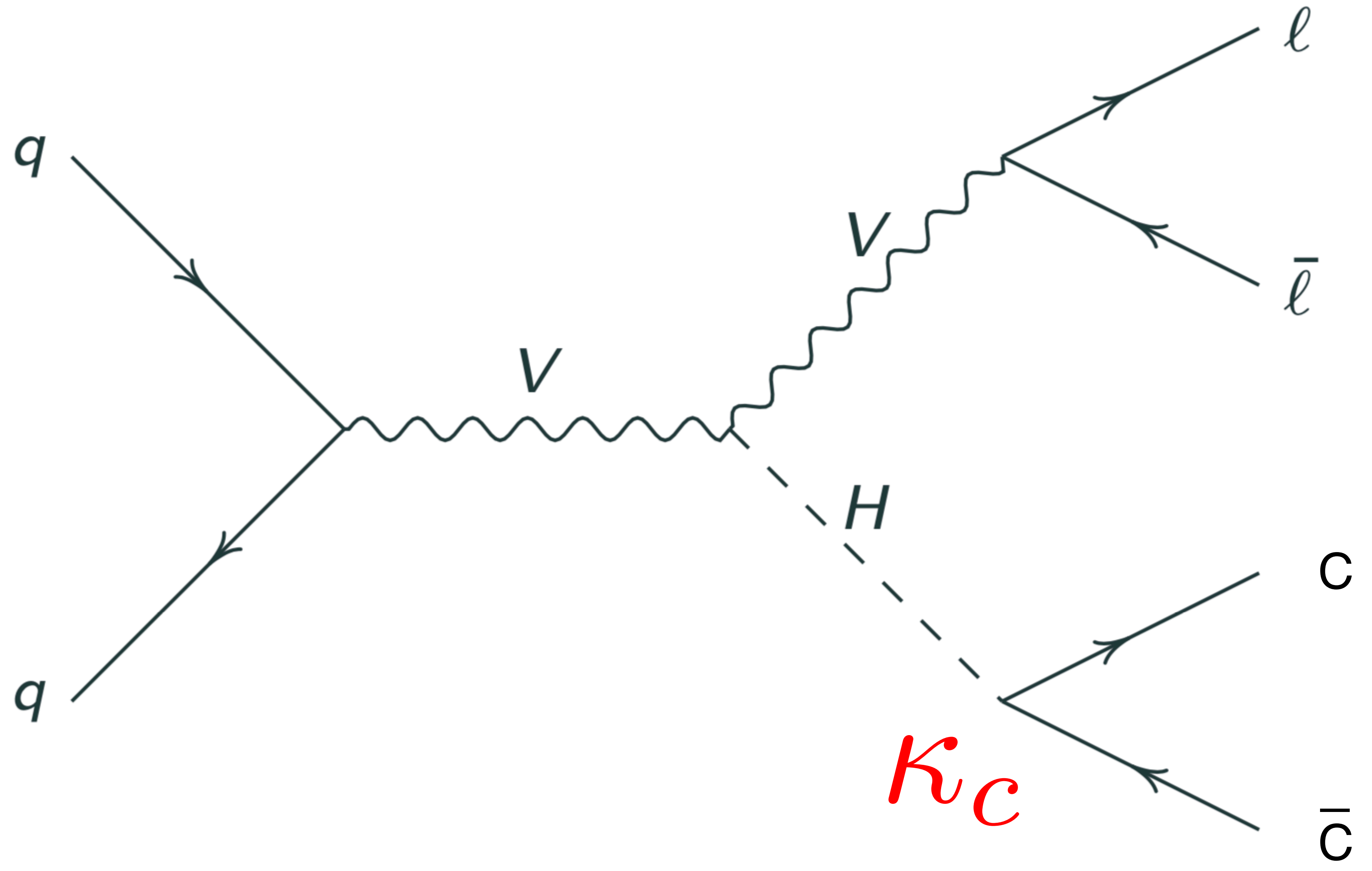


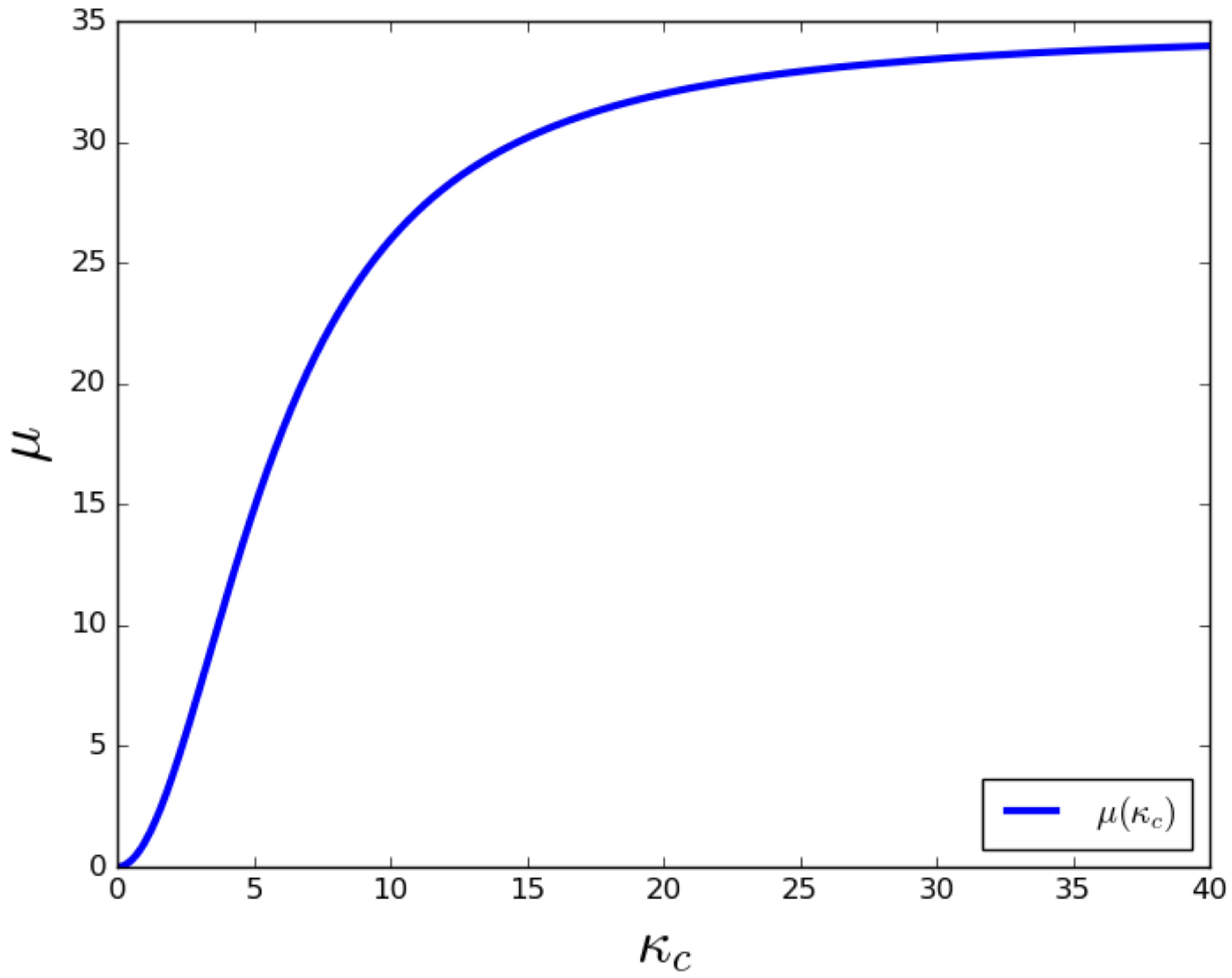
Kappa framework: VH(cc) case study



VH(cc) modified coupling:

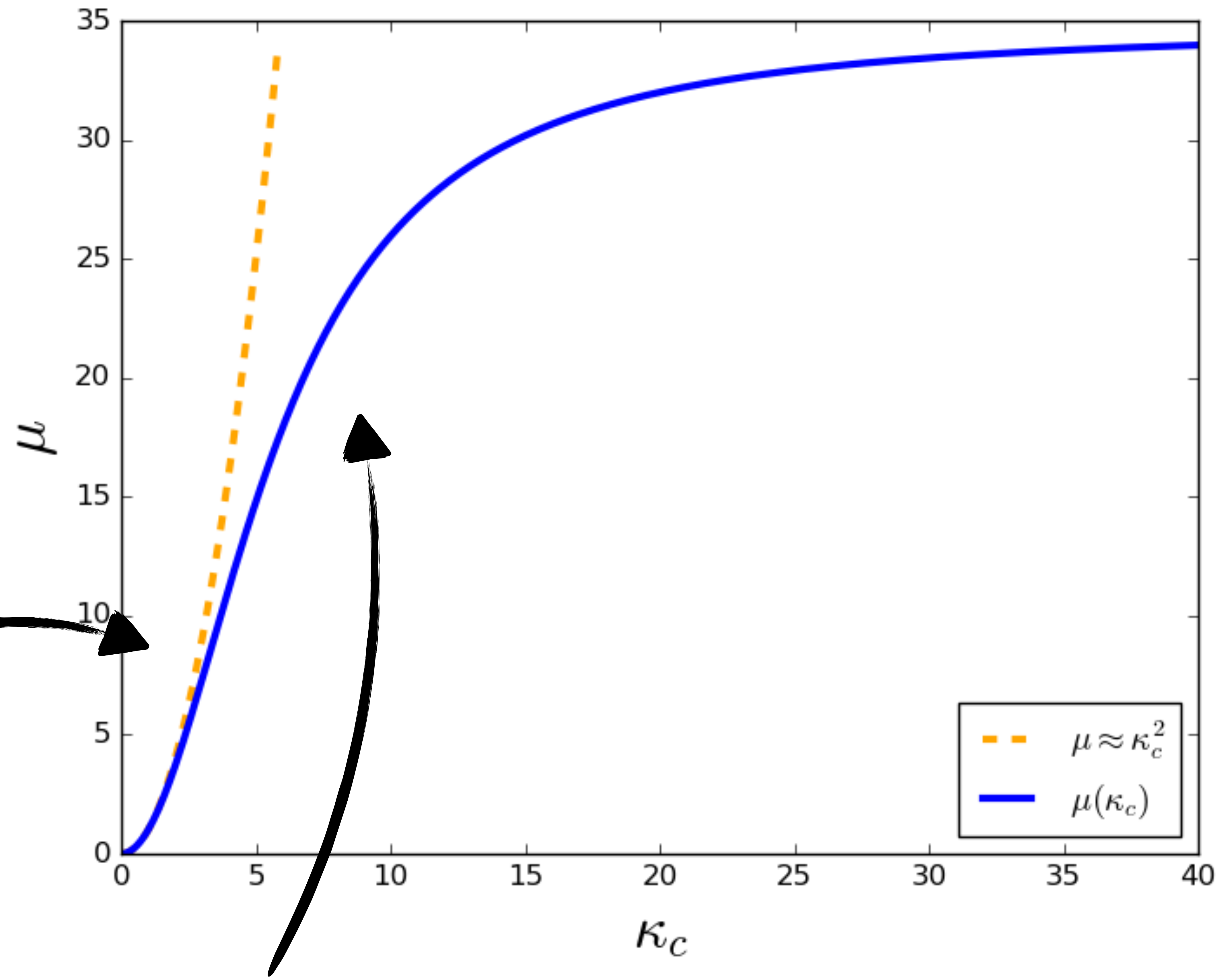
$$\sigma \times BR(VH(\rightarrow cc)) = \sigma_{SM} BR(VH(\rightarrow cc))_{SM} \times \frac{\kappa_c^2}{\Gamma_H}$$

Implications on κ_c interpretations



$$\mu = \frac{\sigma \times BR(VH(\rightarrow cc))}{\sigma_{SM} \times BR(VH(\rightarrow cc))_{SM}} \xrightarrow{\kappa_j \approx 1 \quad \forall j \neq c} \mu \approx \frac{\kappa_c^2}{0.97 + 0.03 \times \kappa_c^2}$$

Implications on κ_c interpretations



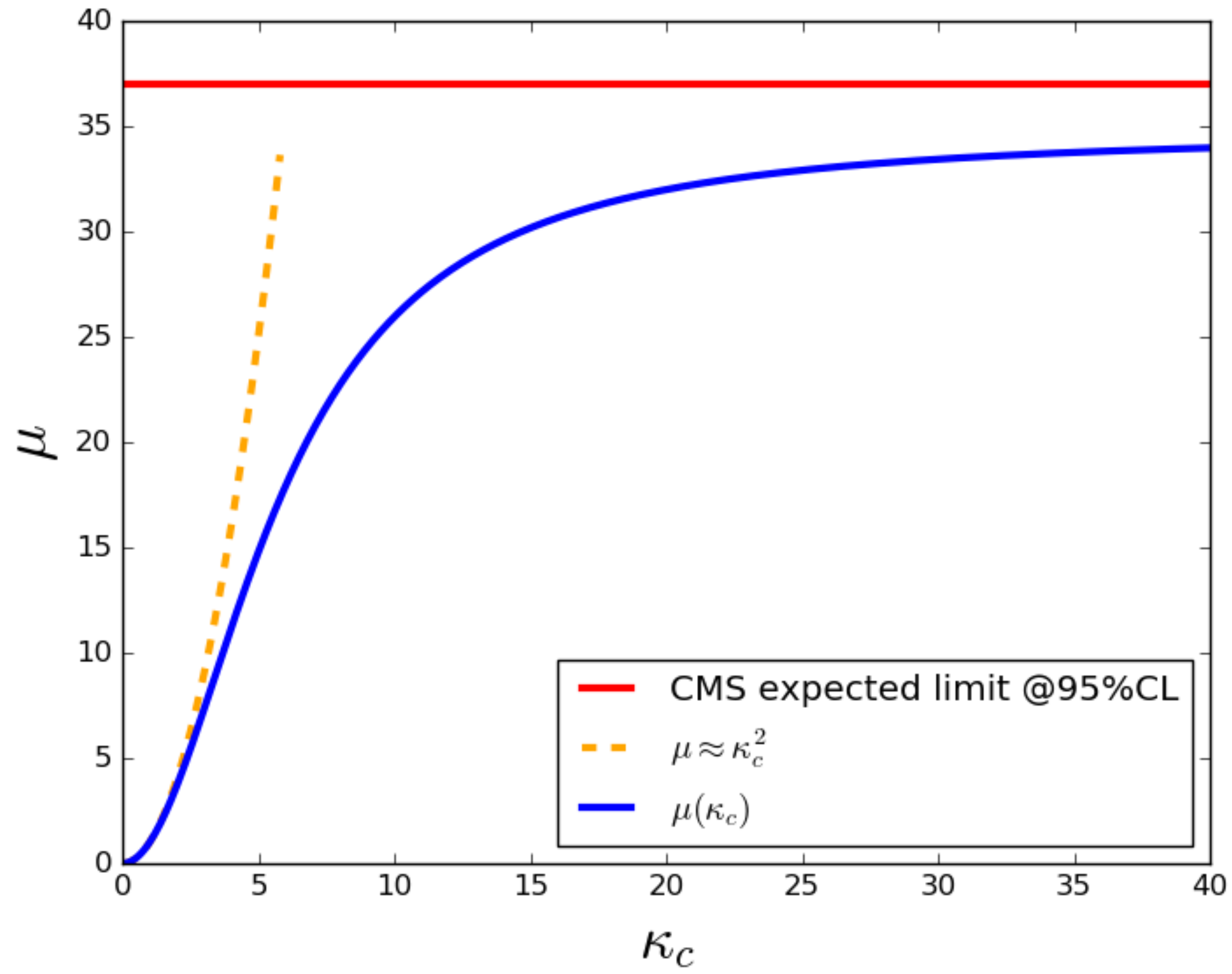
Low κ_c

$\mu \sim \kappa_c^2$

High κ_c

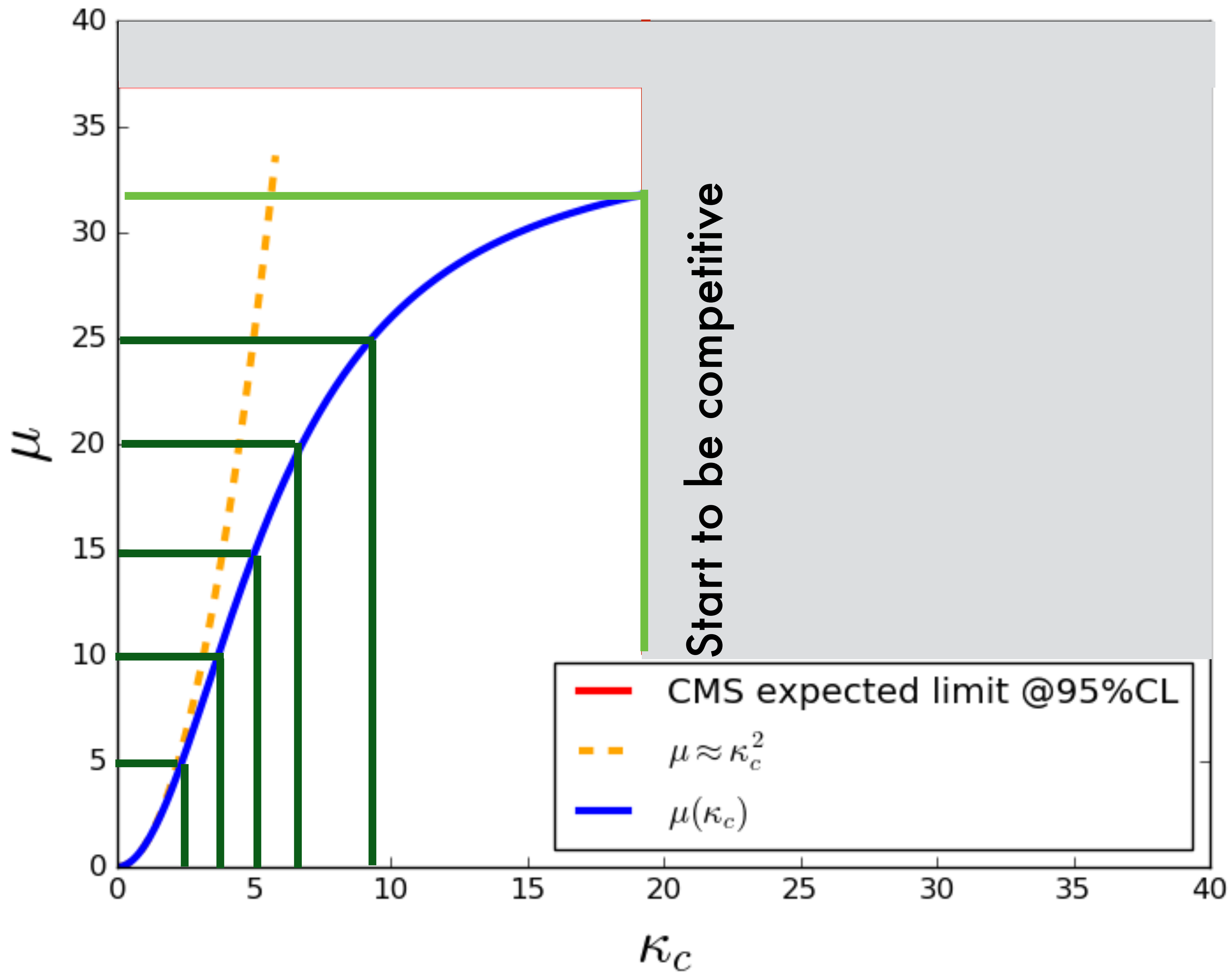
$\mu \neq \kappa_c^2$

Implications on κ_c interpretations



CMS has no sensitivity on κ_c

Implications on κ_c interpretations

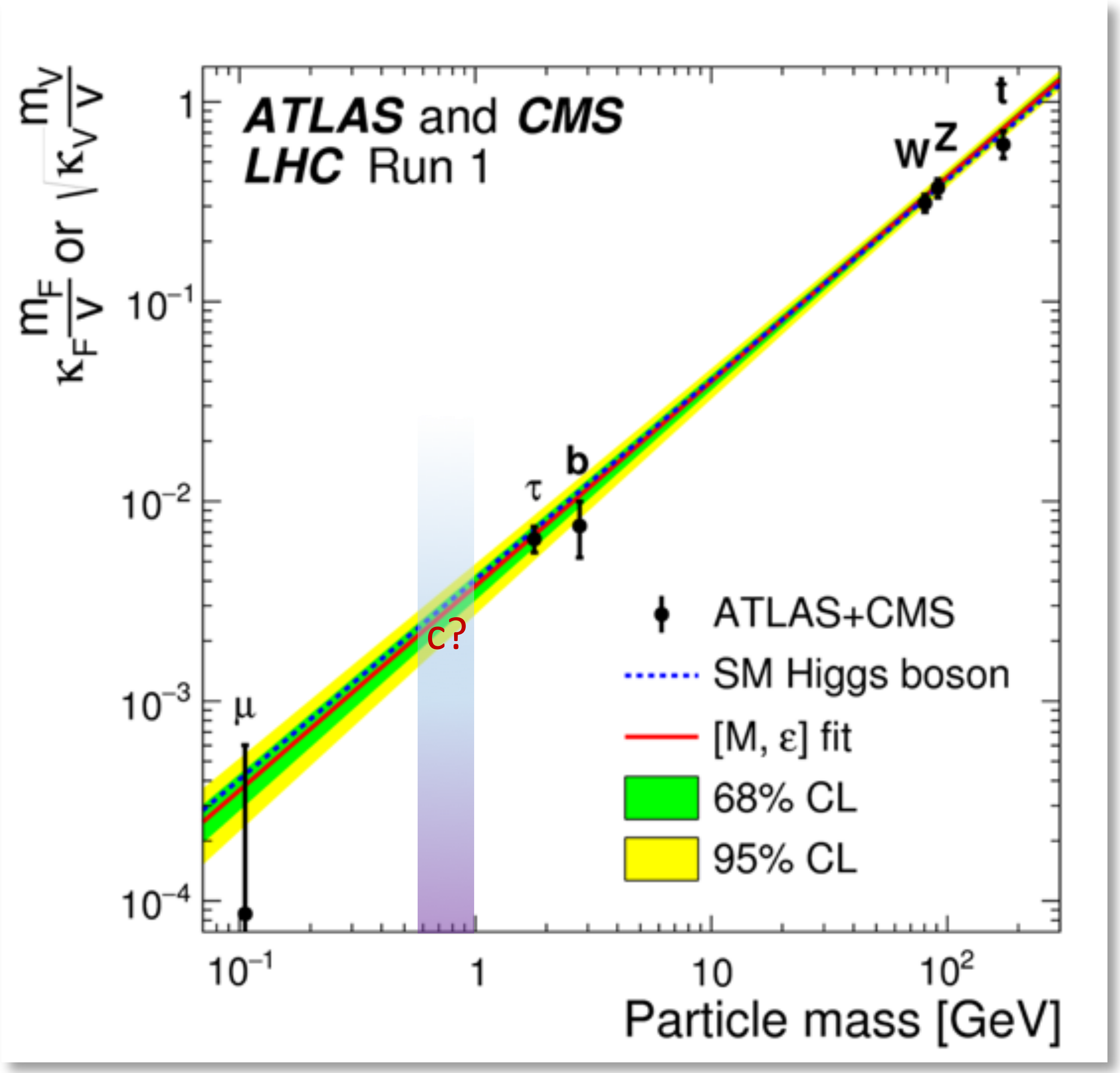


ATLAS VHcc Full Run 2:

- Start to constrain κ_c at $\mu = 30$

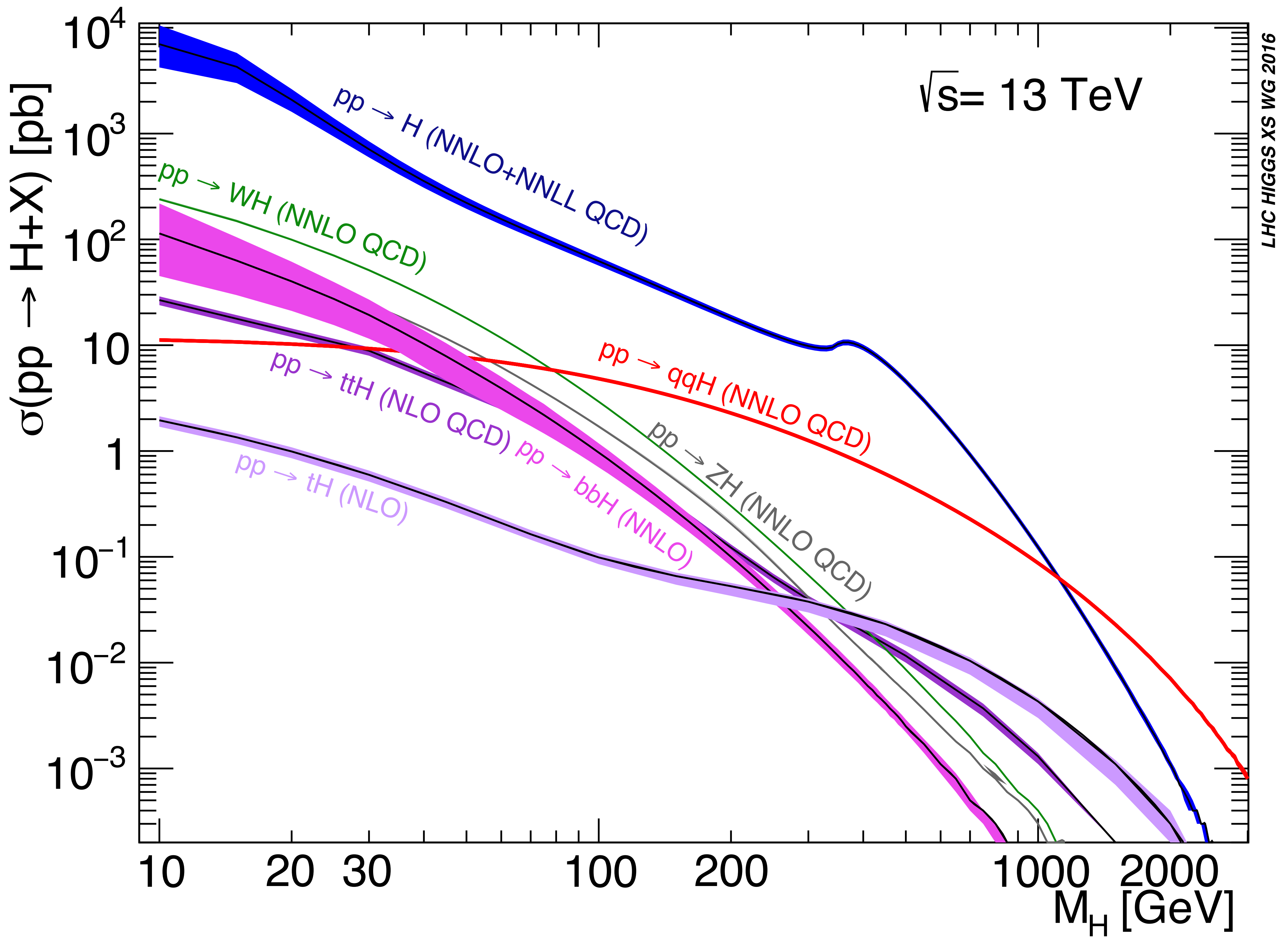
→ Our analysis can set the **first direct** constraint to κ_c

Thanks for you attention!



Back up

Why investigate VH?

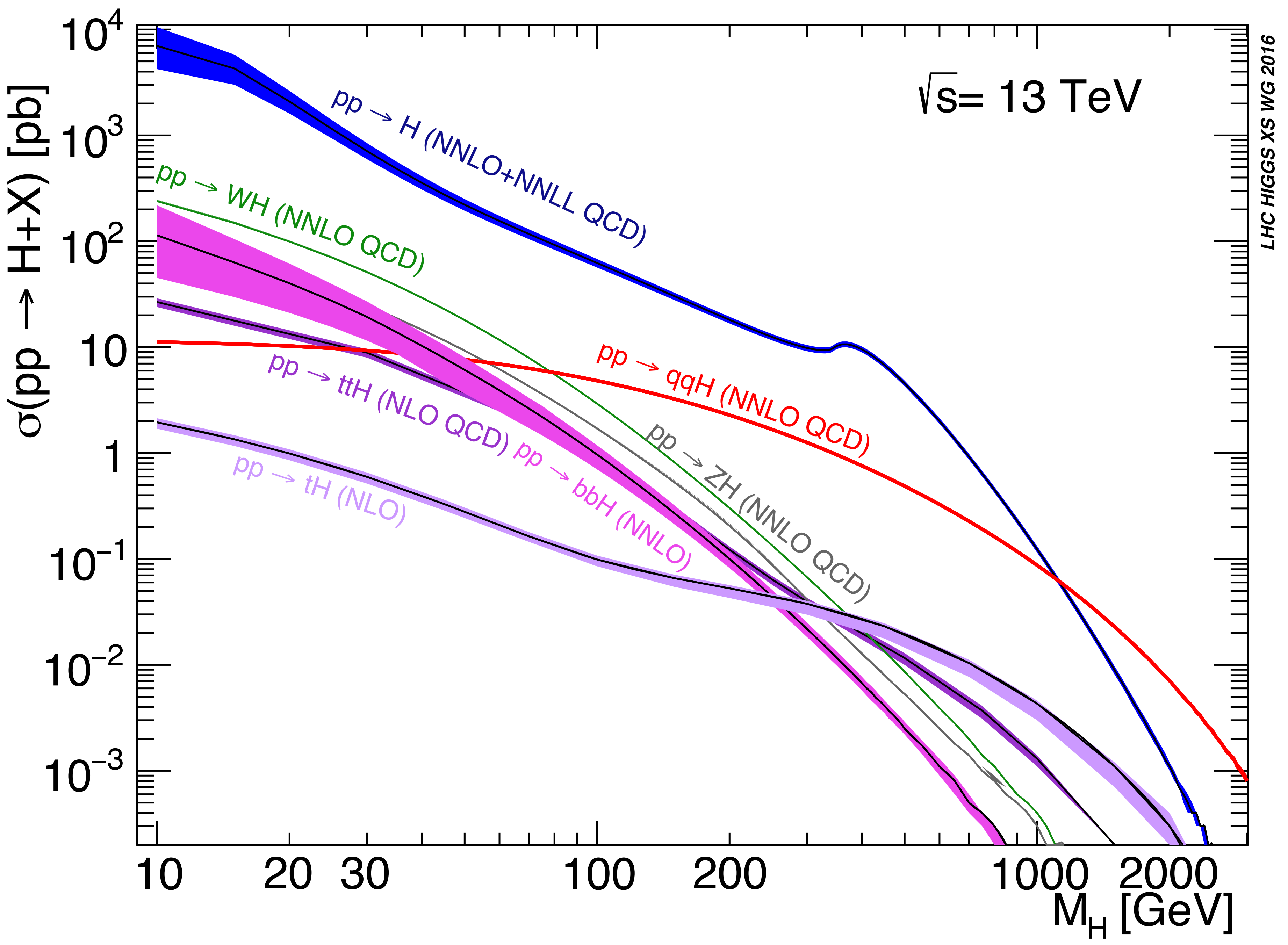


Ranking of production modes:

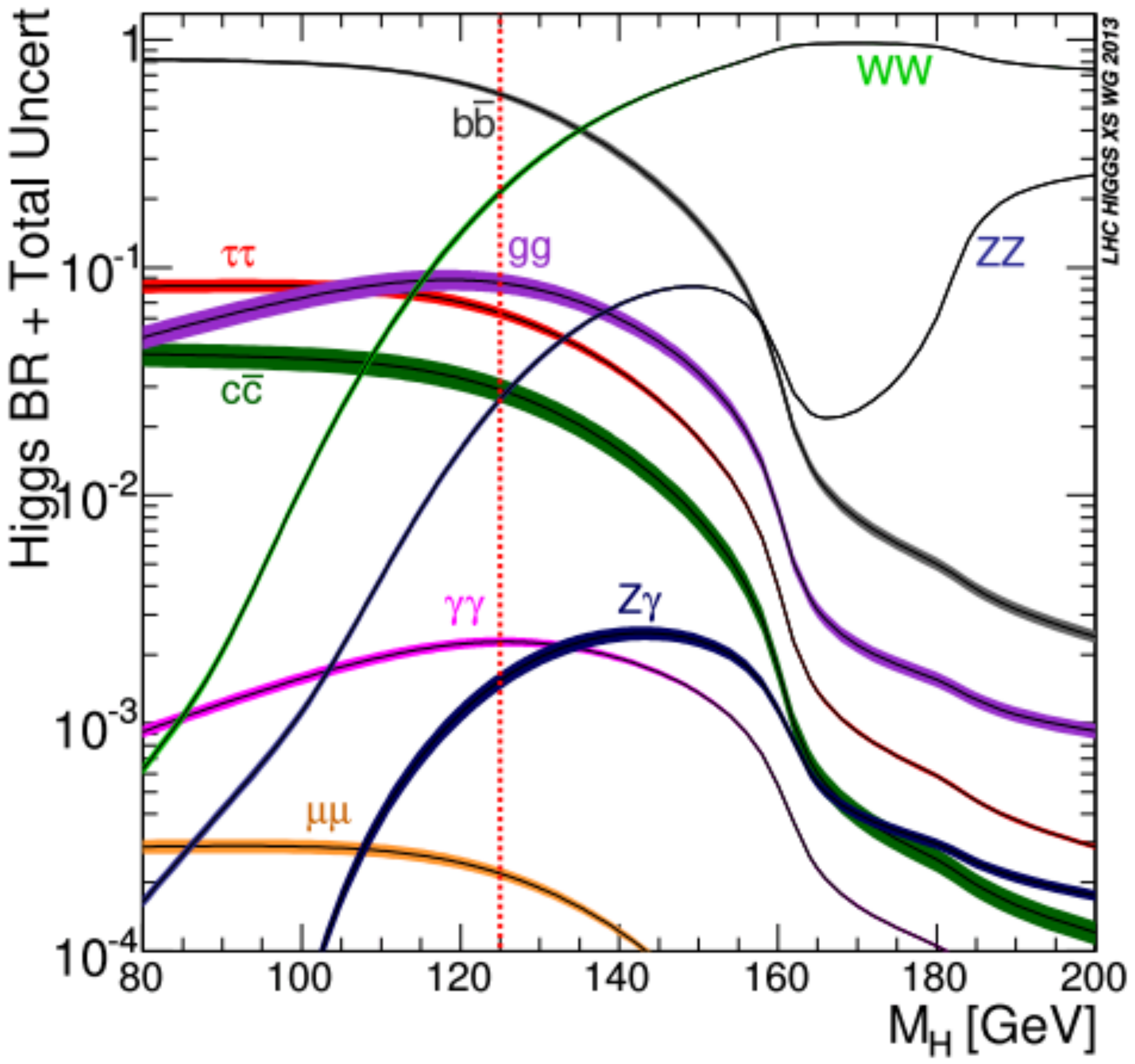
1. Gluon-gluon fusion
2. Vector-boson fusion
3. WH (because needs valence quarks)
4. ZH (because need sea quark (anti-u)
5. bbH (because less energy required for production)
6. ttH (because requires ~ 450 GeV to produce on-shell)
7. tH (off-shell only)

Higgs coupling in a nutshell

Higgs cross section production



Higgs branching ratios



Standard Model Higgs couplings:

Fermions: $g_f = \frac{\sqrt{2} m_f}{v}$

Vector bosons: $g_V = \frac{2 m_V^2}{v}$

Kappa framework

Measure deviations of Higgs couplings from SM:

- Inspired by Leading Order (LO) diagrams of Higgs couplings

3 main assumptions:

- Higgs boson resonance at 125 GeV
- Narrow-width approximation valid (due to 4 MeV Higgs width)
- Tensor structure of the Lagrangian → CP-even scalar

Narrow width approximation:

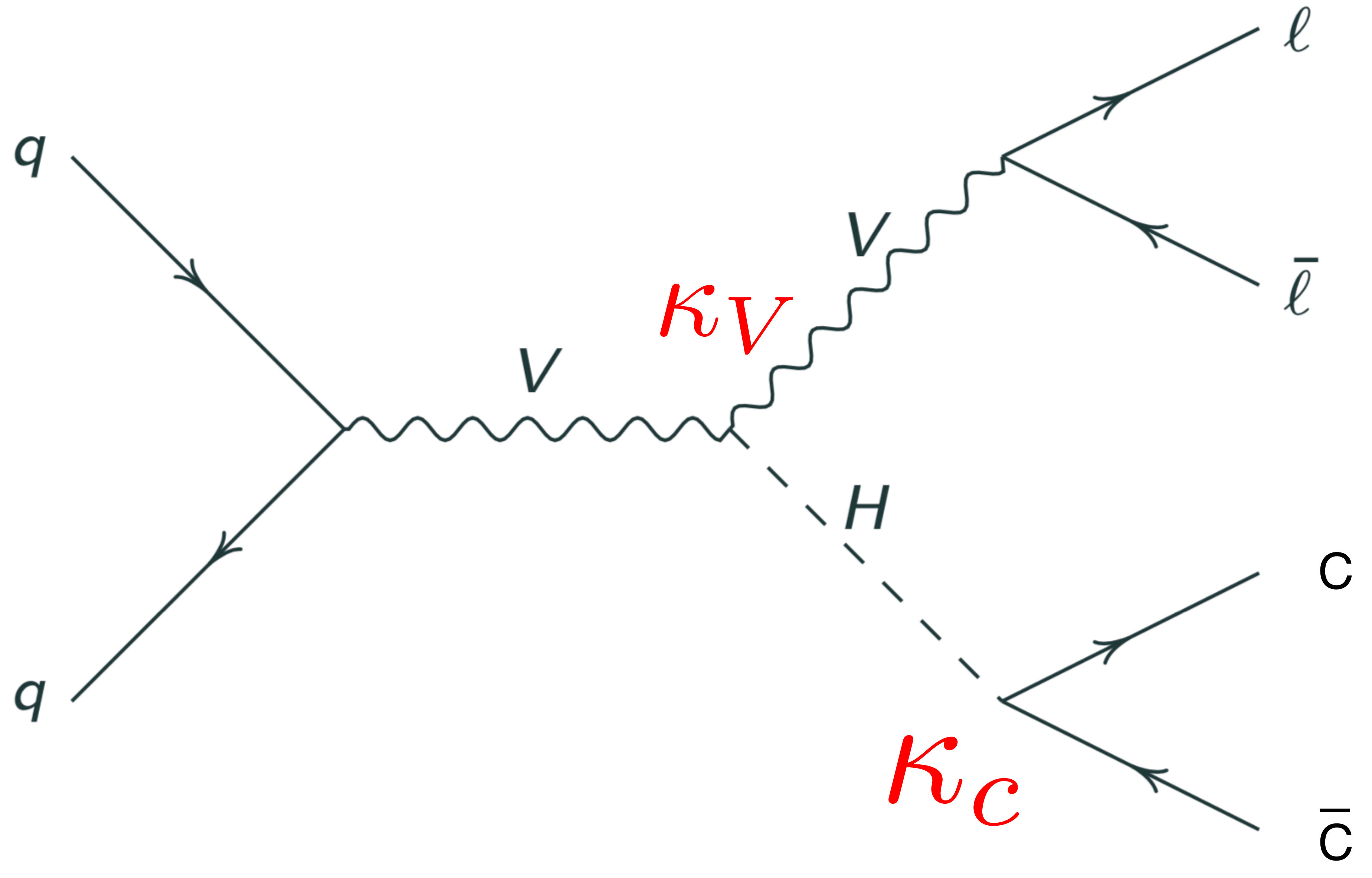
$$\sigma \times BR(i \to H \to f) = \frac{\sigma_i \times \Gamma_f}{\Gamma_H}$$

Kappa framework scaling:

$$g_i \longrightarrow \kappa_i g_i$$

$$\sigma \times BR(i \to H \to f) = \frac{\sigma_i^{SM} \kappa_i^2 \times \Gamma_f^{SM} \kappa_f^2}{\Gamma_H^{SM} \kappa_H^2}$$

Kappa framework: VH(cc) case study

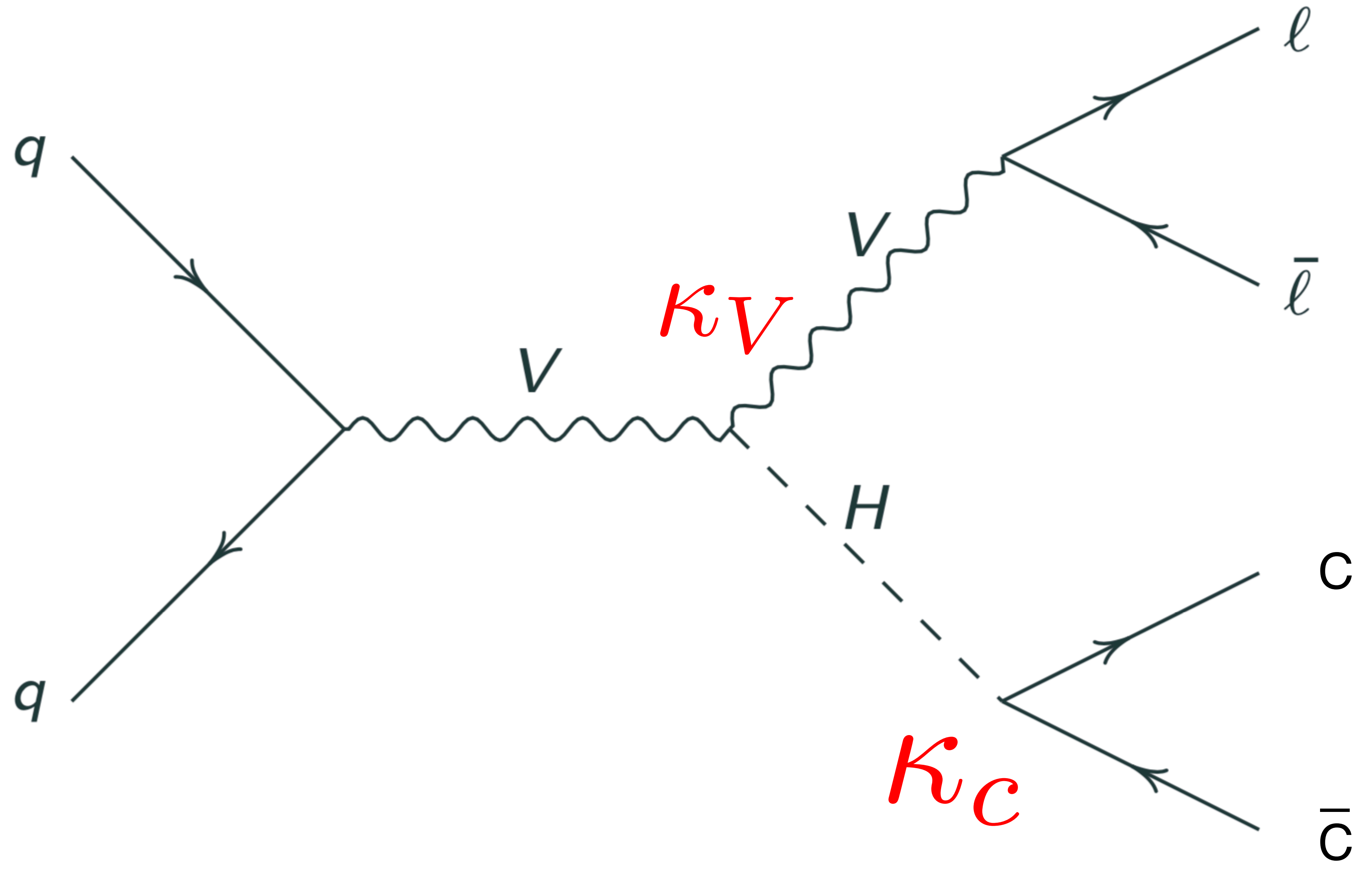


VH(cc) modified coupling:

$$\sigma \times BR(VH(\rightarrow cc)) = \sigma_{SM} \times BR(VH(\rightarrow cc))_{SM} \times \frac{\kappa_V^2 \kappa_c^2}{\kappa_H^2}$$

$$\kappa_H^2 = \frac{\sum_j \Gamma_j}{\Gamma_H^{SM}} = \frac{\sum_j \Gamma_j^{SM} \times \kappa_j^2}{\Gamma_H^{SM}}$$

Kappa framework: VH(cc) case study



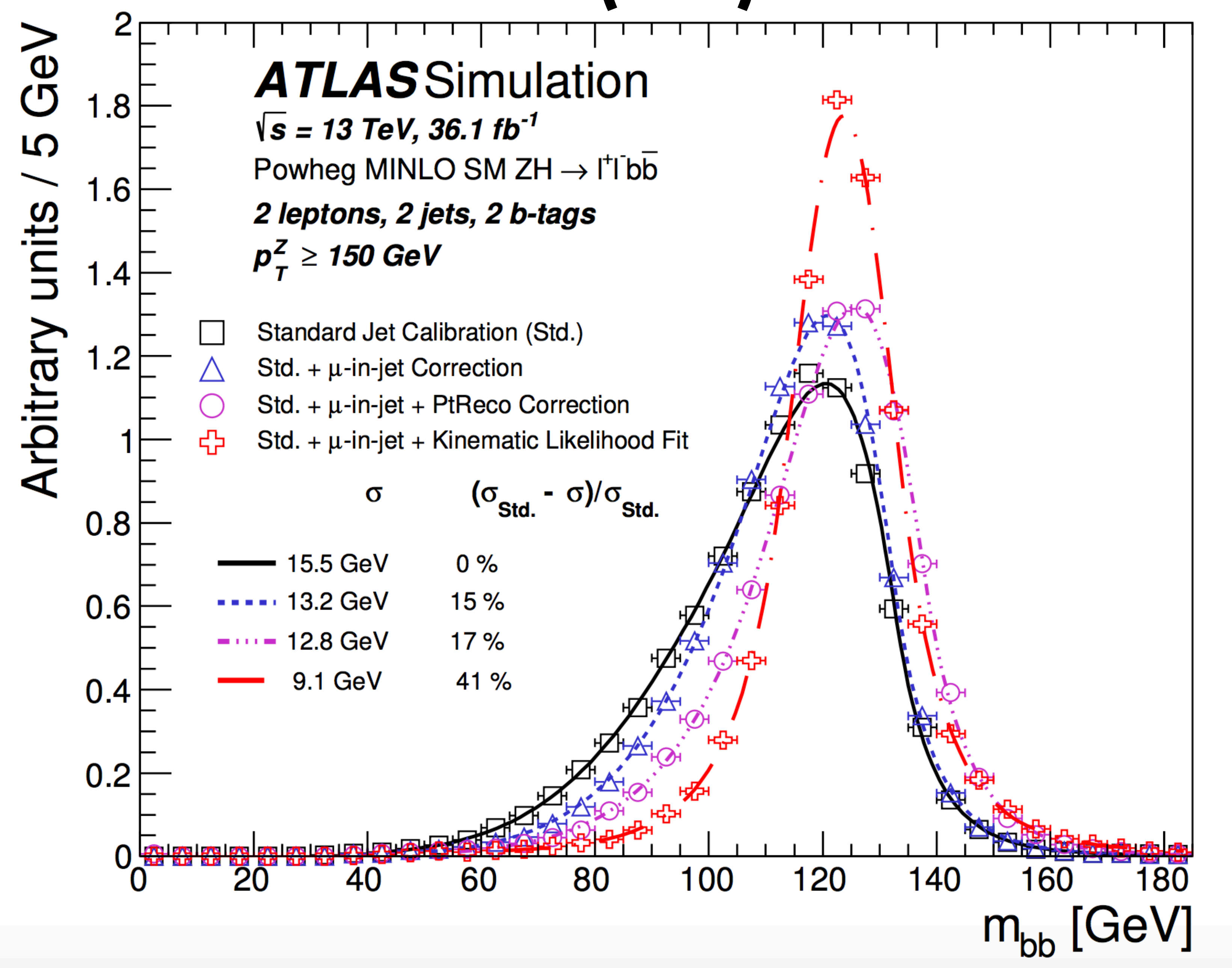
VH(cc) measurement:

$$\mu = \frac{\sigma \times BR(VH(\to cc))}{\sigma_{SM} \times BR(VH(\to cc))_{SM}} \xrightarrow{\kappa_j \approx 1 \quad \forall j \neq c} \mu \approx \frac{\kappa_c^2}{0.97 + 0.03 \times \kappa_c^2}$$

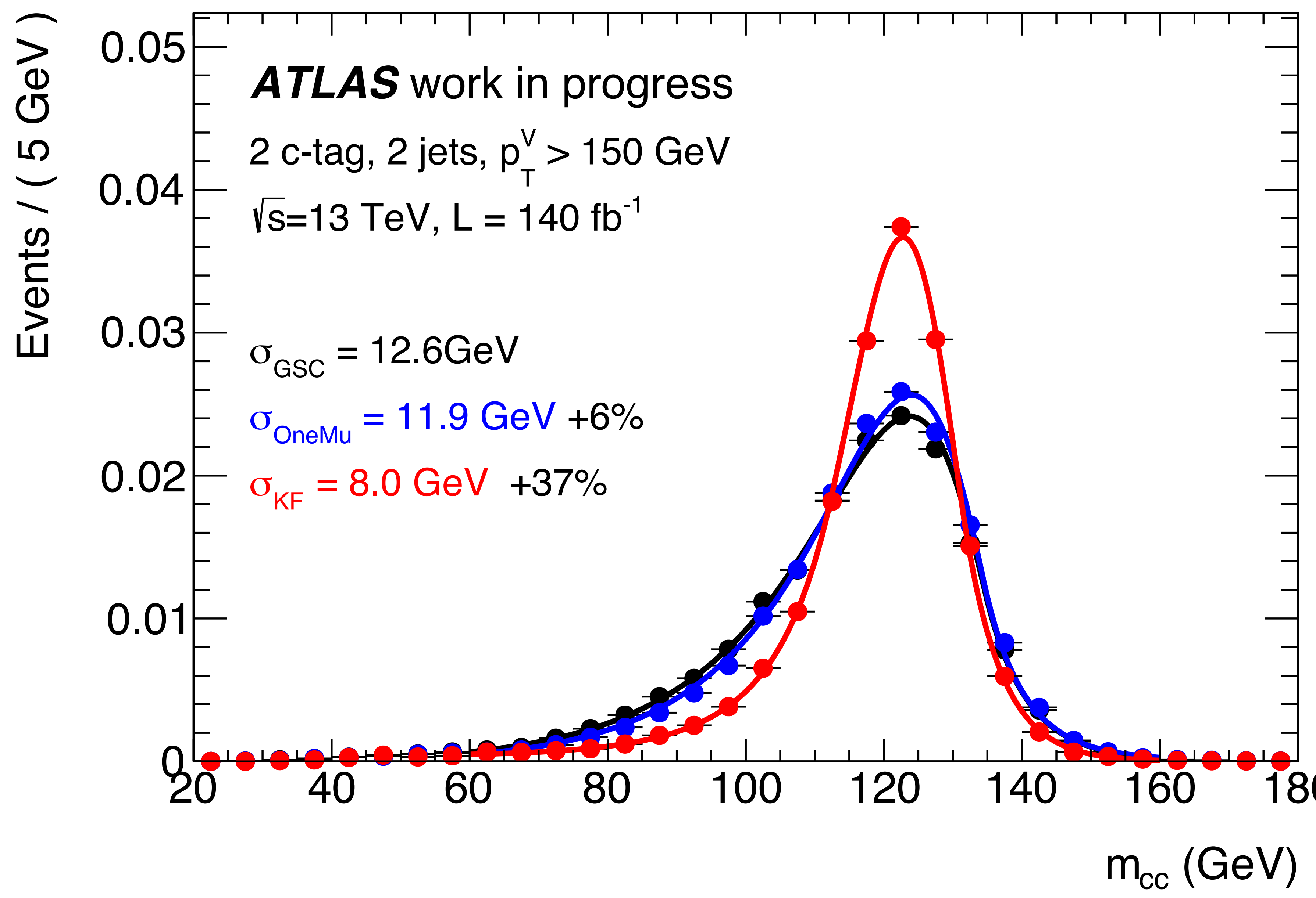
VH(bb) vs VH(cc) comparison

2 c-tag
2 jets
pTV > 150 GeV
qqZH

VH(bb)



VH(cc)



σ_{GSC} = 15.5 GeV

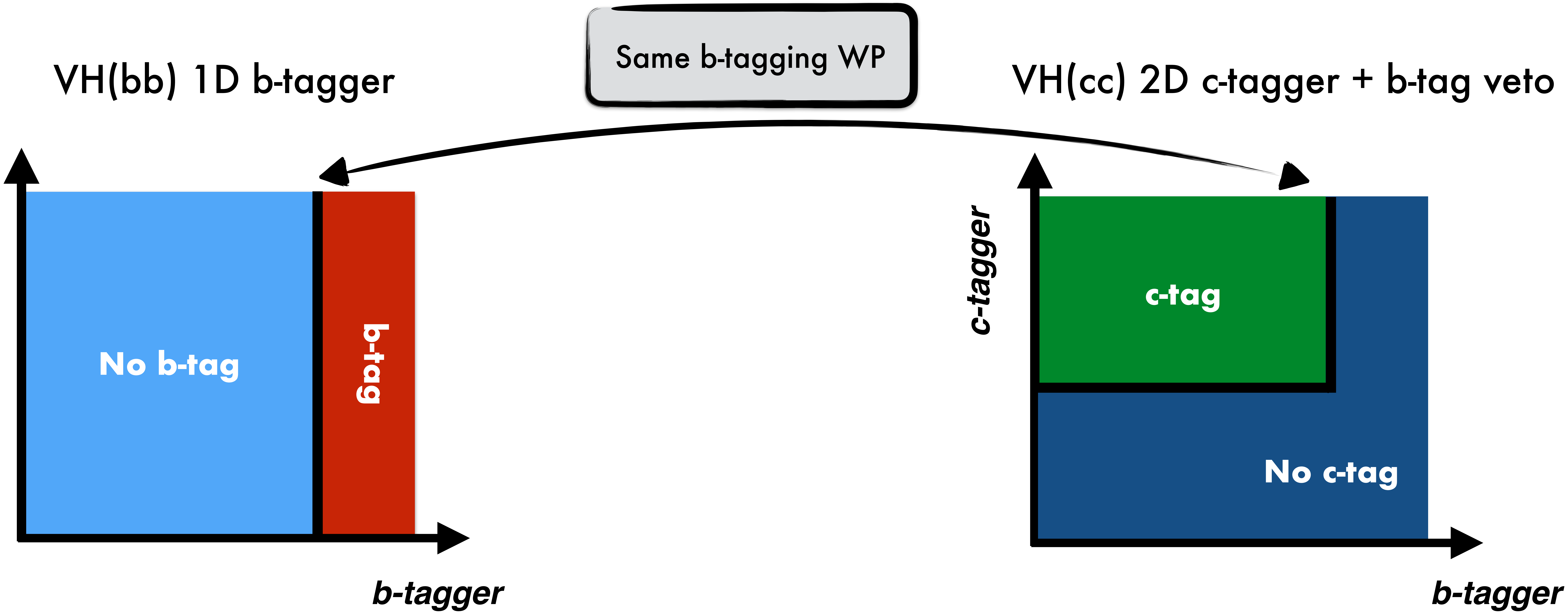
σ_{KF} = 9.1 GeV

σ_{GSC} = 12.6 GeV ⟵ 19% better

σ_{KF} = 8.0 GeV ⟵ 10% better

VH(cc) mass resolution better than VH(bb) due to less muons in c-hadrons decay chains

VH(bb) and VH(cc) orthogonality



Exclusive flavour tagging between VH(bb) and VH(cc):

- Reduced VH(bb) contamination in VH(cc) signal region ✓
- Possible combined measurement of VH(bb) and VH(cc) ✓