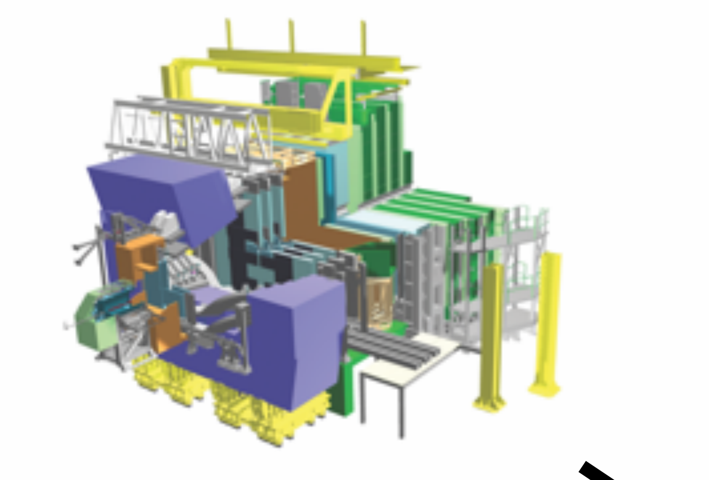
# Theory prospects with electroweak physics, Higgs & exotica

Uli Haisch
University of Oxford

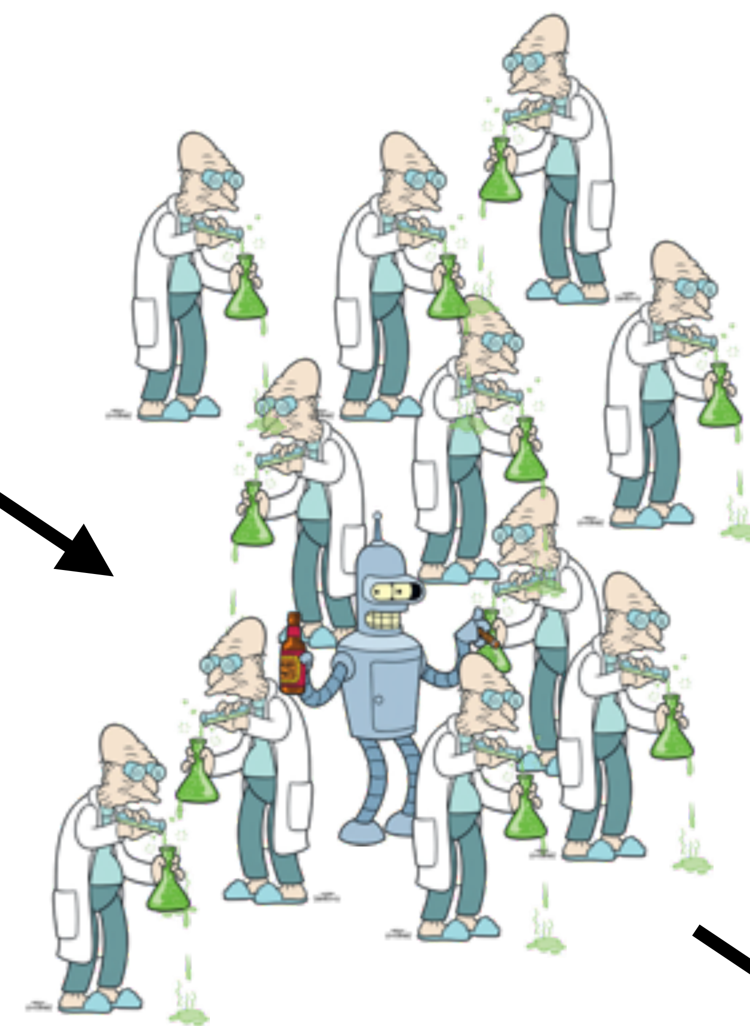
Beyond the LHCb Phase-I Upgrade, 28-31 May 2017 La Biodola, Isola d'Elba (Italy)

# So far …



LHCb

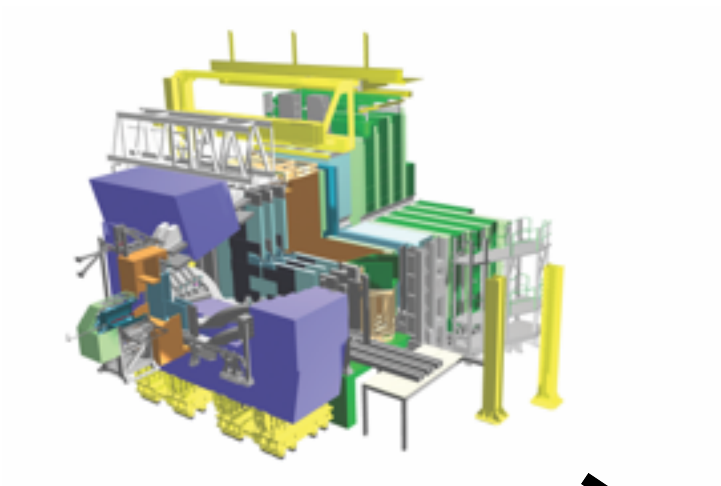
$P_i', R_K,$
$R_{K^*}, \ldots$



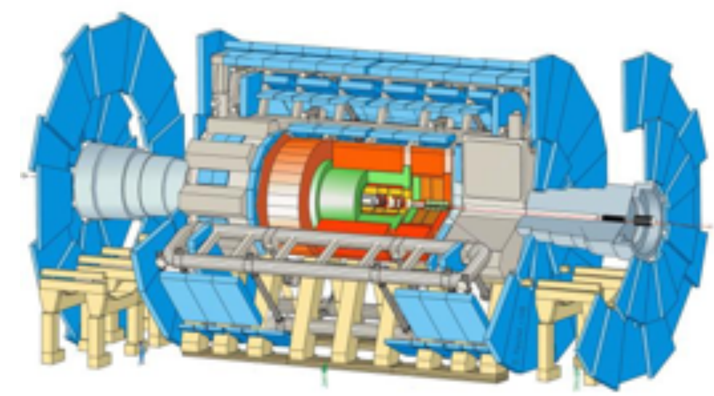
theory

$C_9 \simeq -1$

# while in this talk …

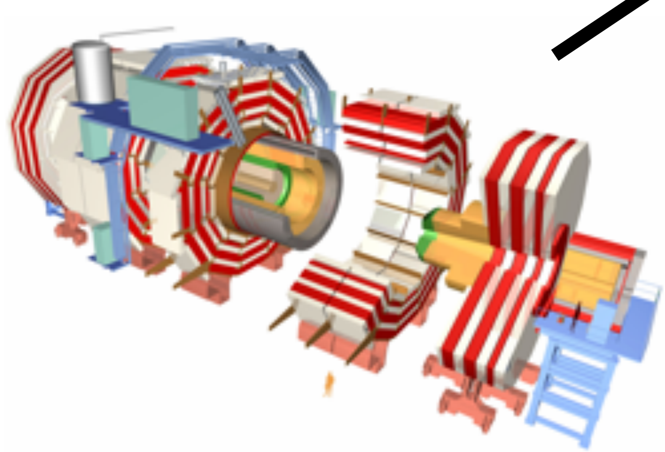


LHCb



ATLAS

$$Z, W, t, h, \ldots$$



CMS

theory

?

thanks to Fady Bishara & Mika Vesterinen for brainstorming

# Z/W-boson physics at LHCb

LHCb Phase-II Upgrade EoI document mentions 14 studies of electroweak boson production, i.e. 10% of all citations


[11] LHCb collaboration, R. Aaij *et al.*, *Measurement of the forward-backward asymmetry in $Z/\gamma^* \to \mu^+\mu^-$ decays and determination of the effective weak mixing angle*, JHEP **11** (2015) 190, arXiv:1509.07645.

…

[74] LHCb collaboration, R. Aaij *et al.*, *Measurement of forward $W \to e\nu$ production in pp collisions at $\sqrt{s} = 8$ TeV*, JHEP **10** (2016) 030, arXiv:1608.01484.

[75] LHCb collaboration, R. Aaij *et al.*, *Measurement of the forward $Z^0$ boson production cross-section in pp collisions at $\sqrt{s} = 13$ TeV*, JHEP **09** (2016) 136, arXiv:1607.06495.

[76] LHCb collaboration, R. Aaij *et al.*, *Measurement of forward $W$ and $Z^0$ boson production in association with jets in proton-proton collisions at $\sqrt{s} = 8$ TeV*, JHEP **05** (2016) 131, arXiv:1605.00951.

[77] LHCb collaboration, R. Aaij *et al.*, *Measurement of forward $W$ and $Z^0$ boson production in pp collisions at $\sqrt{s} = 8$ TeV* , JHEP **01** (2016) 155, arXiv:1511.08039.

[78] LHCb collaboration, R. Aaij *et al.*, *Measurement of the forward $Z^0$ boson cross-section in pp collisions at $\sqrt{s} = 7$ TeV*, JHEP **08** (2015) 039, arXiv:1505.07024.

[79] LHCb collaboration, R. Aaij *et al.*, *Study of $W$ boson production in association with beauty and charm*, Phys. Rev. **D92** (2015) 052012, arXiv:1505.04051.

[80] LHCb collaboration, R. Aaij *et al.*, *Measurement of $Z^0 \to e^+e^-$ production at $\sqrt{s} = 8$ TeV*, JHEP **05** (2015) 109, arXiv:1503.00963.

[81] LHCb collaboration, R. Aaij *et al.*, *Measurement of the $Z^0 + b$-jet cross-section in pp collisions at $\sqrt{s} = 7$ TeV in the forward region*, JHEP **01** (2015) 064, arXiv:1411.1264.

[82] LHCb collaboration, R. Aaij *et al.*, *Measurement of the forward $W$ boson production cross-section in pp collisions at $\sqrt{s} = 7$ TeV*, JHEP **12** (2014) 079, arXiv:1408.4354.

[83] LHCb collaboration, R. Aaij *et al.*, *Study of forward $Z^0$+jet production in pp collisions at $\sqrt{s} = 7$ TeV*, JHEP **01** (2014) 033, arXiv:1310.8197.

[84] LHCb collaboration, R. Aaij *et al.*, *Measurement of the cross-section for $Z^0 \to e^+e^-$ production in pp collisions at $\sqrt{s} = 7$ TeV*, JHEP **02** (2013) 106, arXiv:1212.4620.

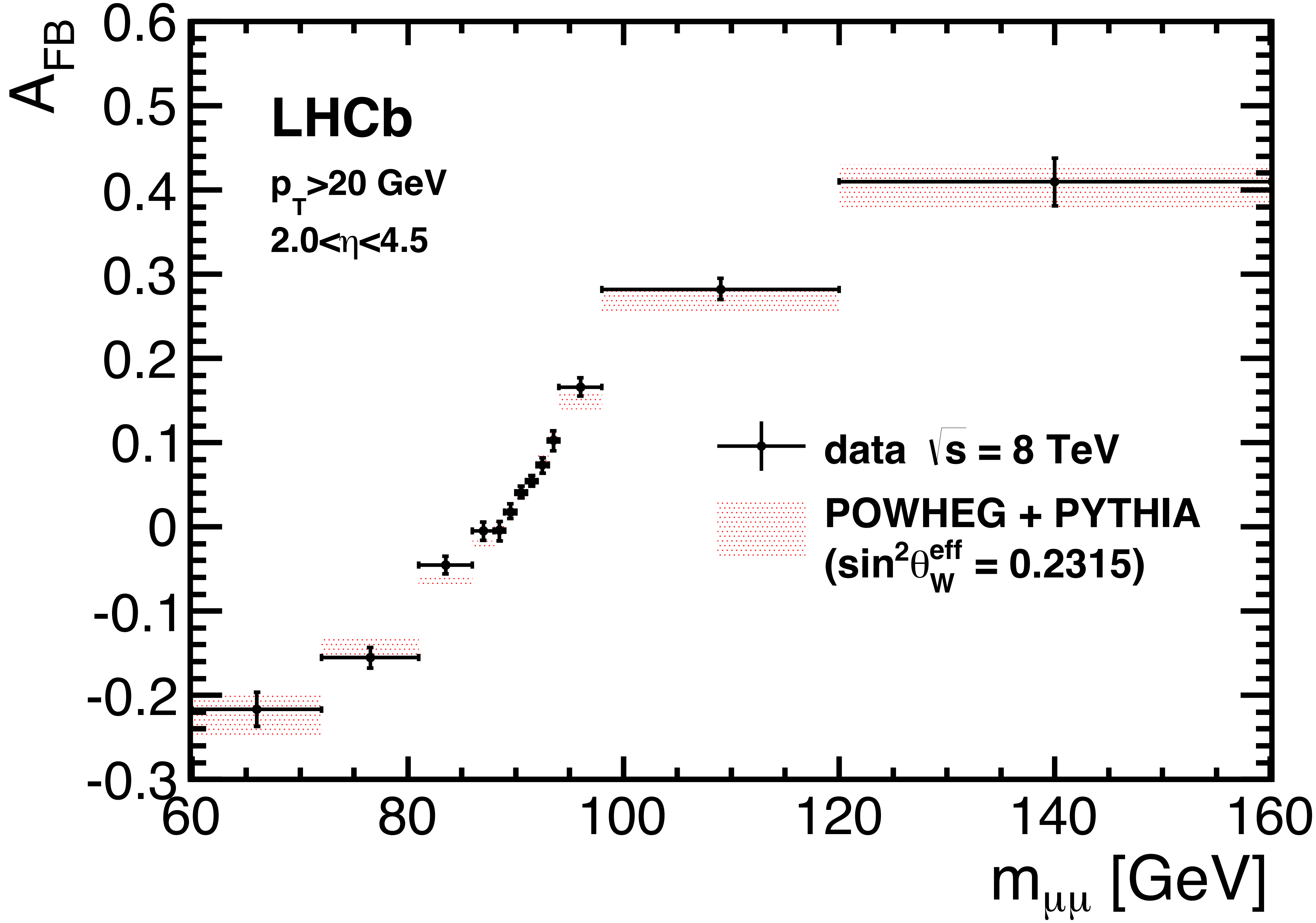
[85] LHCb collaboration, R. Aaij *et al.*, *A study of the $Z^0$ production cross-section in pp collisions at $\sqrt{s} = 7$ TeV using tau final states*, JHEP **01** (2013) 111, arXiv:1210.6289.

[86] LHCb collaboration, R. Aaij *et al.*, *Inclusive $W$ and $Z^0$ production in the forward region at $\sqrt{s} = 7$ TeV*, JHEP **06** (2012) 058, arXiv:1204.1620.

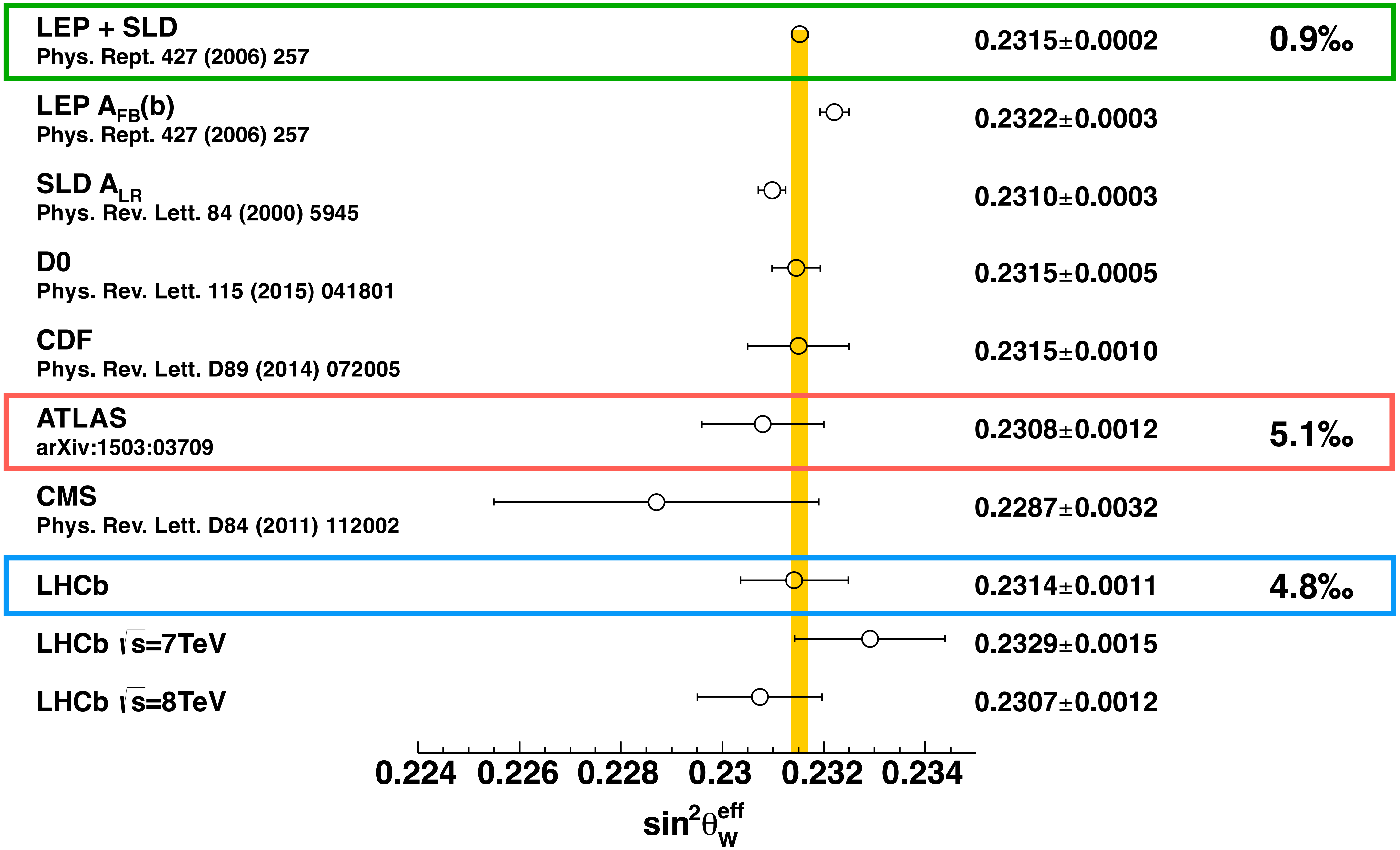

CERN-LHCC-2017-003

# Drell-Yan (DY) production

LHCb, 1509.07645



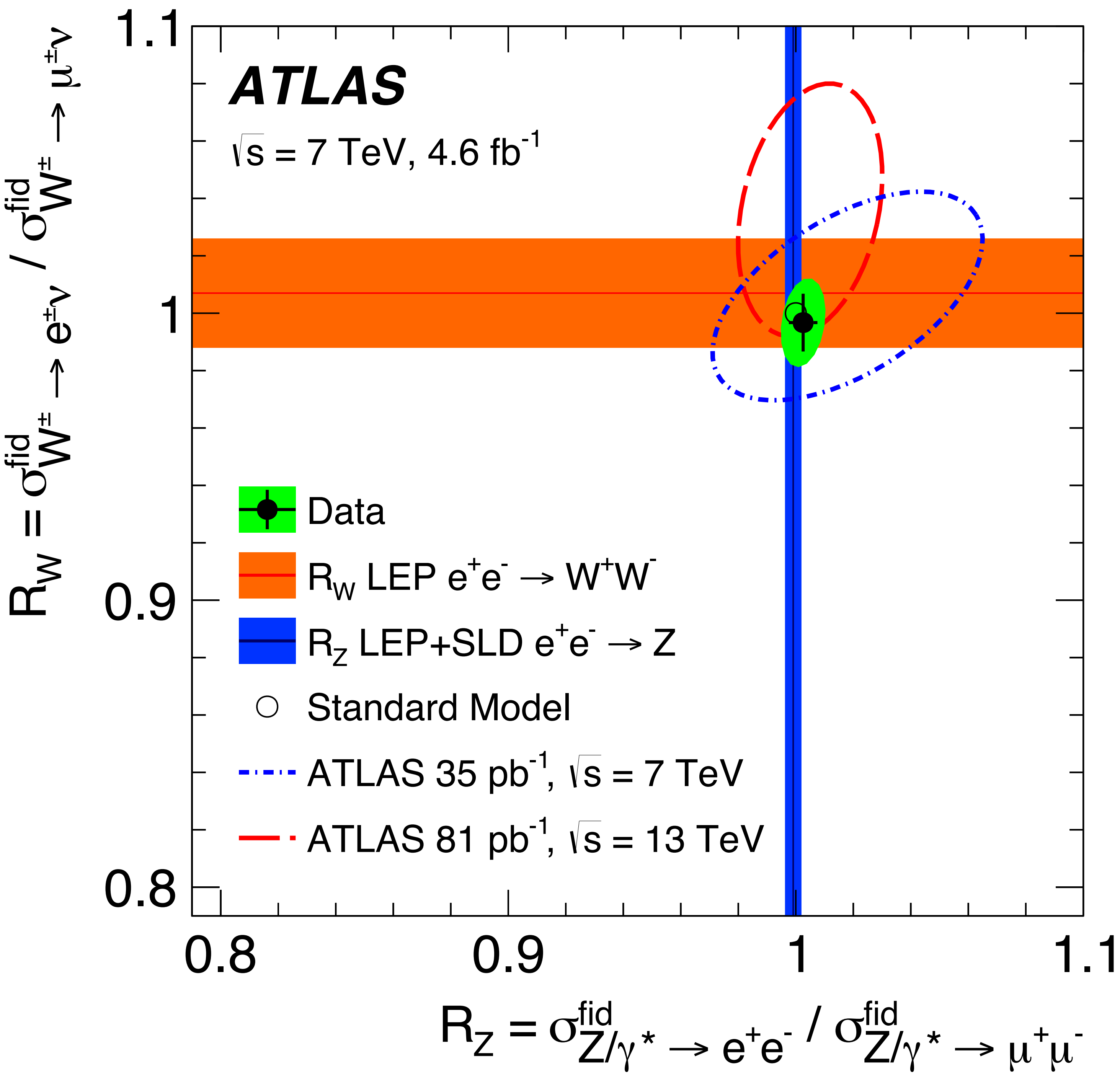
# Weak mixing angle




for LHCb Phase-II Upgrade prospects see talk by William Barter

# Lepton flavour universality in DY

ATLAS, 1612.03016



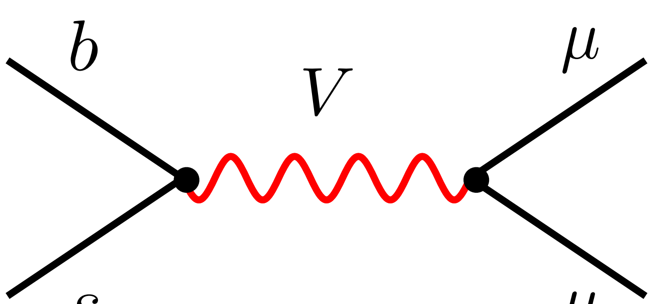

$$R_Z^{\mathrm{ATLAS}} = 1.0026\,(1 \pm \boxed{5.0‰})$$

$$R_Z^{\mathrm{LEP+SLD}} = 0.9991\,(1 \pm \boxed{2.8‰})$$

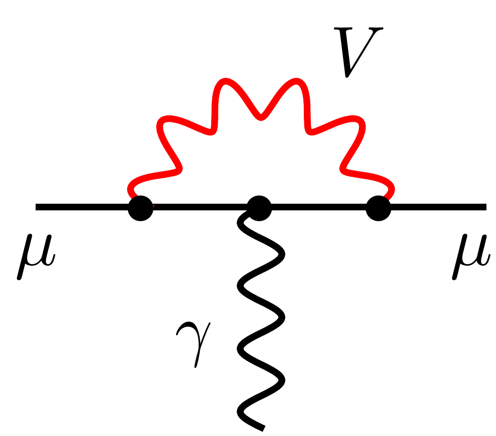
# 1‰ DY measurements $\longrightarrow$ ?

Example of light spin-1 di-muon resonance V:

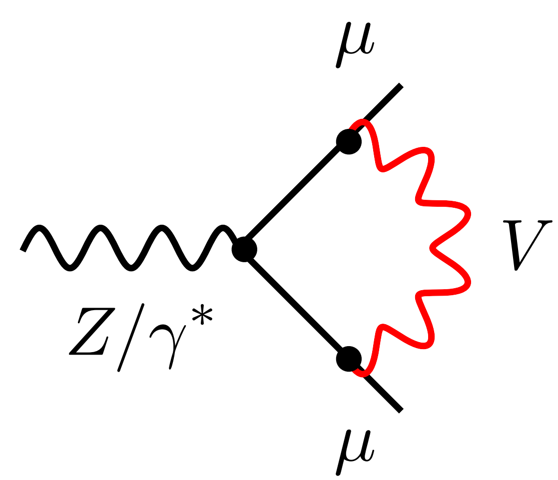
$$\mathcal{L} \supset \left(g_L^{sb}\,\bar{s}_L \not{V} b_L + \text{h.c.}\right) + \bar{\mu}\left(g_V^{\mu} - g_A^{\mu}\gamma_5\right)\not{V}\mu$$




$P_5', R_K, R_{K^*}$



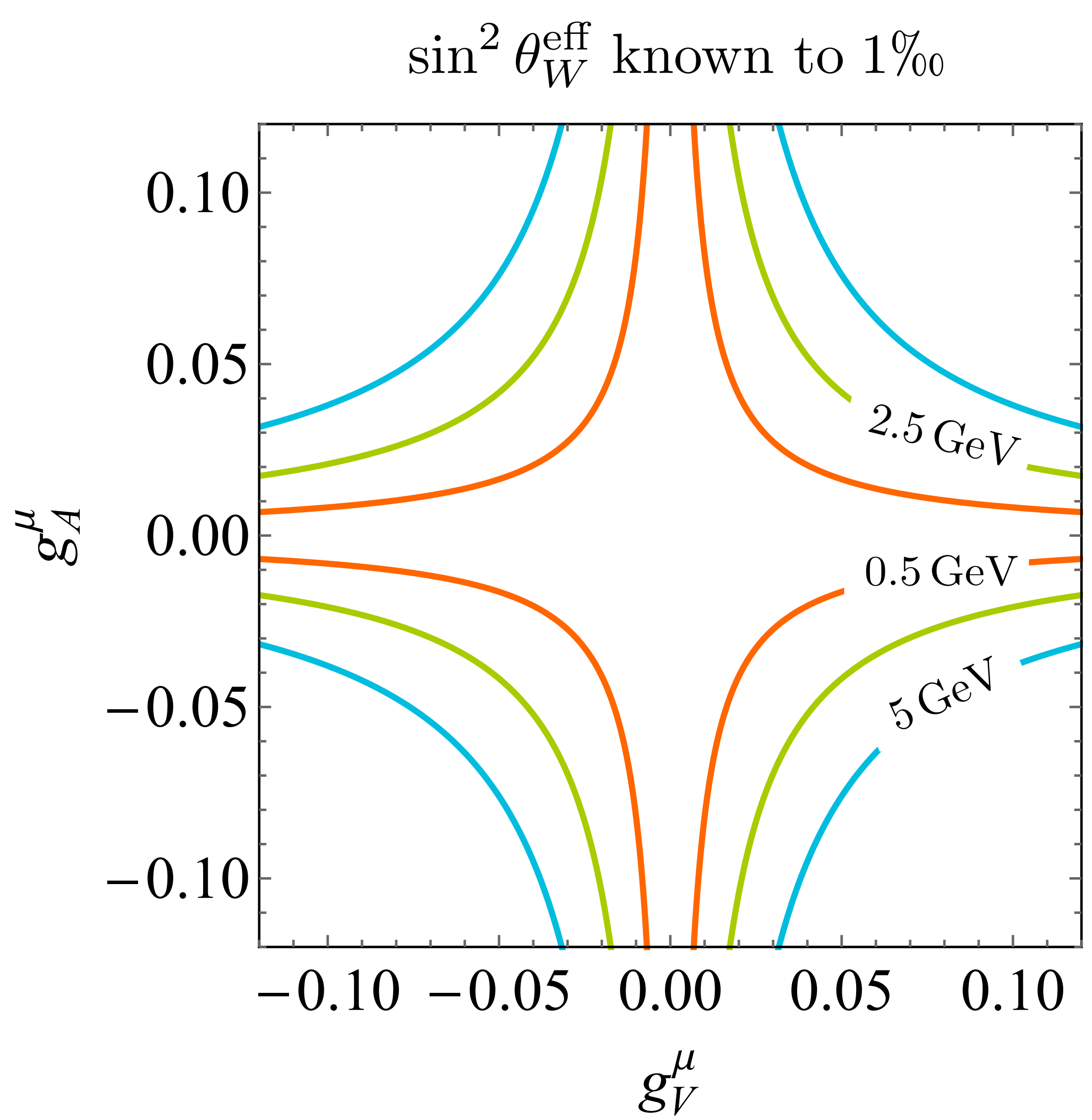

$a_\mu = \left((g-2)/2\right)_\mu$

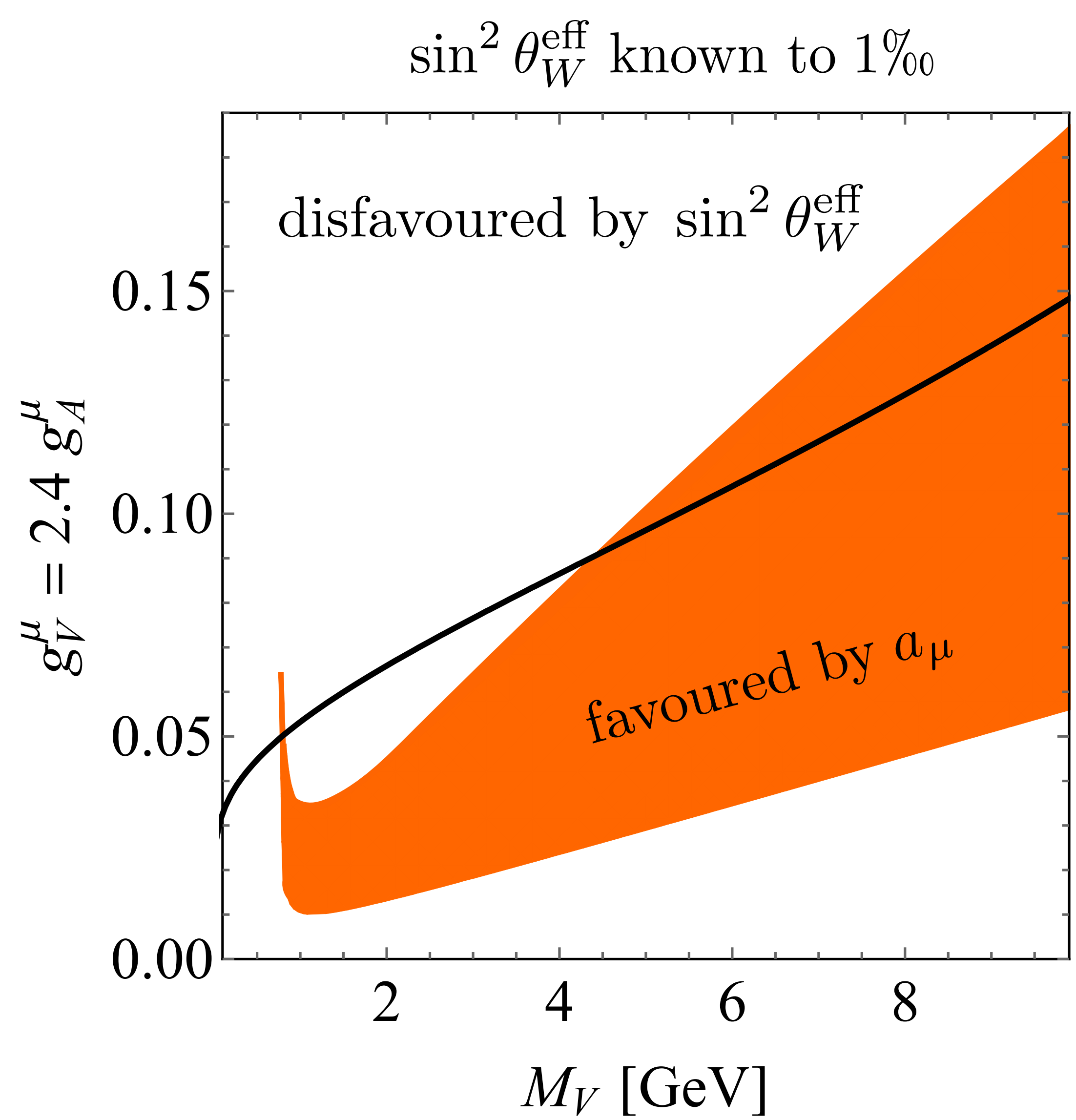



DY

inspired by Sala & Straub, 1704.06188; Bishara, UH & Monni, 1705.03465

# 1‰ DY measurements → ?




With 1‰ precision can test couplings below O(0.1)

& can exclude fine-tuned explanations of $a_\mu$

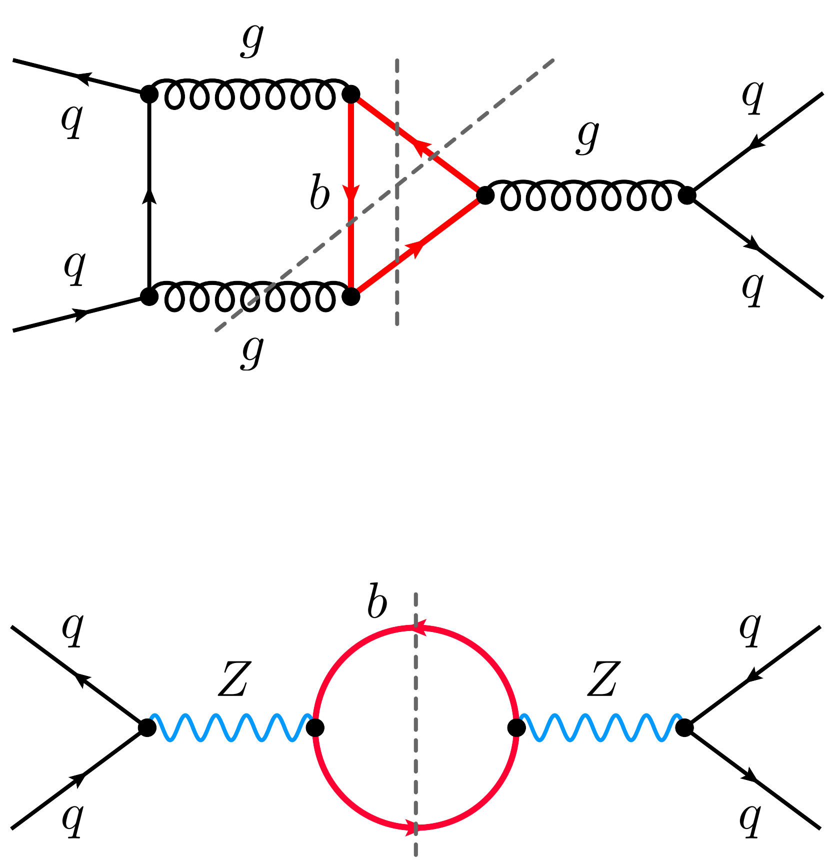
# Precision on Z/W couplings

| | |
|---|---|
| $Ze^+e^-$ couplings | $(0.1\%)_L, (0.1\%)_R$ |
| $Zc\bar{c}$ couplings | $(1.0\%)_L, (3.2\%)_R$ |
| $Zb\bar{b}$ couplings | $(0.4\%)_L, (6.5\%)_R$ |
| $Zt\bar{t}$ couplings | $> 100\%$ |
| $WWZ$ coupling | $2.3\%$ |
| $WW\gamma$ coupling | $3.4\%$ |

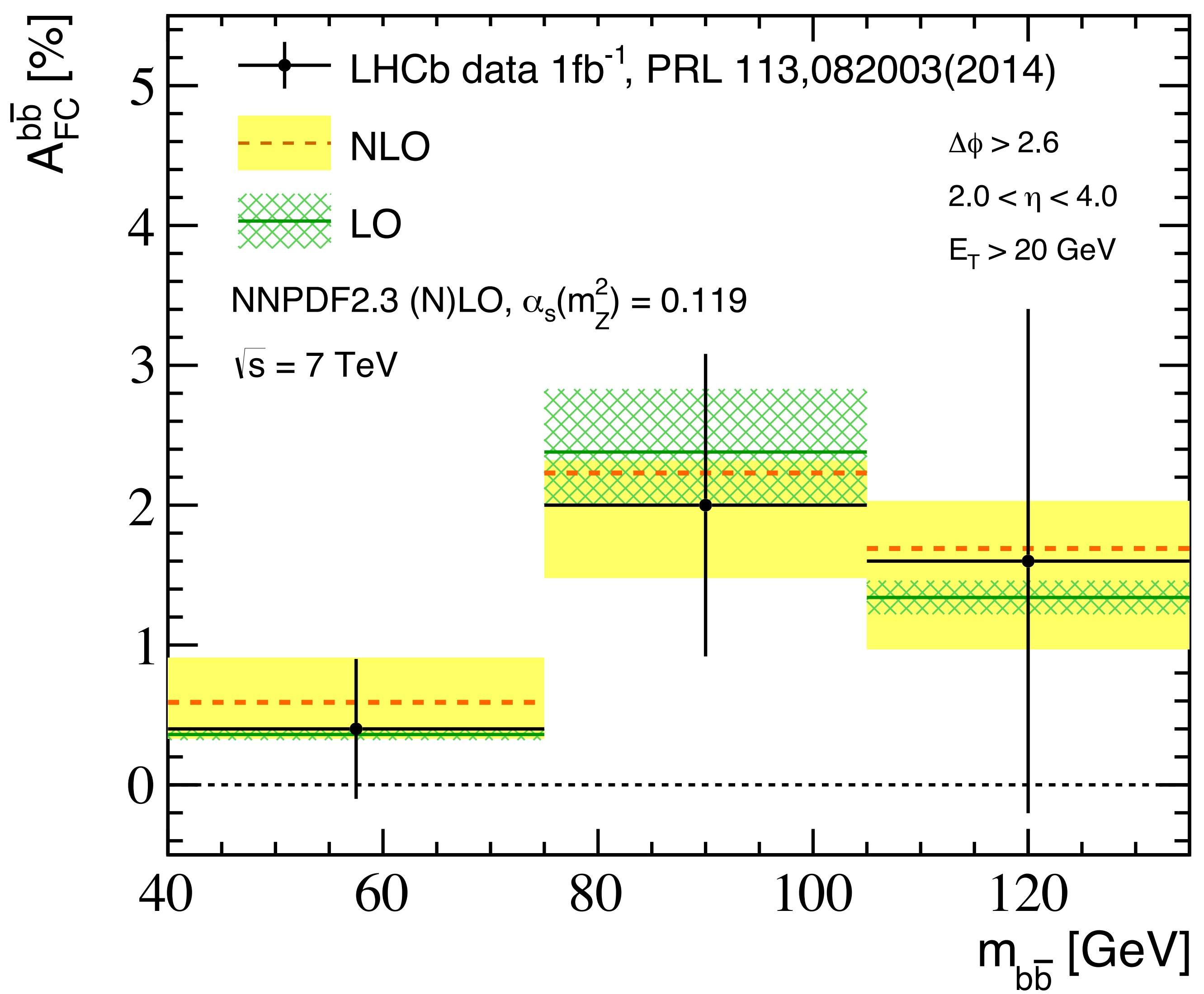
Z-boson couplings to heavy flavours & triple-gauge boson couplings are only known at % level

LEPEWWG, hep-ex/0509008; CMS, 1303.3239; Falkowski et al., 1508.0058

# $Zb\bar{b}$ couplings from $A_{FC}^{b\bar{b}}$ at LHCb



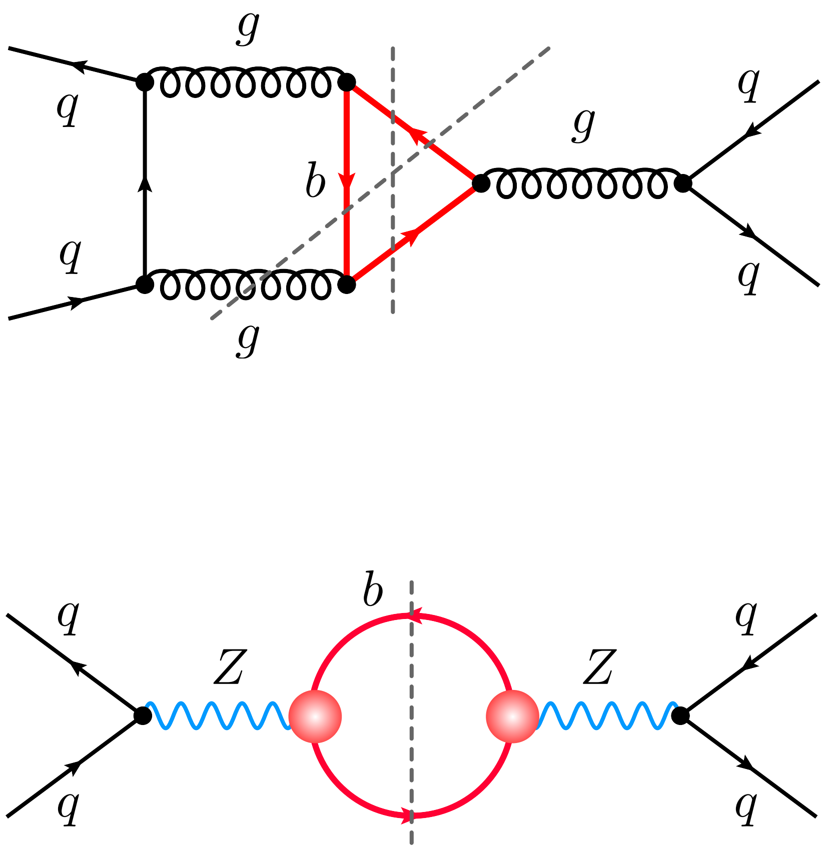

Gauld et al., 1505.02429

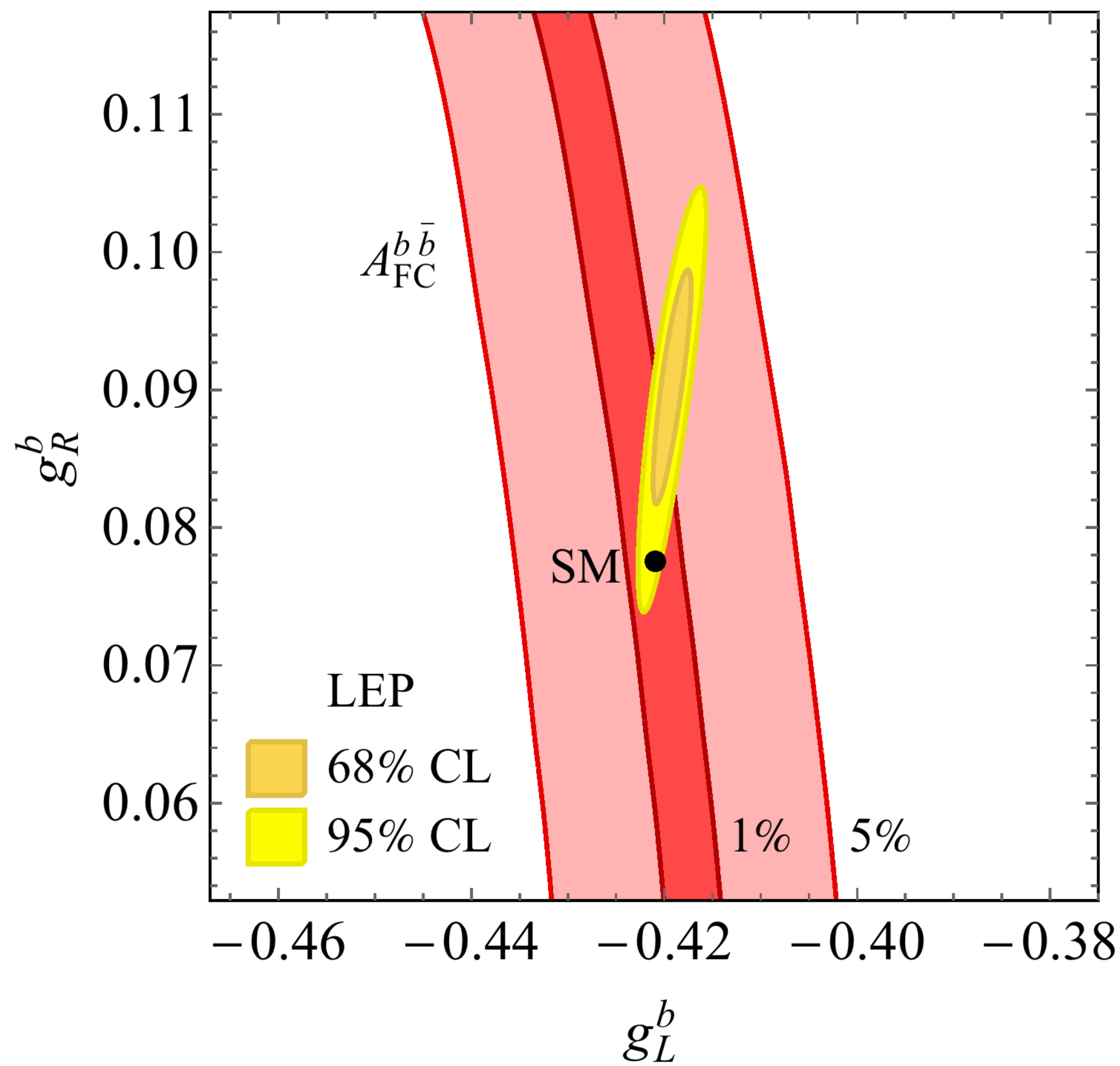



LHCb has measured forward-central $b\bar{b}$ asymmetry with O(50%) precision, while theory prediction has uncertainty of O(15%)

# $Zb\bar{b}$ couplings from $A_{FC}^{b\bar{b}}$ at LHCb

UH with help from Gauld

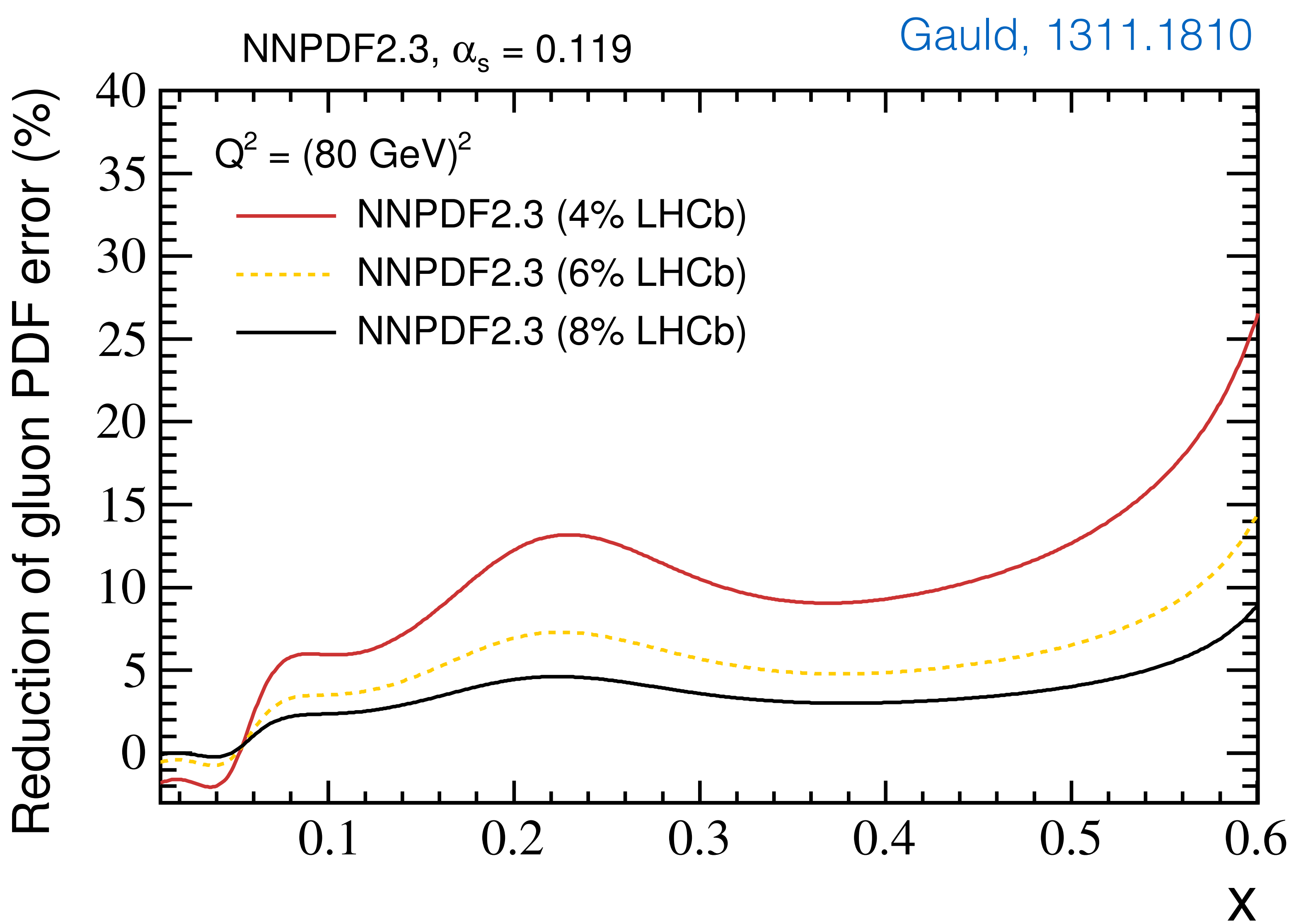



To reach LEP sensitivity need to achieve total relative error on $A_{FC}^{b\bar{b}}$ at % level. Needs dedicated LHCb & theory effort

discussion of $Zt\bar{t}$ & trilinear gauge couplings in backup

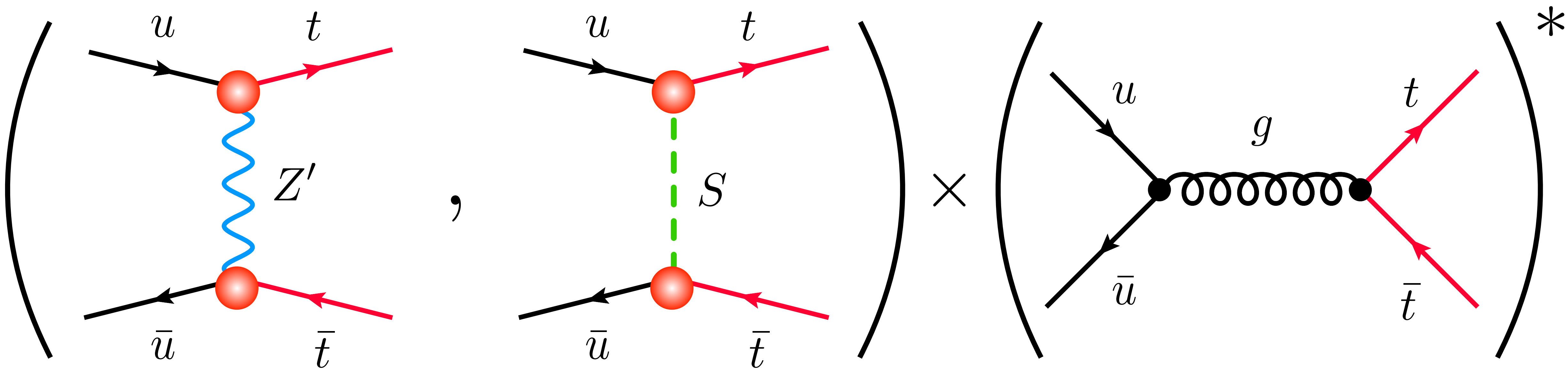
# Why $t\bar{t}$ production at LHCb?




LHCb measurements of $t\bar{t}$ production will lead to improved understanding of gluon parton distribution function

much more details on top production in talk by William Barter

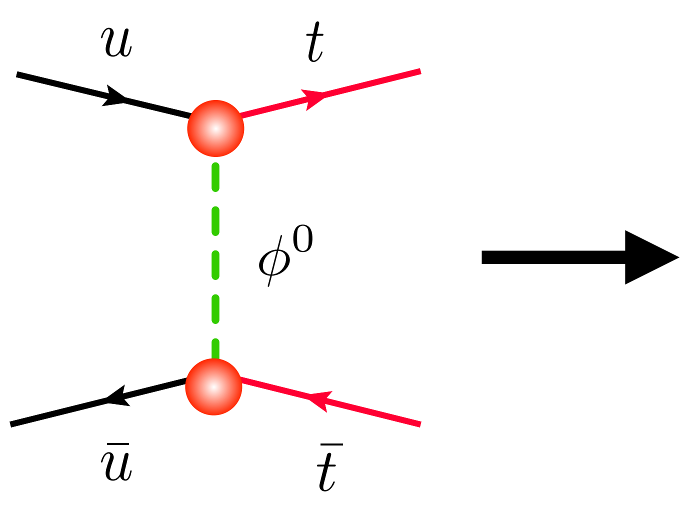
# Why $t\bar{t}$ production at LHCb?

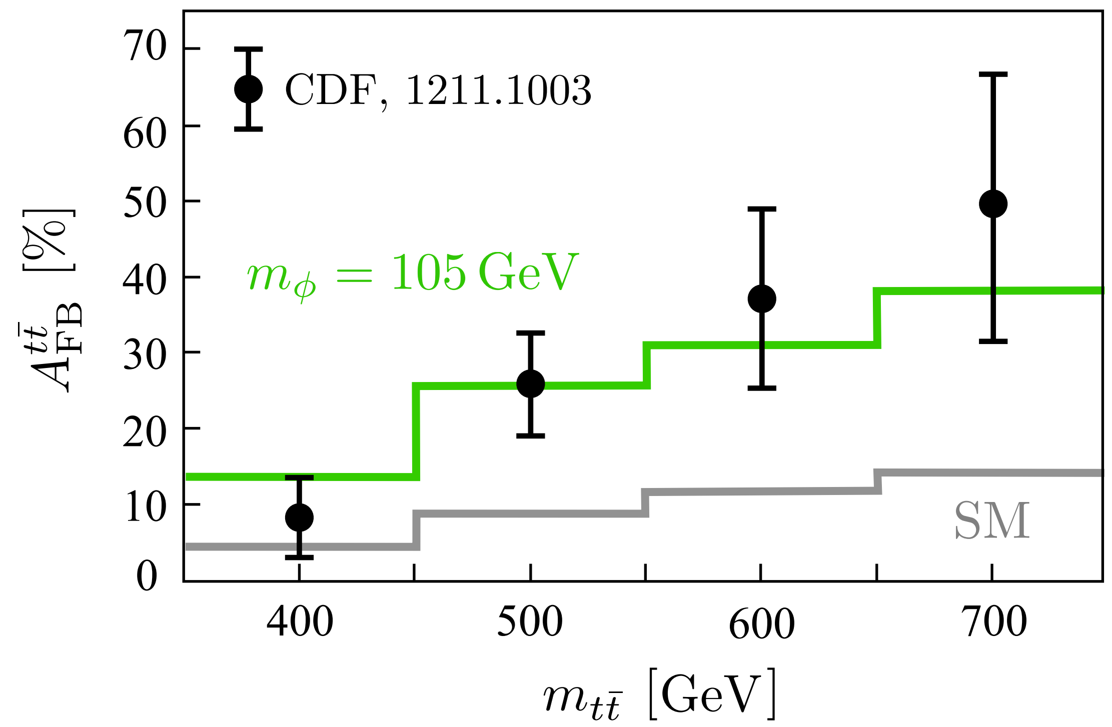



In new-physics models in which top production proceeds via t-channel exchange, cross section & asymmetry enhanced at large pseudo-rapidities not accessible at ATLAS & CMS

in LHCb context see Kagan, Kamenik, Perez & Stone, 1103.3747

# $A_{FB}^{t\bar{t}}$ vs. $A_{FB}^{b\bar{b}}$: historical example

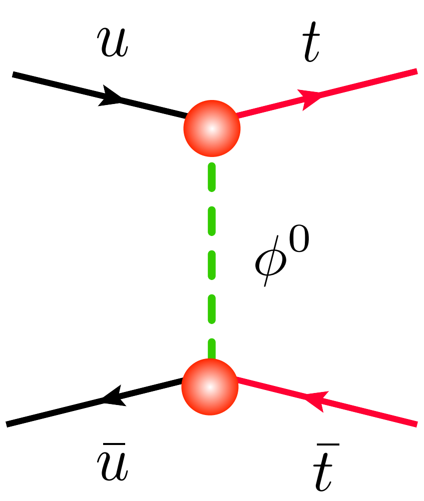


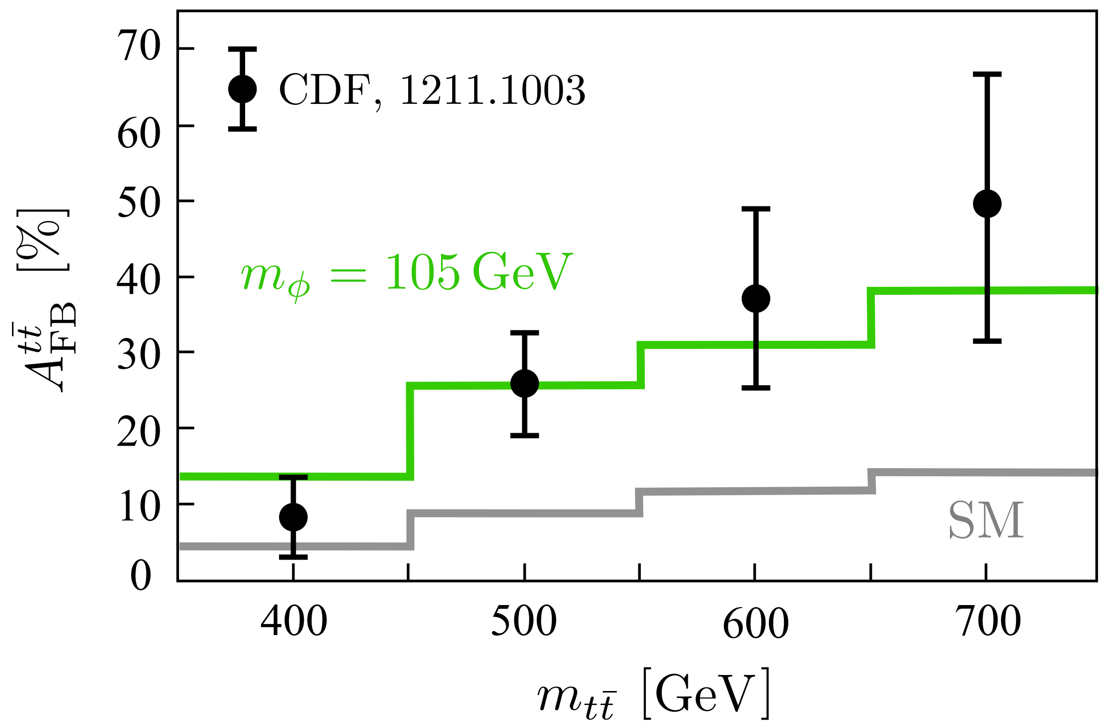



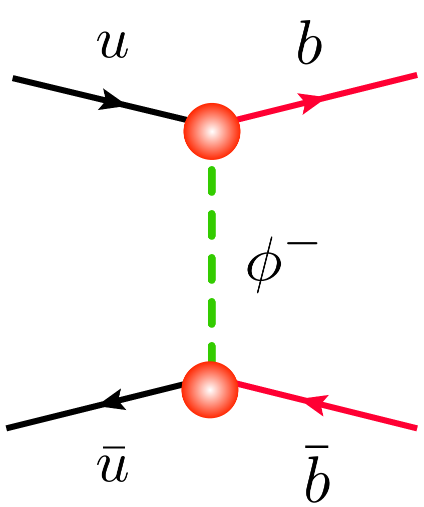

$$\mathcal{L} \supset \lambda \left( \phi^0 \, V_{tb} \bar{t}_L u_R + \phi^- \, \bar{b}_L u_R \right) + \text{h.c.}$$

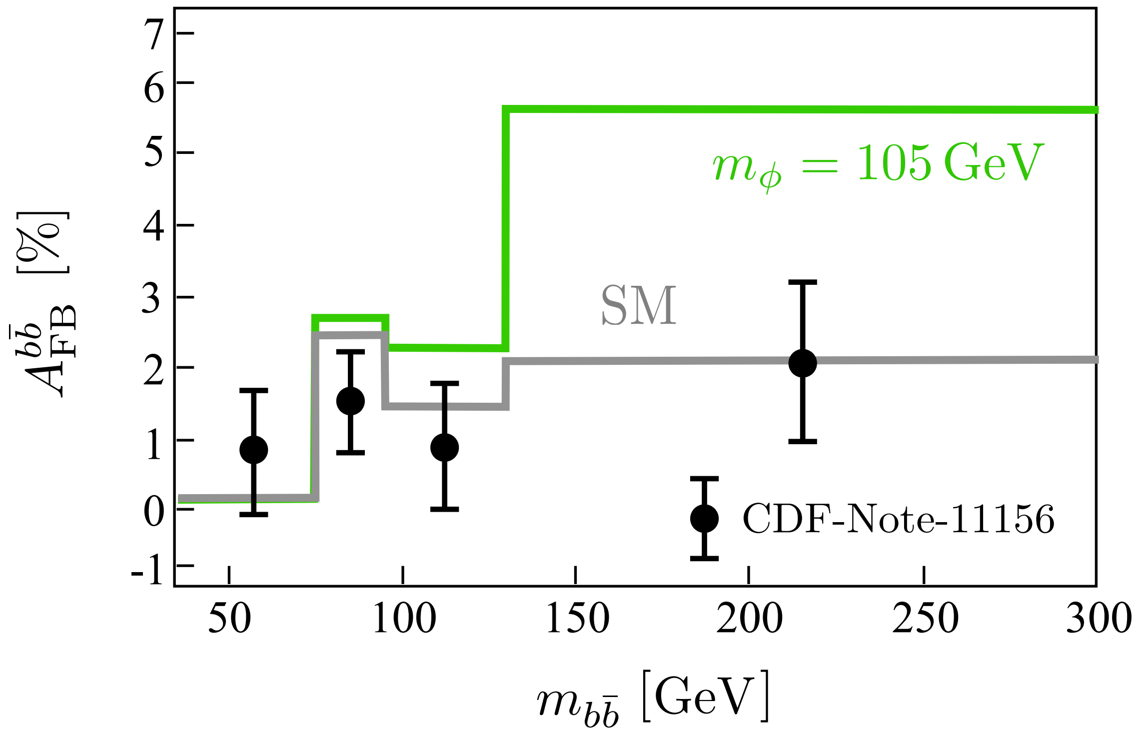
Blum, Hochberg & Nir, 1107.4350; Grinstein & Murphy, 1302.6995

# $A_{FB}^{t\bar{t}}$ vs. $A_{FB}^{b\bar{b}}$: historical example



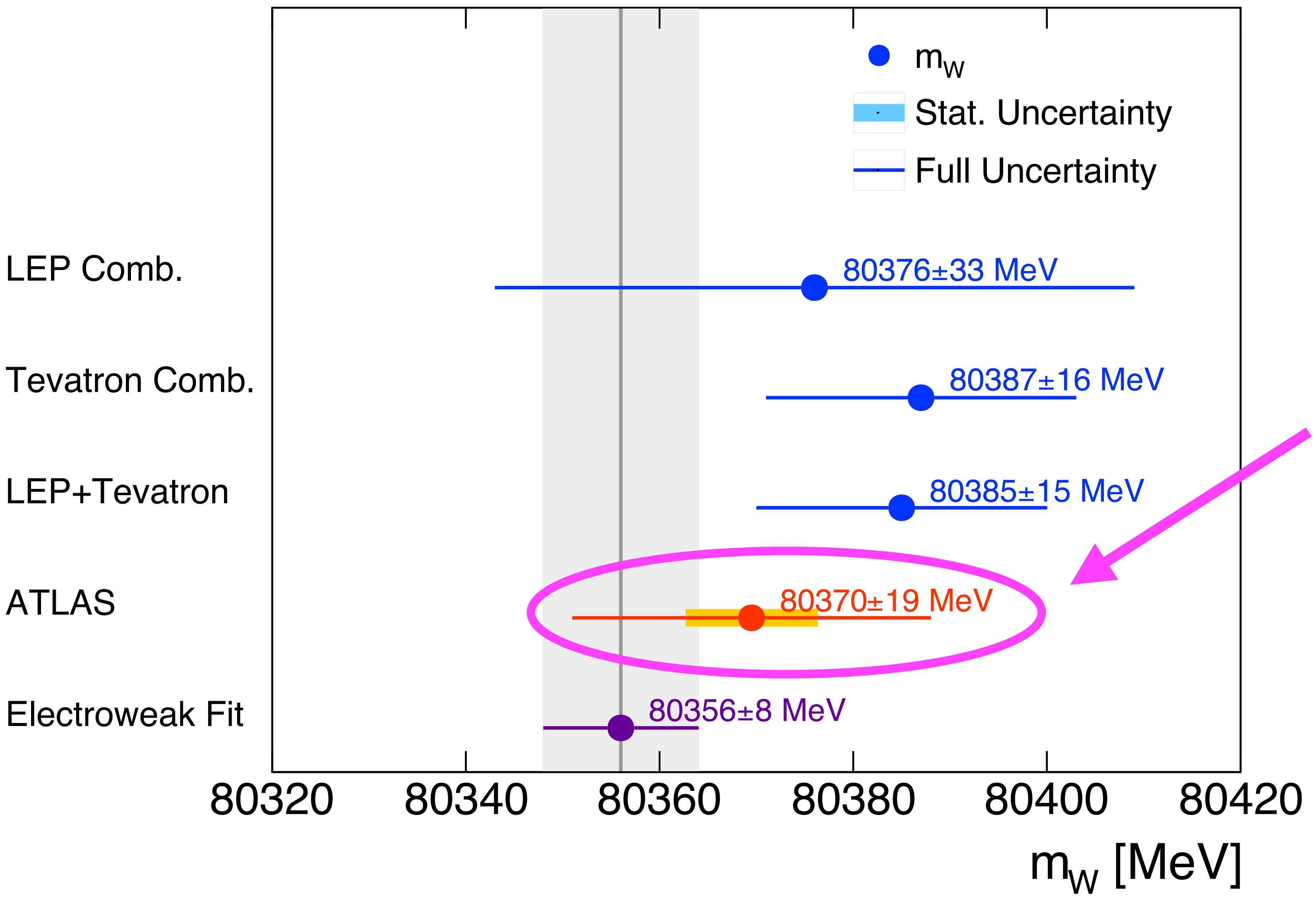




Murphy, 1504.02439

# W mass measurement at LHC

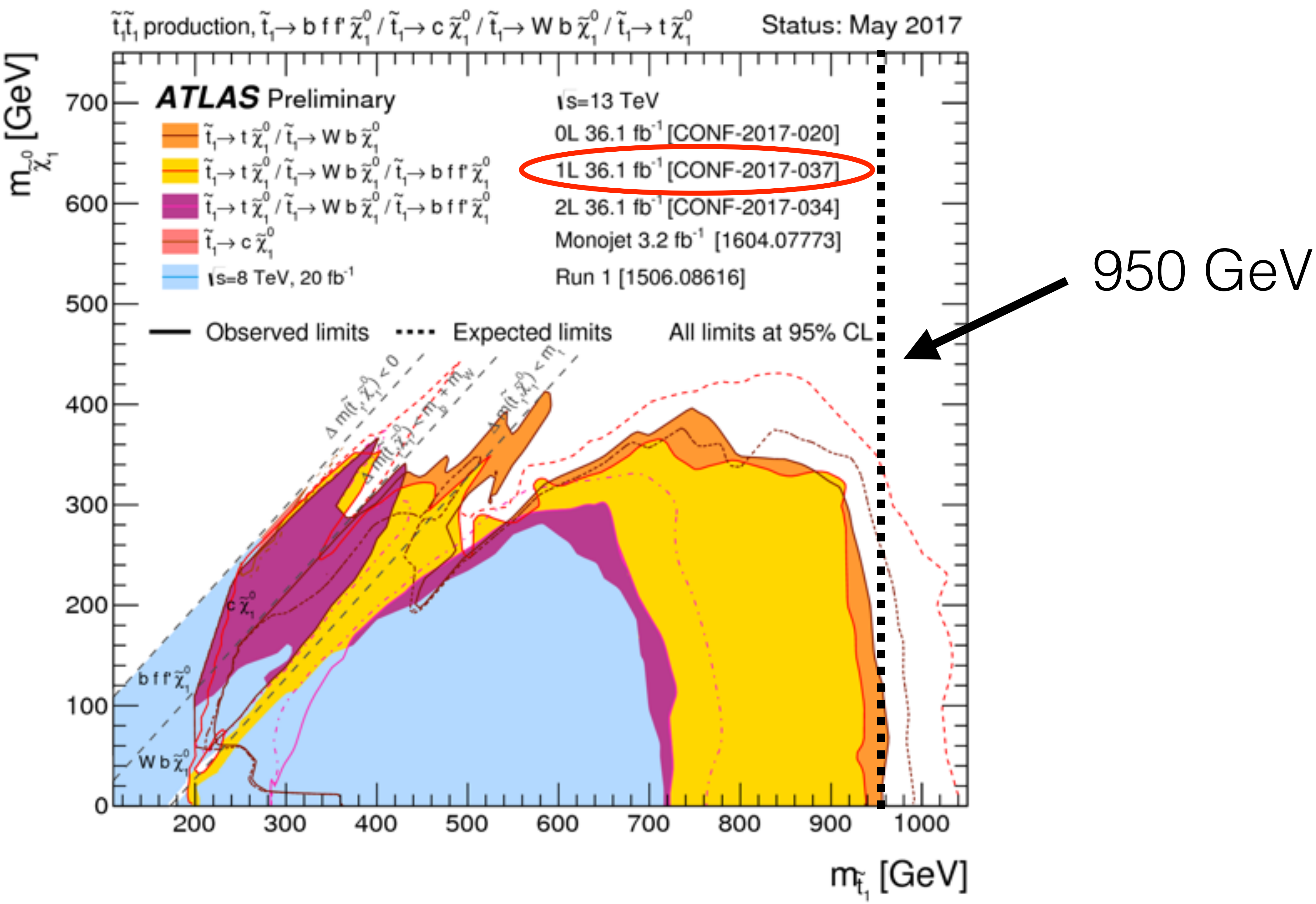
ATLAS, 1701.07240




including ATLAS, CMS & LHCb data as well as theory progress might be possible to reduce uncertainty to 5 MeV in long run

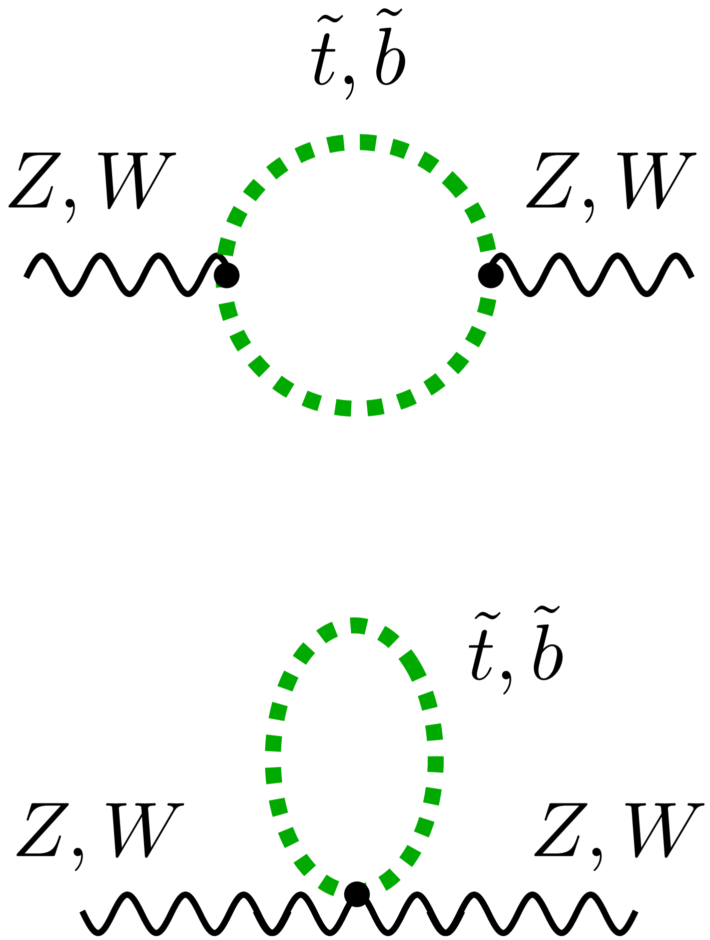
see talk by William Barter for LHCb Phase-II Upgrade prospects

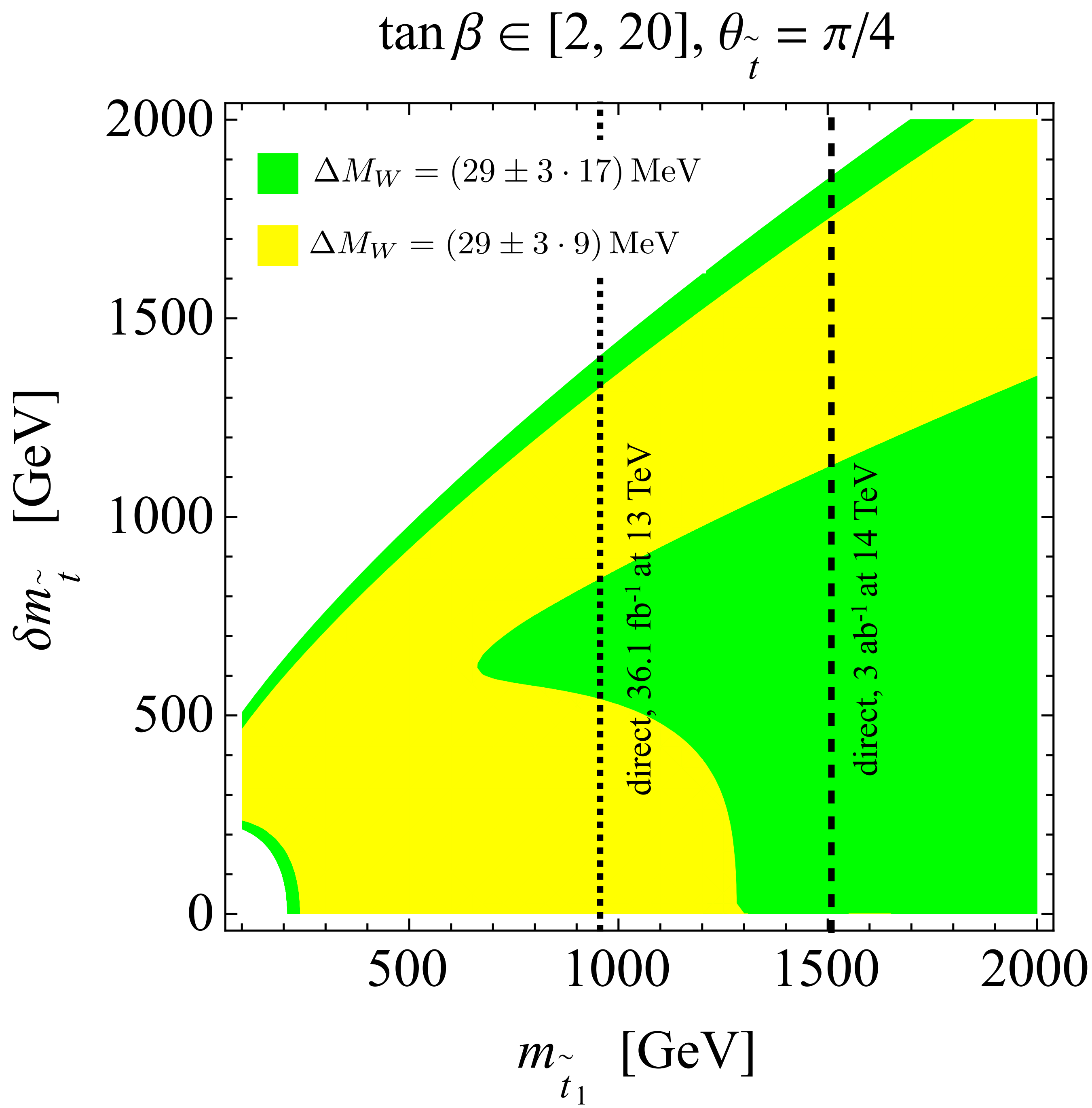
# Stop searches at LHC




https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults

# $\delta M_W = 5$ MeV $\longrightarrow$ ?

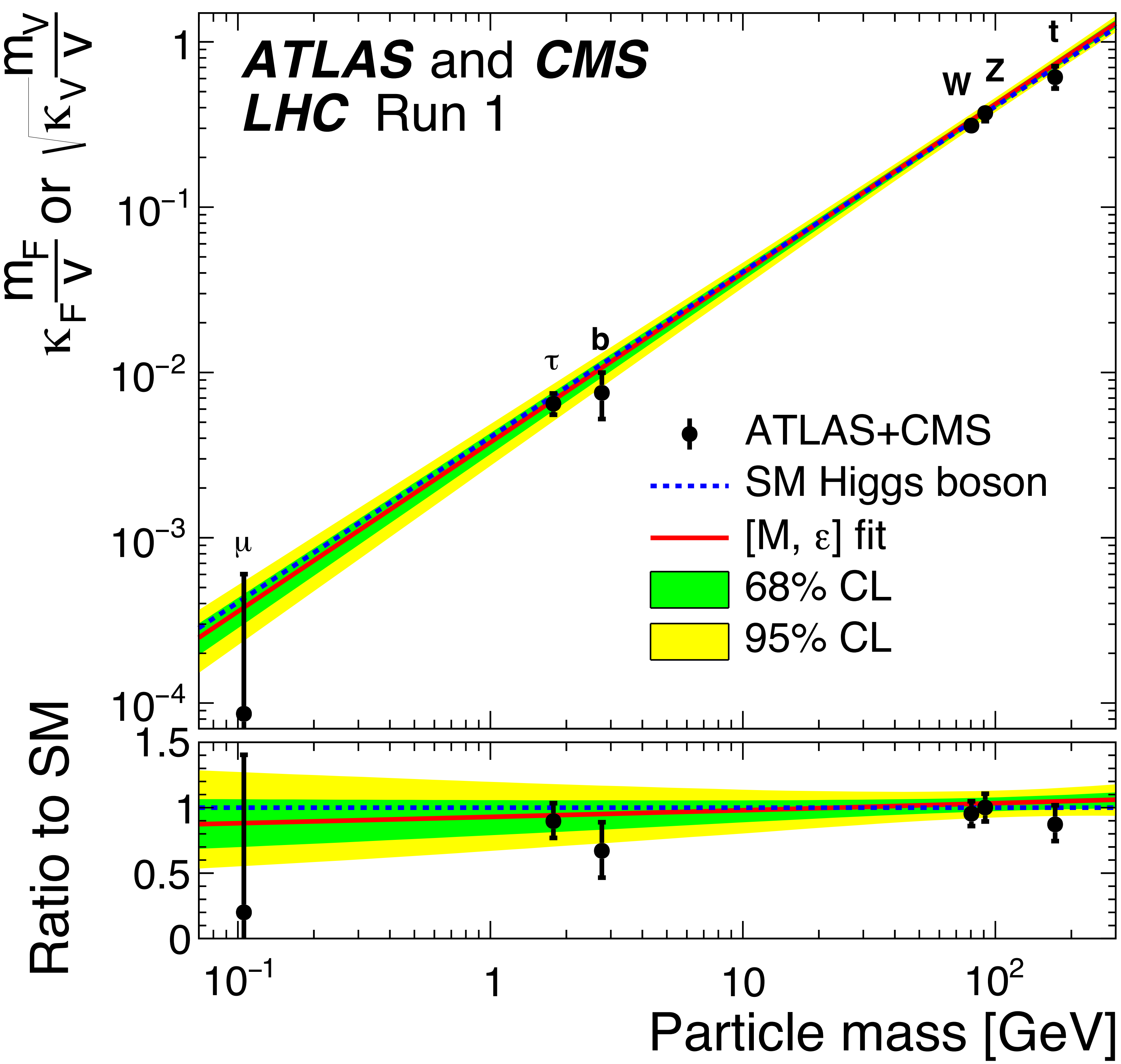



W mass provides complementary constraints on stop sector

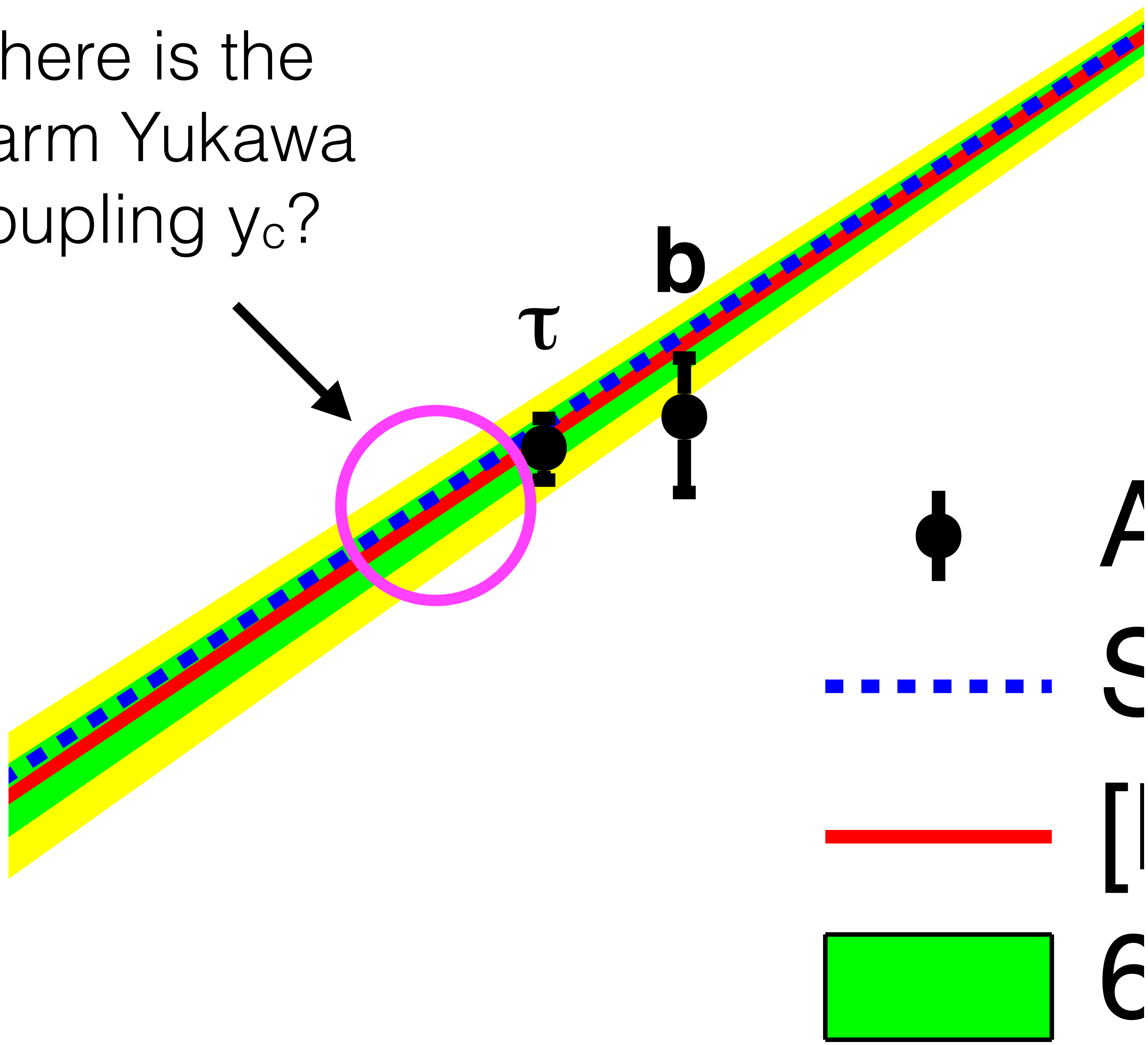
# Higgs couplings after Run I

ATLAS & CMS, 1606.02266



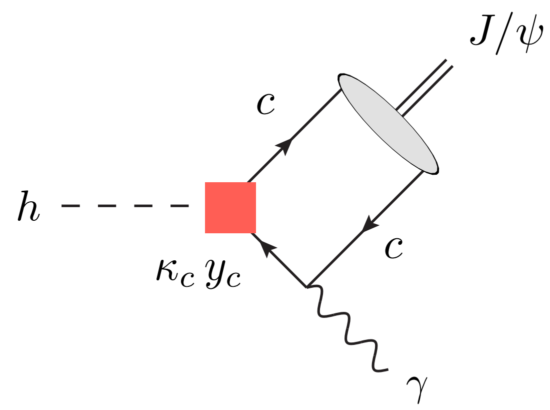
# Higgs couplings after Run I

where is the
charm Yukawa
coupling $y_c$?



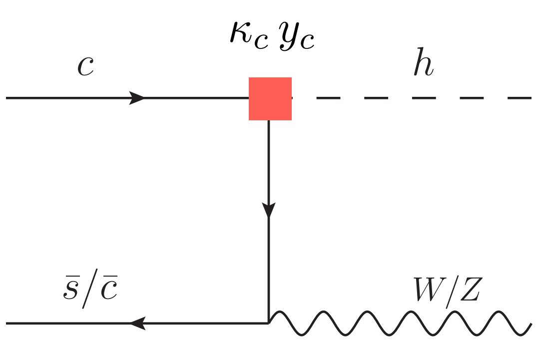
# Assortment of Run I bounds on $y_c$

exclusive Higgs decay



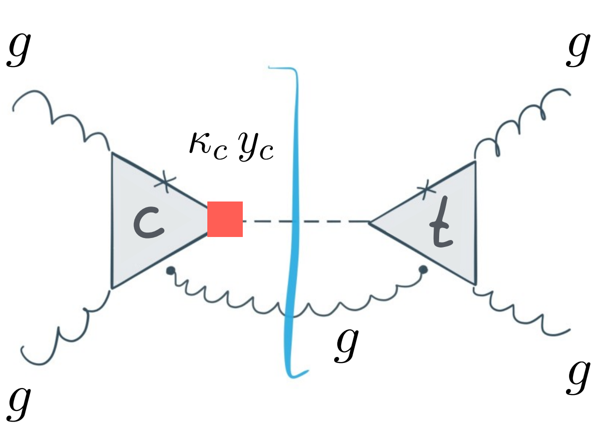

$|\kappa_c| < 429$

Vh production




$|\kappa_c| < 234$

Higgs $p_T$ spectrum

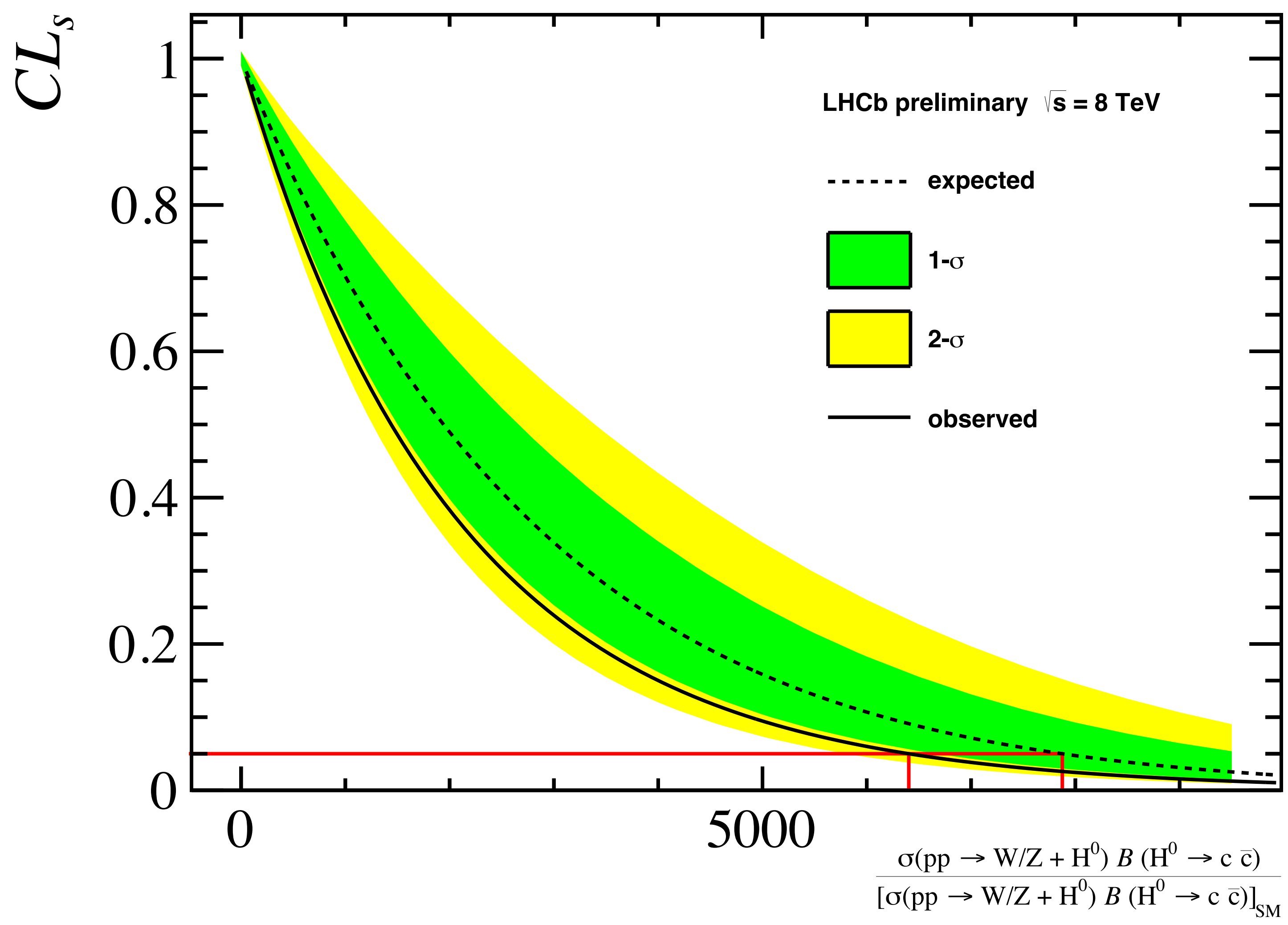



$\kappa_c \in [-16, 18]$

Perez et al., 1503.00290, 1505.06689; König & Neubert, 1505.03870; Bishara et al., 1606.09253

# Run I: Vh production at LHCb

LHCb-CONF-2016-006

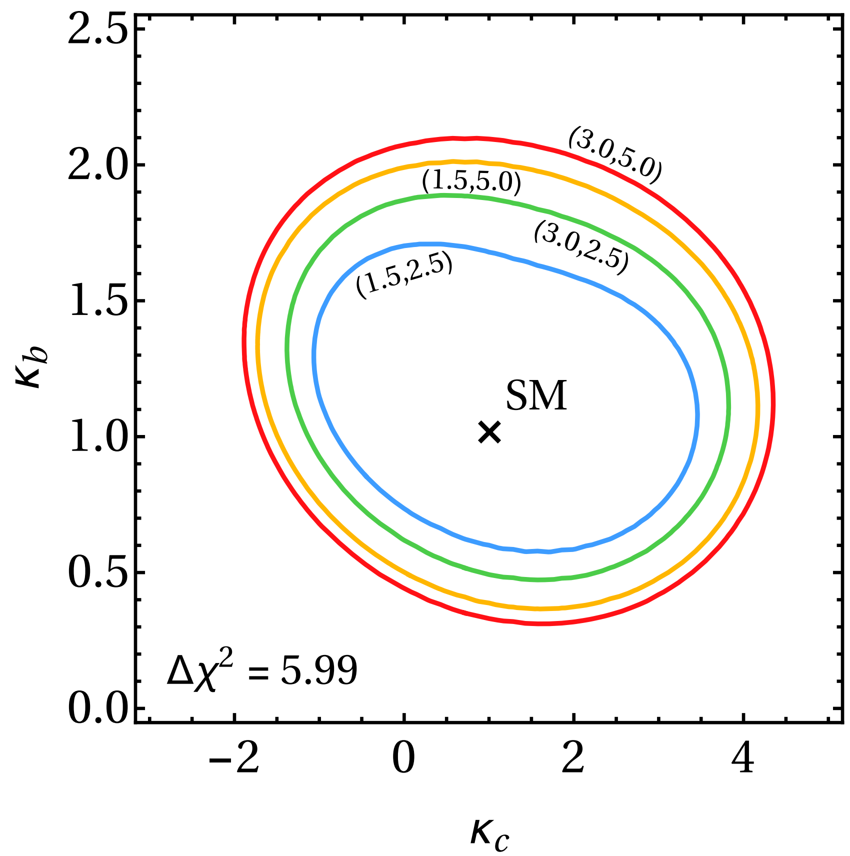



$$\rightarrow \quad |\kappa_c| < 80$$

Bound is better as recast of ATLAS & CMS Vh analyses

Perez, Soreq, Stamou & Tobioka, 1503.00290

# HL-LHC: constraints on $\kappa_c$ from $p_{T,h}$




| | experimental [%] | theoretical [%] | $\kappa_c \in$ |
|---|---|---|---|
| $S_1$ | 1.5 | 2.5 | [-0.6, 3.0] |
| $S_2$ | 3.0 | 2.5 | [-0.9, 3.3] |
| $S_3$ | 1.5 | 5.0 | [-1.2, 3.6] |
| $S_4$ | 3.0 | 5.0 | [-1.3, 3.7] |

Under realistic assumptions about experimental & theoretical progress possible to probe $|\kappa_c| = O(3)$ using $p_{T,h}$ spectrum

Bishara, UH, Monni & Re, supplemental material to 1606.09253

# LHCb Upgrade II: constraints on $\kappa_c$

300 fb$^{-1}$ at 14 TeV: $|\kappa_c| \lesssim 7$

30% di-c-tagging efficiency: $|\kappa_c| \lesssim 4$

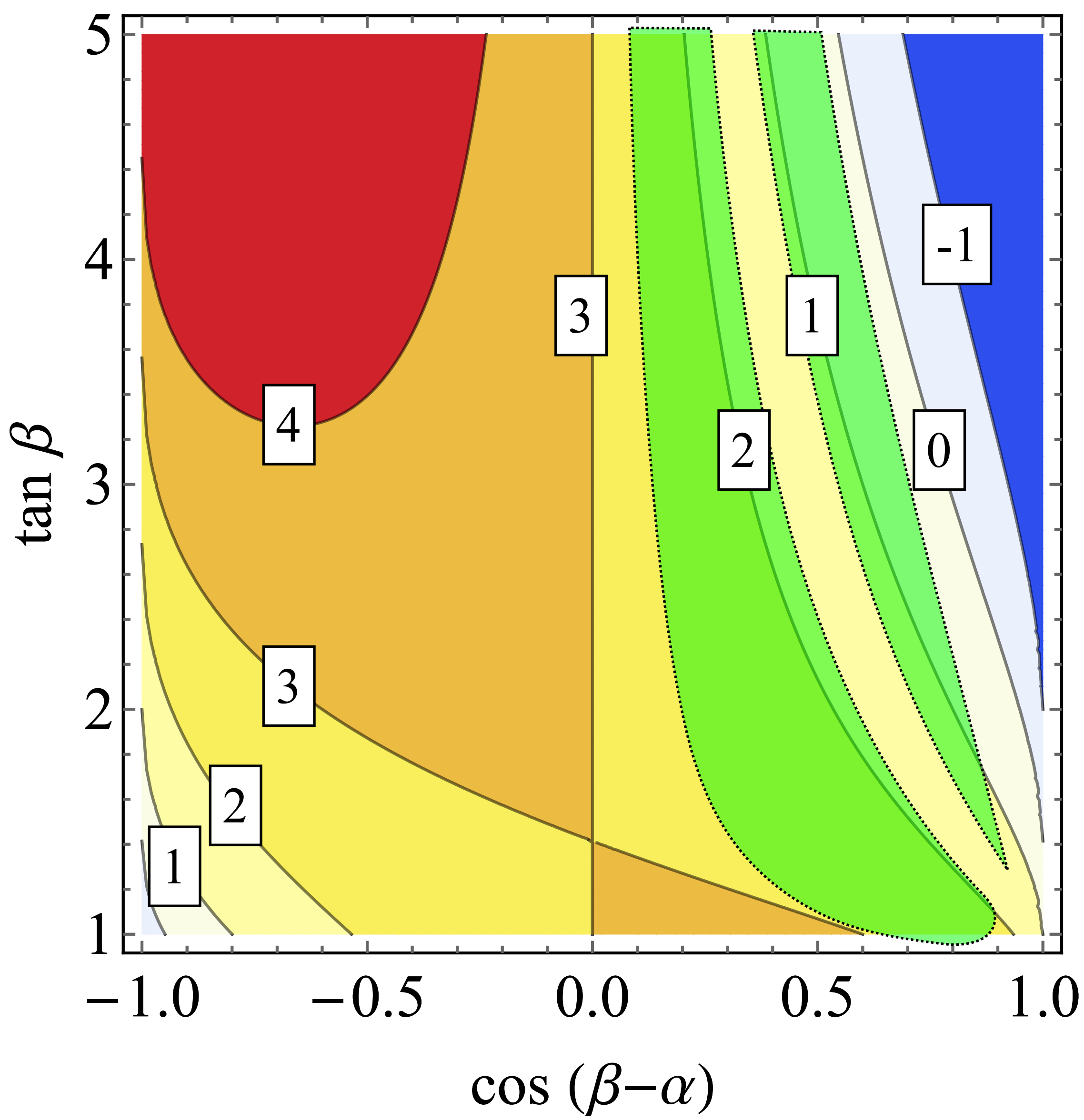
better electron reconstruction: $|\kappa_c| \lesssim 3$

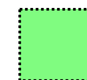
further improvements: $|\kappa_c| \lesssim 2.2$

projections taken from talk by Mike Williams

# $\kappa_c$ = O(2) bound → ?

UH based on Bauer et al., 1506.01719



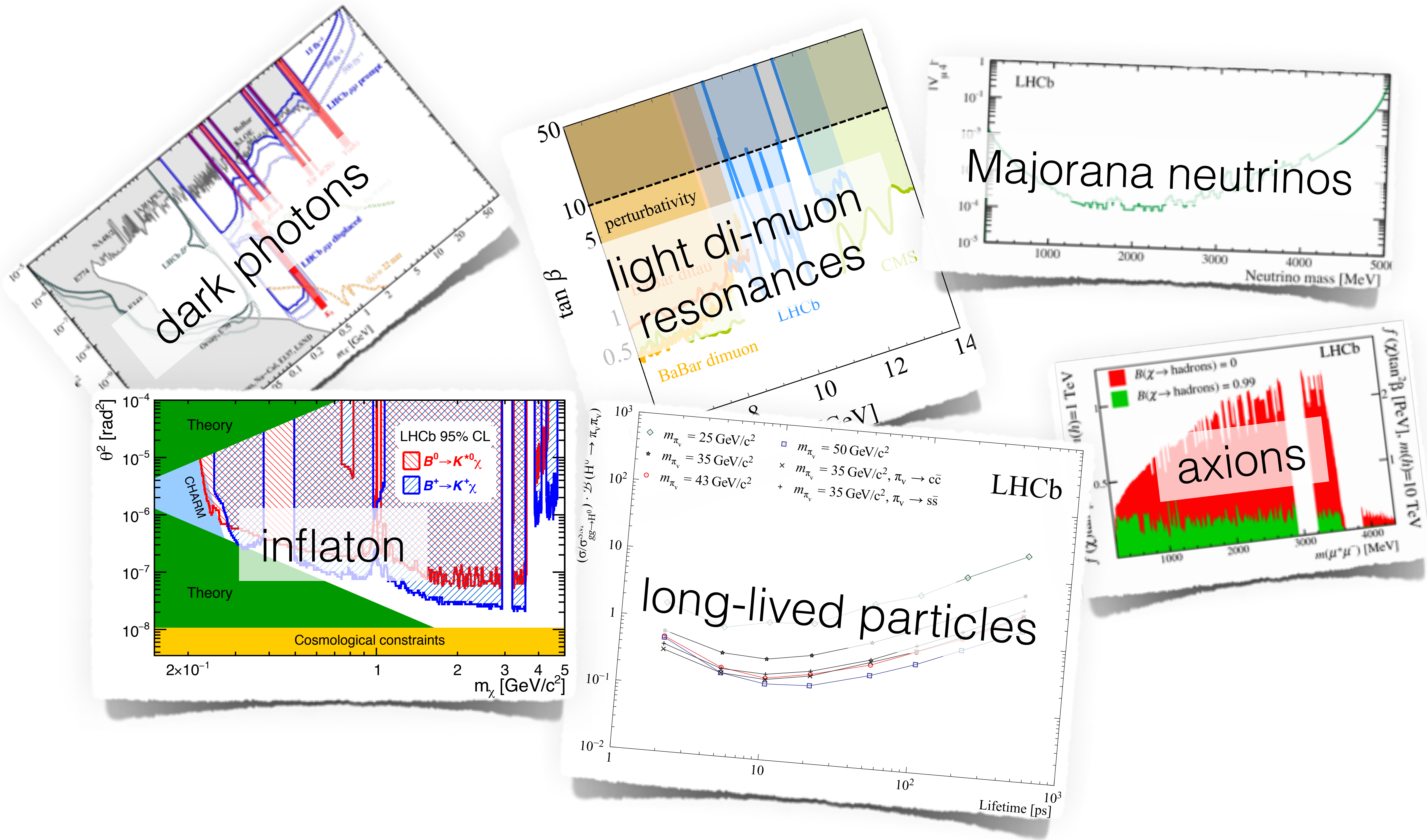
allowed by global fits to Run I Higgs data

(Only?) models with Higgs-dependent Yukawas allow for $|\kappa_c|$ = O(2). To test such scenarios at LHCb requires dedicated effort

see e.g. Babu & Nandi, hep-ph/9907213; Giudice & Lebedev, 0804.1753

# Exotics at LHCb

http://lhcbproject.web.cern.ch/lhcbproject/Publications/LHCbProjectPublic/Summary_QEE.html

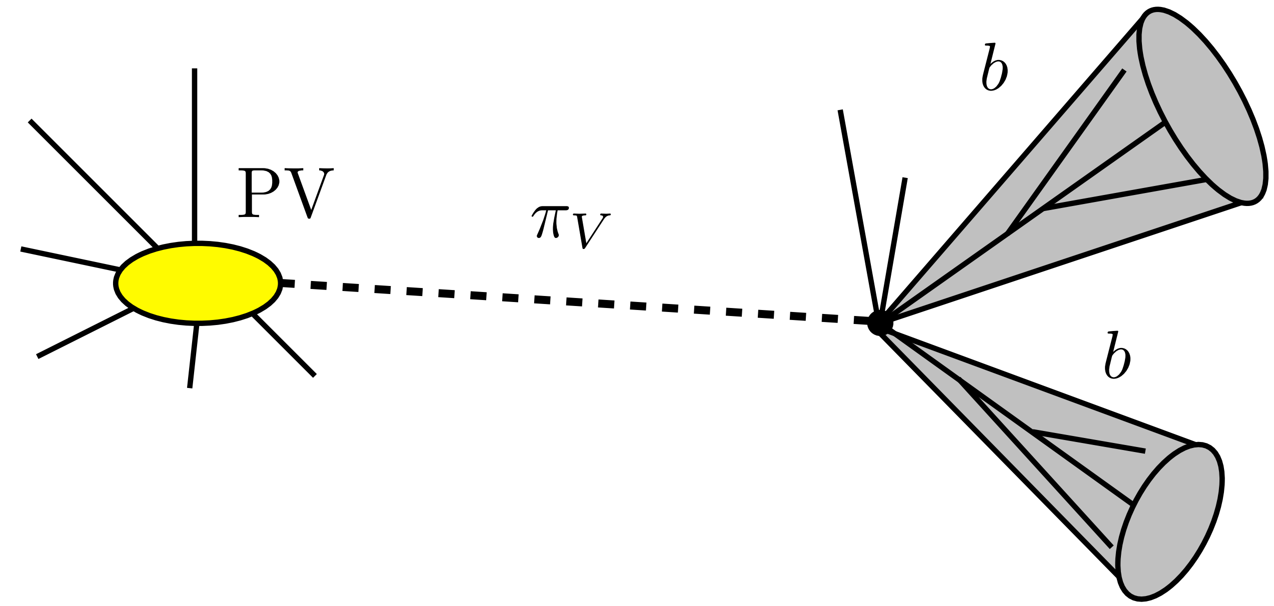



see talk by Mike Williams & backup for light di-muon resonance searches

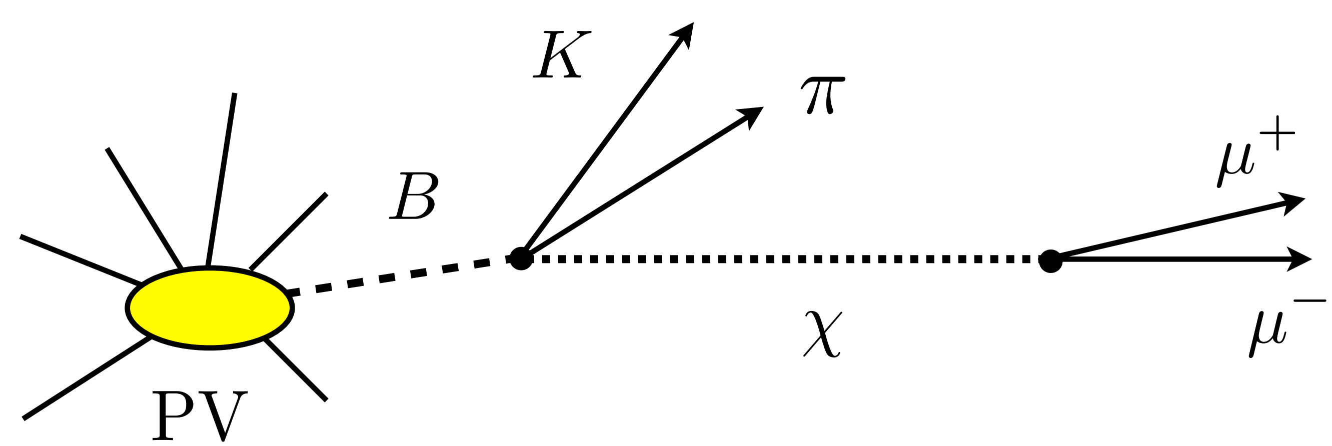
# Long-lived particles (LLPs)

LHCb looks for LLPs in:

- di-jet events
- muon plus jet events
- rare decays of heavy flavours



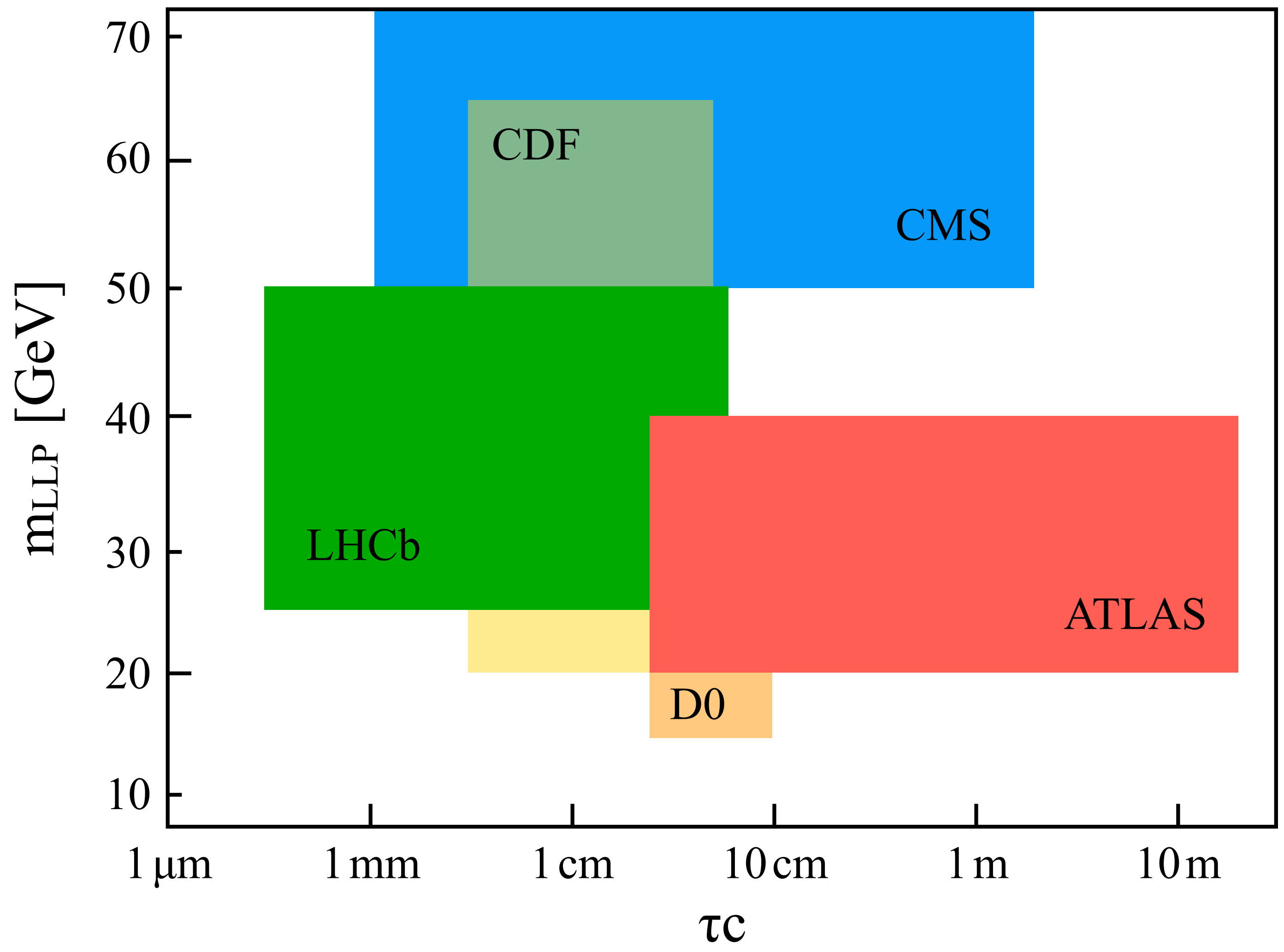

In addition searches for charged massive stable particles using RICH are performed




di-jet searches discussed in what follows other topics in backup

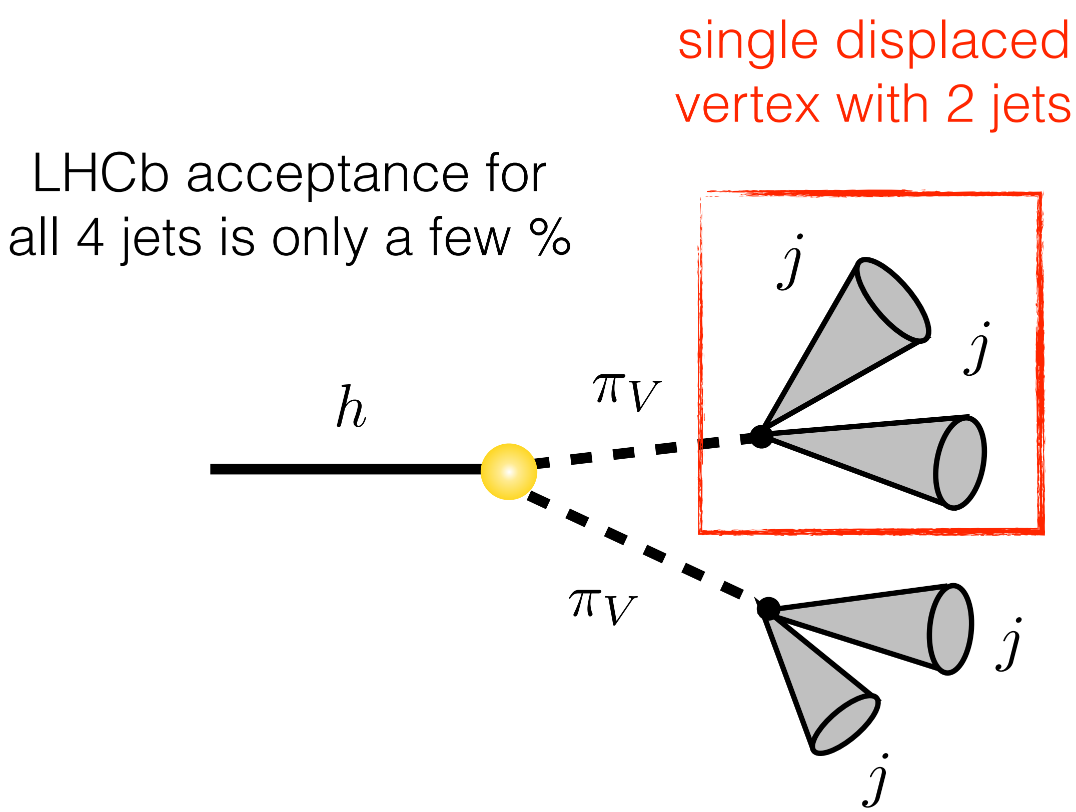
# Di-jet searches for LLPs

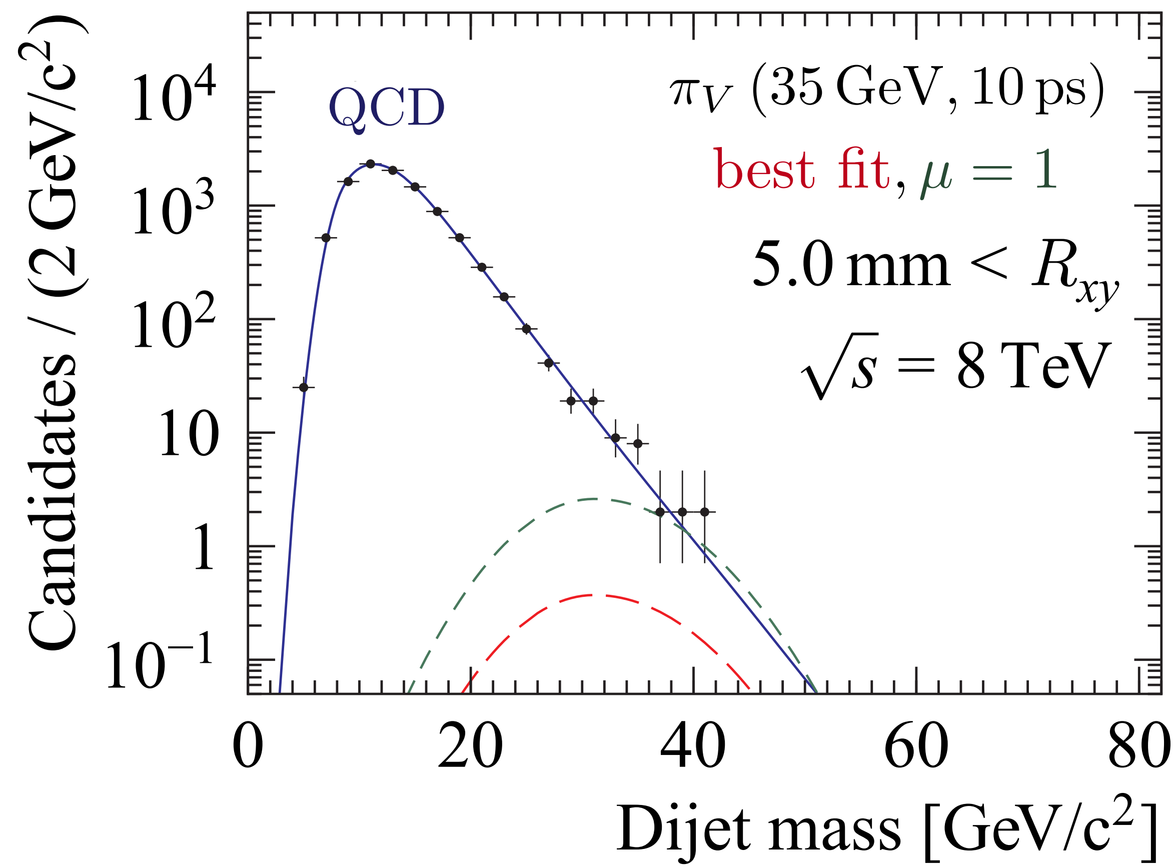
David, CERN-THESIS-2016-077




LHCb coverage complementary to ATLAS & CMS: lower lifetimes down to 1ps (excellent vertexing & boost) as well as lower masses down to 25 GeV (soft trigger & forward acceptance)

# Displaced Higgs decay

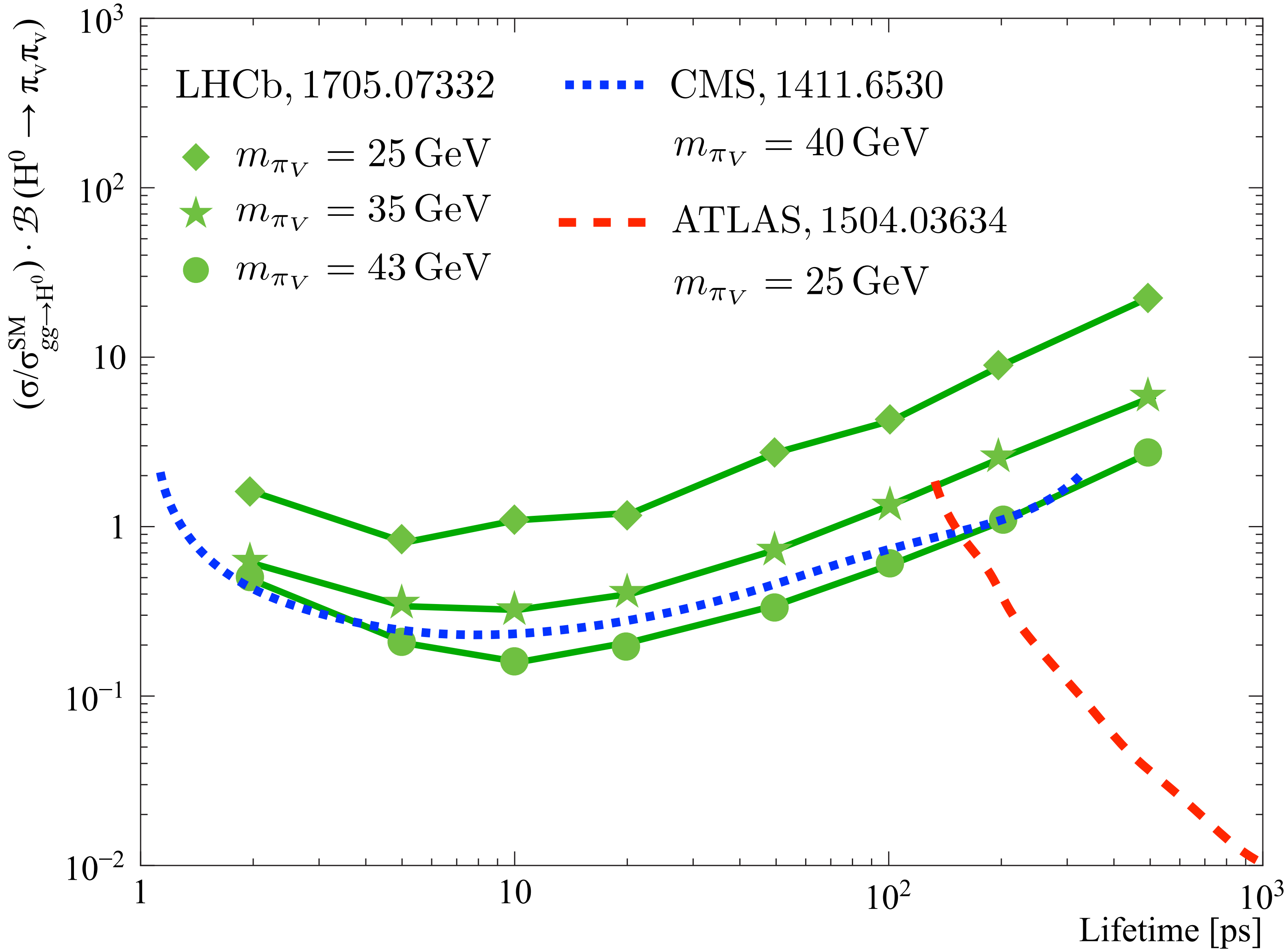



Triggering on displaced vertex & quality requirements on jets & di-jet pointing. Signature extracted from di-jet mass fit in bins of beam-axis displacement $R_{xy}$ using both 7 TeV & 8 TeV data

LHCb, 1705.07332

# Displaced Higgs decay

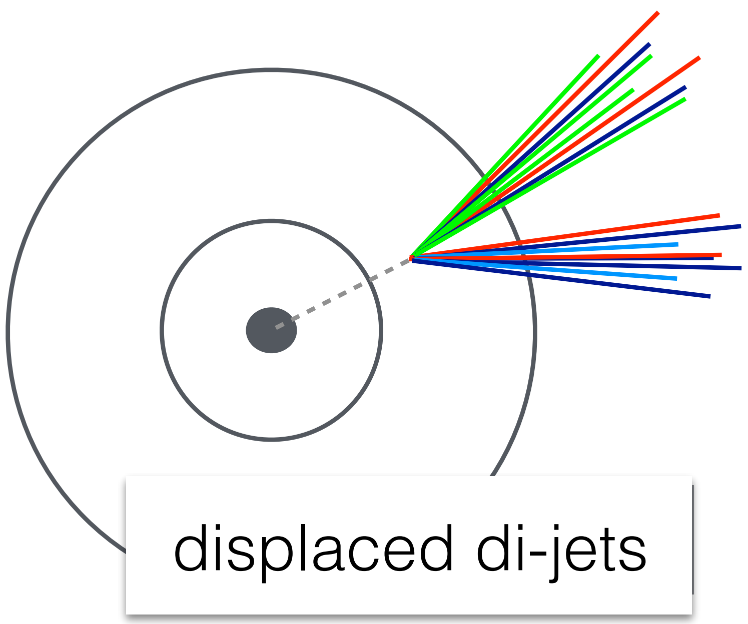



At low lifetimes & masses, LHCb constraints as good as CMS bounds despite lower luminosity & acceptance

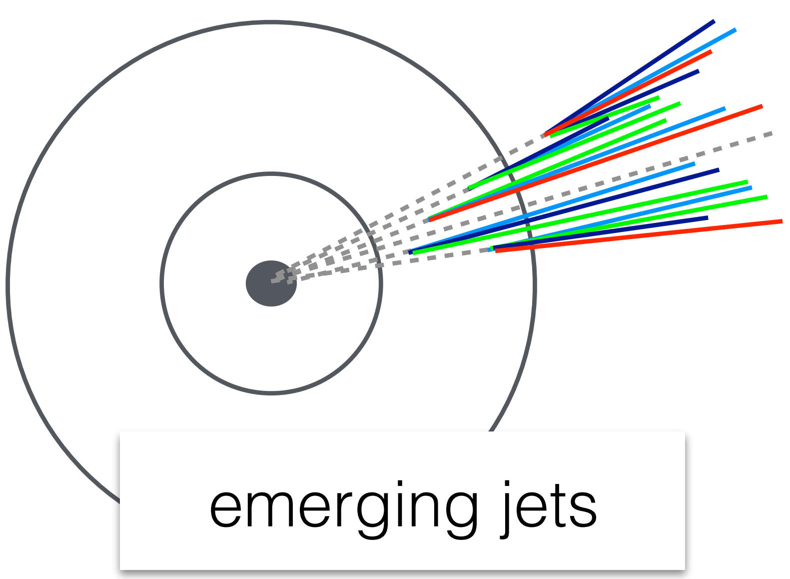
# Future: emerging jets

Emerging jets, i.e. jets with many displaced vertices arising from dark parton shower, are smoking gun signals of composite dark matter models

Schwaller, Stolarski & Weiler, 1502.05409




In view of precise jet vertexing & sensitivity to low mediator masses, LHCb has great potential to study emerging jets



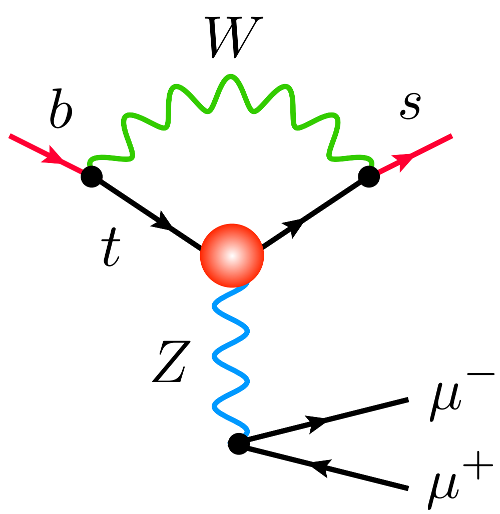
# Conclusions

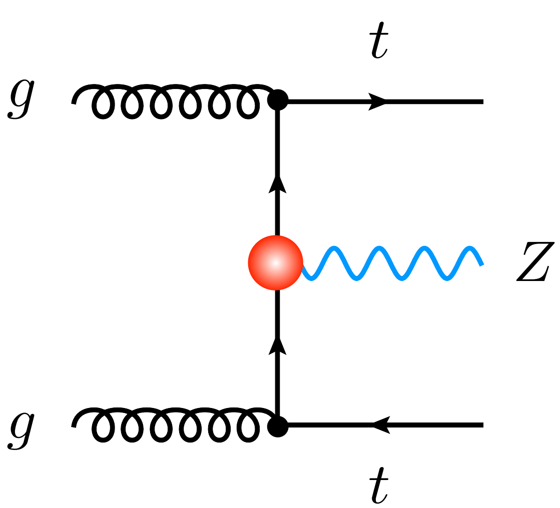
In Run I, LHCb has developed & pursued a wide programme of general physics measurements. Obtained results are often complementary to that of ATLAS & CMS

Potential of general physics programme at LHCb Phase-II Upgrade essentially unexplored. IMHO a lot of interesting physics, great to broaden horizon, plenty room for new & crazy ideas …

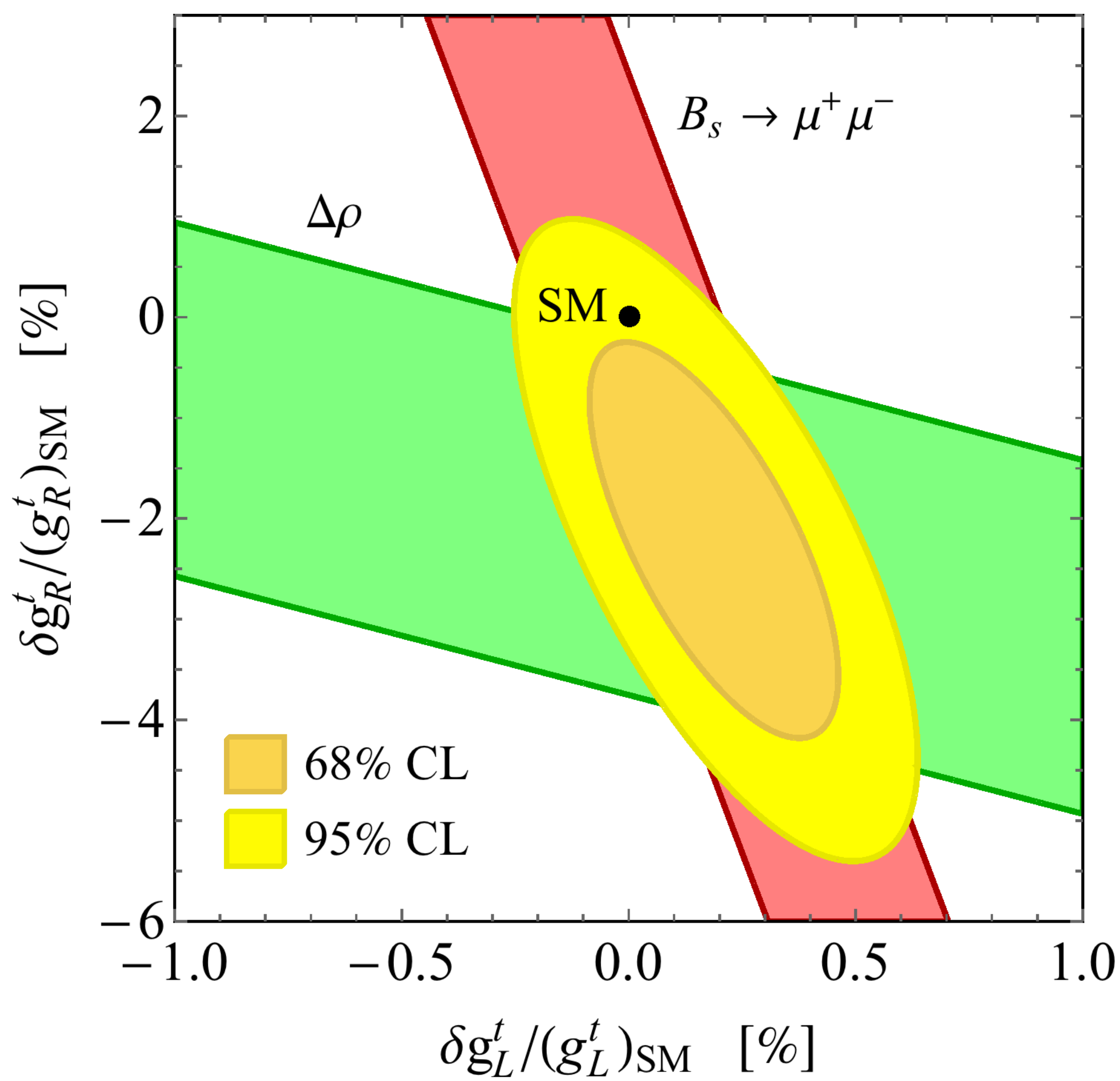
# Backup

# $Zt\bar{t}$ couplings from $B_s \to \mu^+\mu^-$



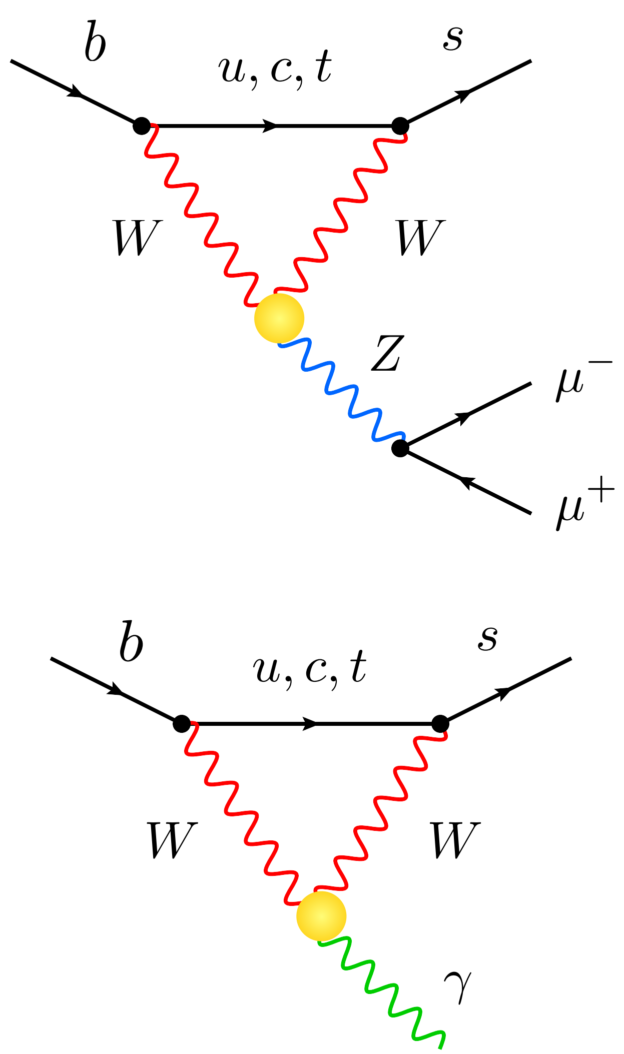

UH based on Brod et al., 1408.0792

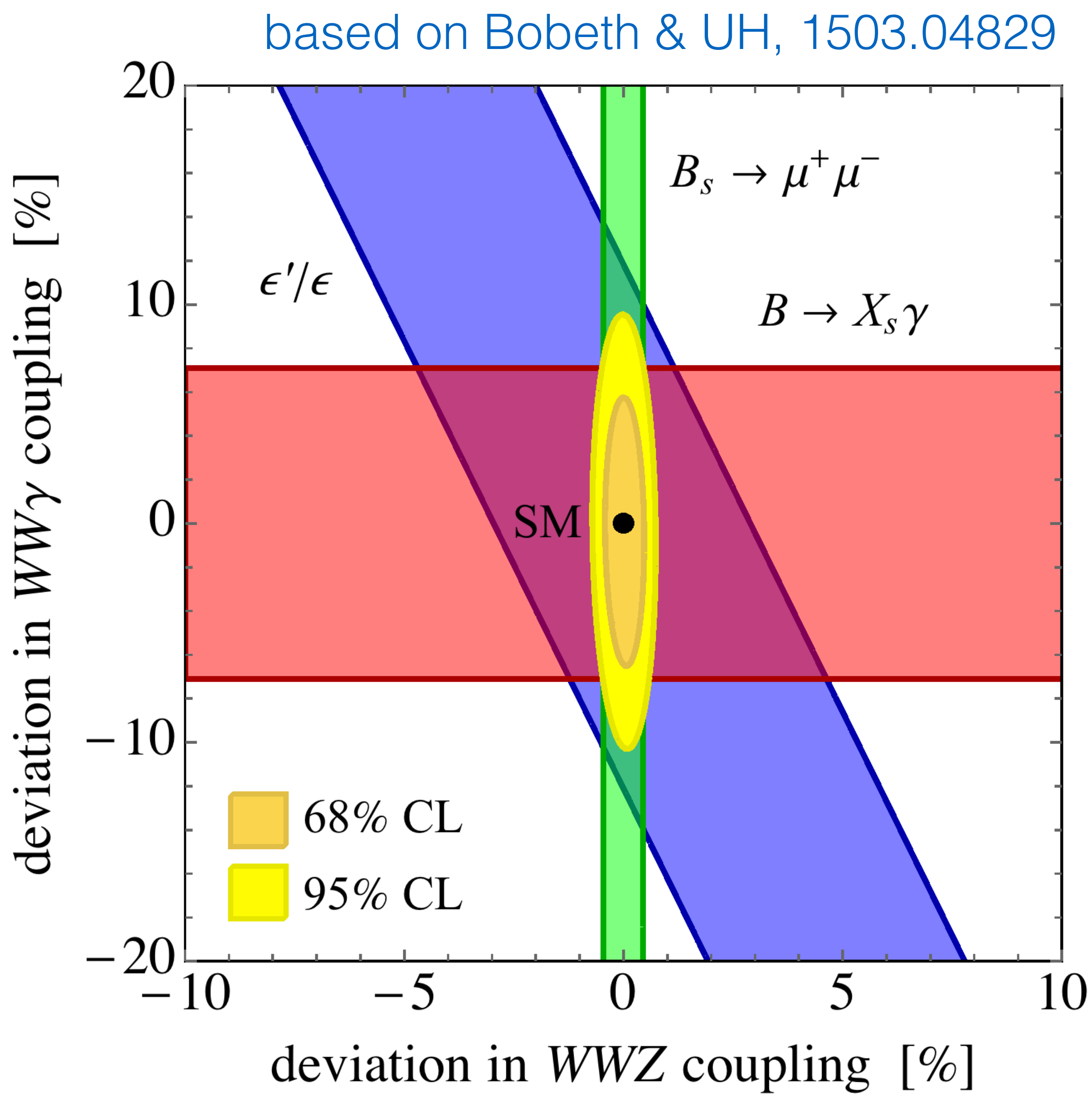



Future $B_s \to \mu^+\mu^-$ measurements may constrain $Zt\bar{t}$ couplings at few % level. Direct measurements only able to reach O(30%) precision

Röntsch & Schulze,1404.1005

# WWZ/γ couplings from flavour

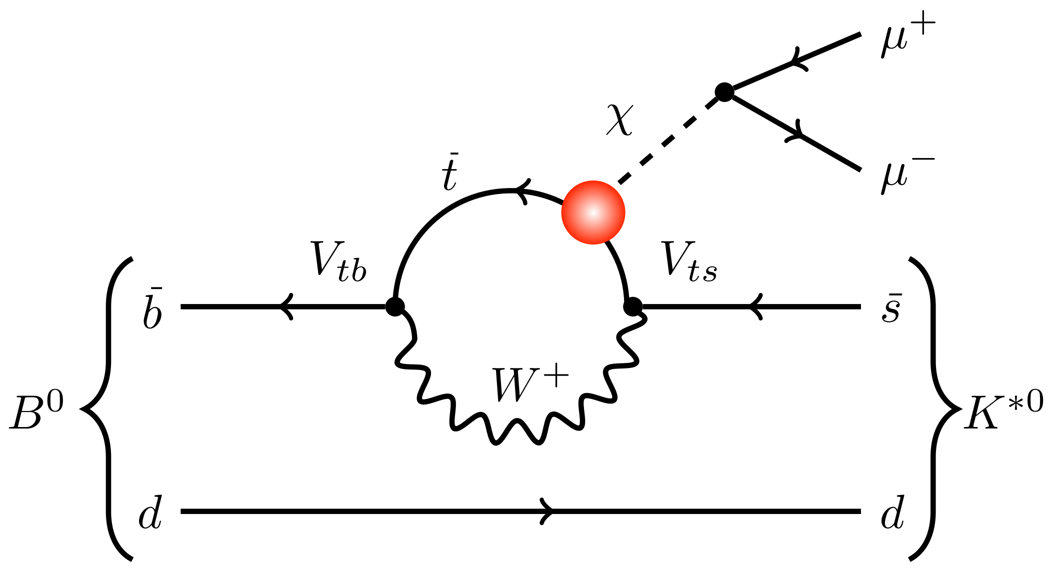


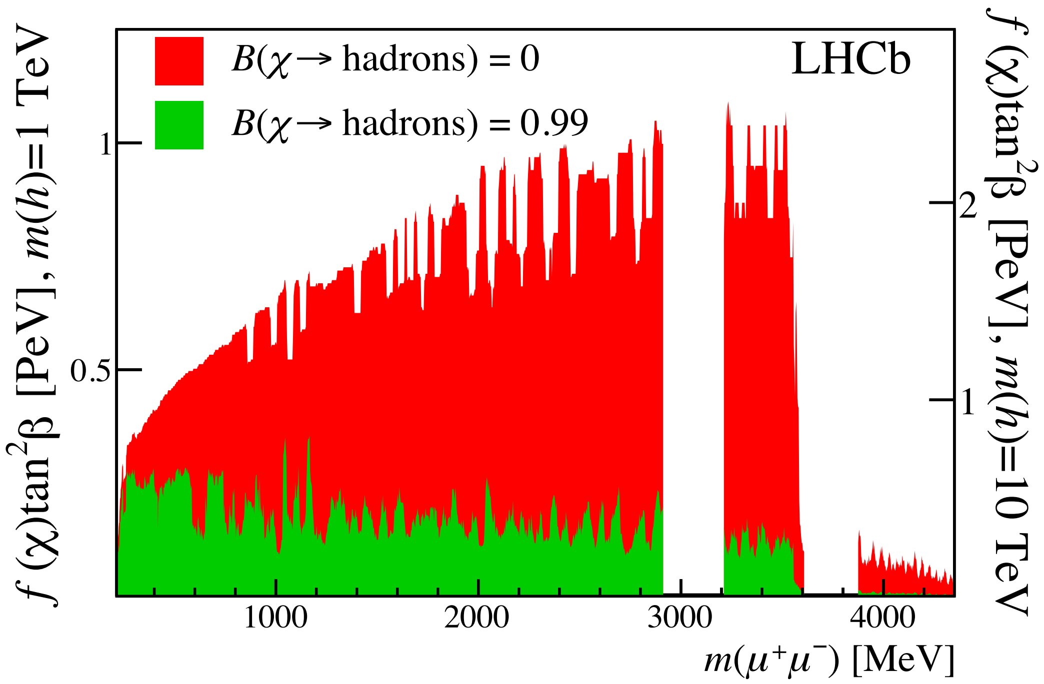




Future $B_s \to \mu^+\mu^-$ measurements can test WWZ coupling with O(1%) precision. Only O(10%) sensitivity in case of WWγ from $B \to X_s\gamma$

# Axions in di-muon spectrum

LHCb, 1508.04094

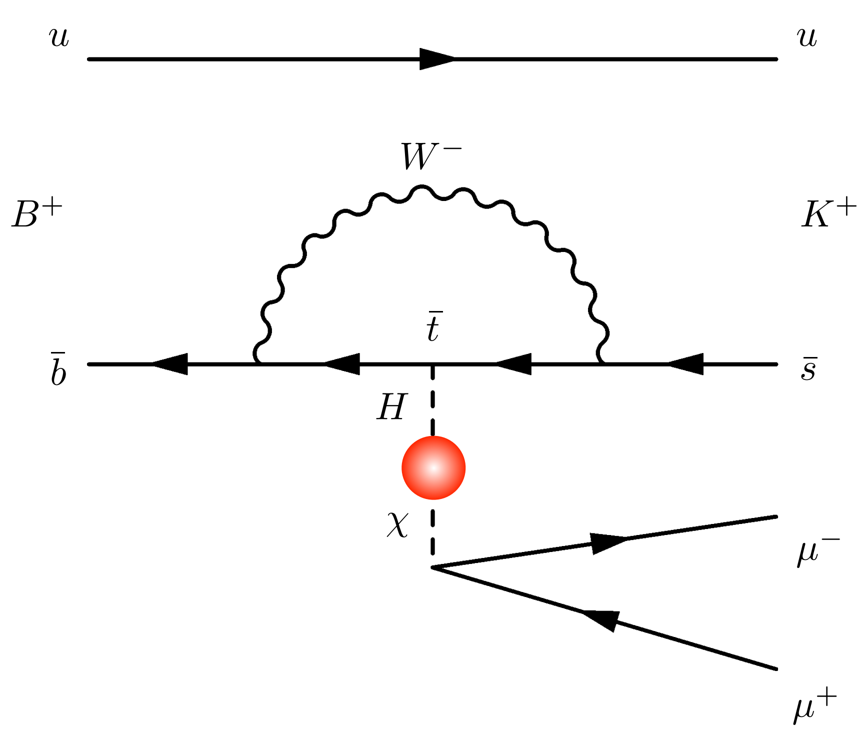


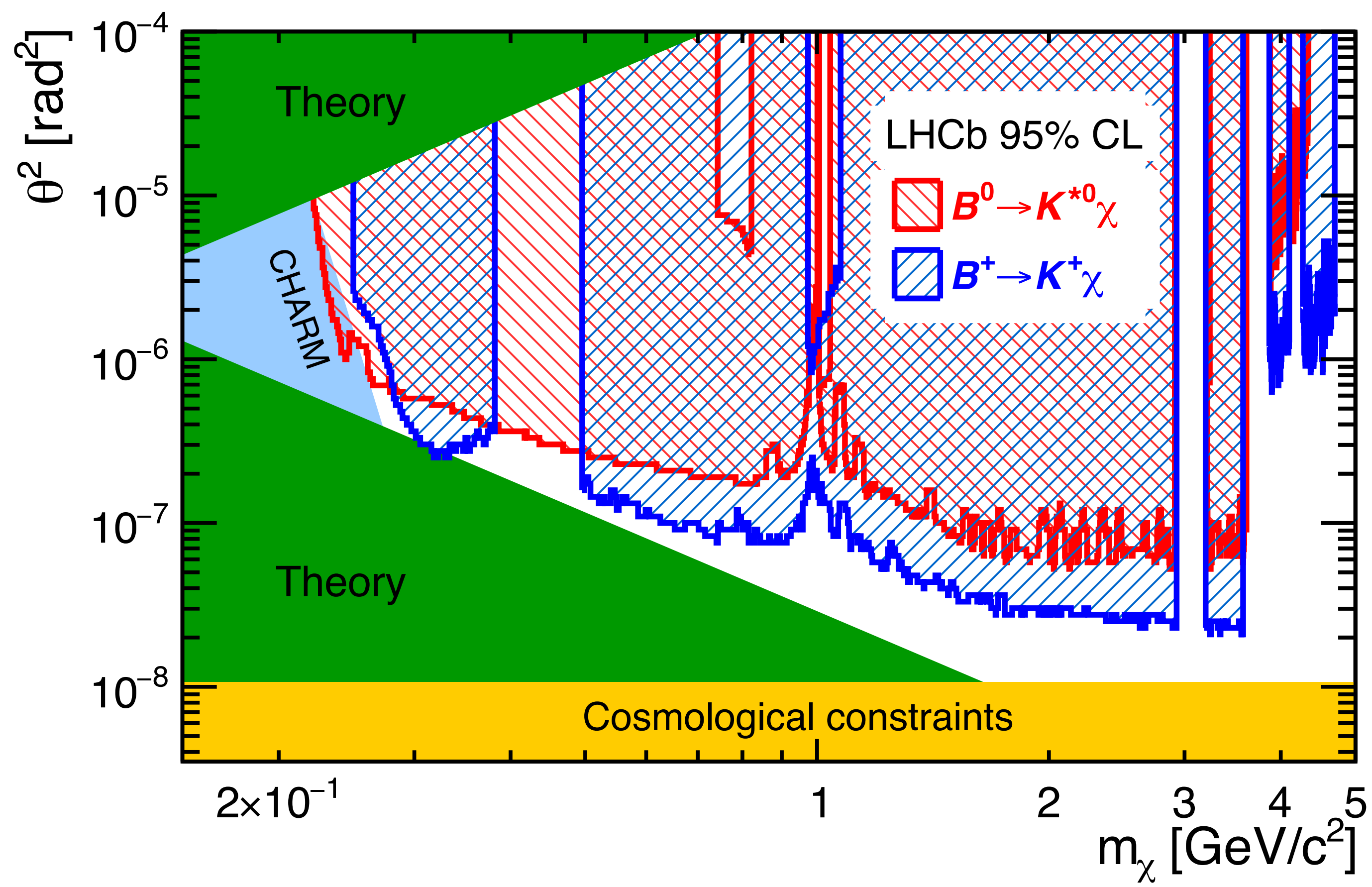

LHCb measurement of di-muon spectrum in $B\to K^*\mu^+\mu^-$ decay sets strong constraints on axion-top couplings in axion-portal models

Freytsis, Ligeti & Thaler, 0911.5355

# Inflatons in di-muon spectrum




LHCb, 1612.07818

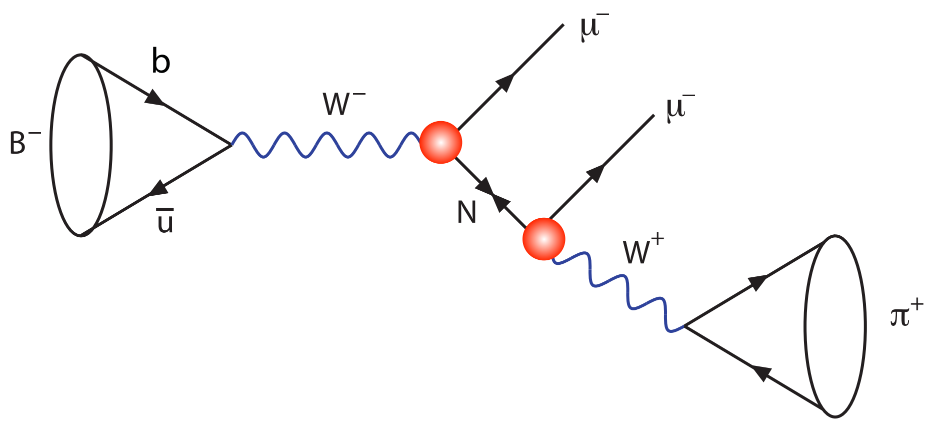


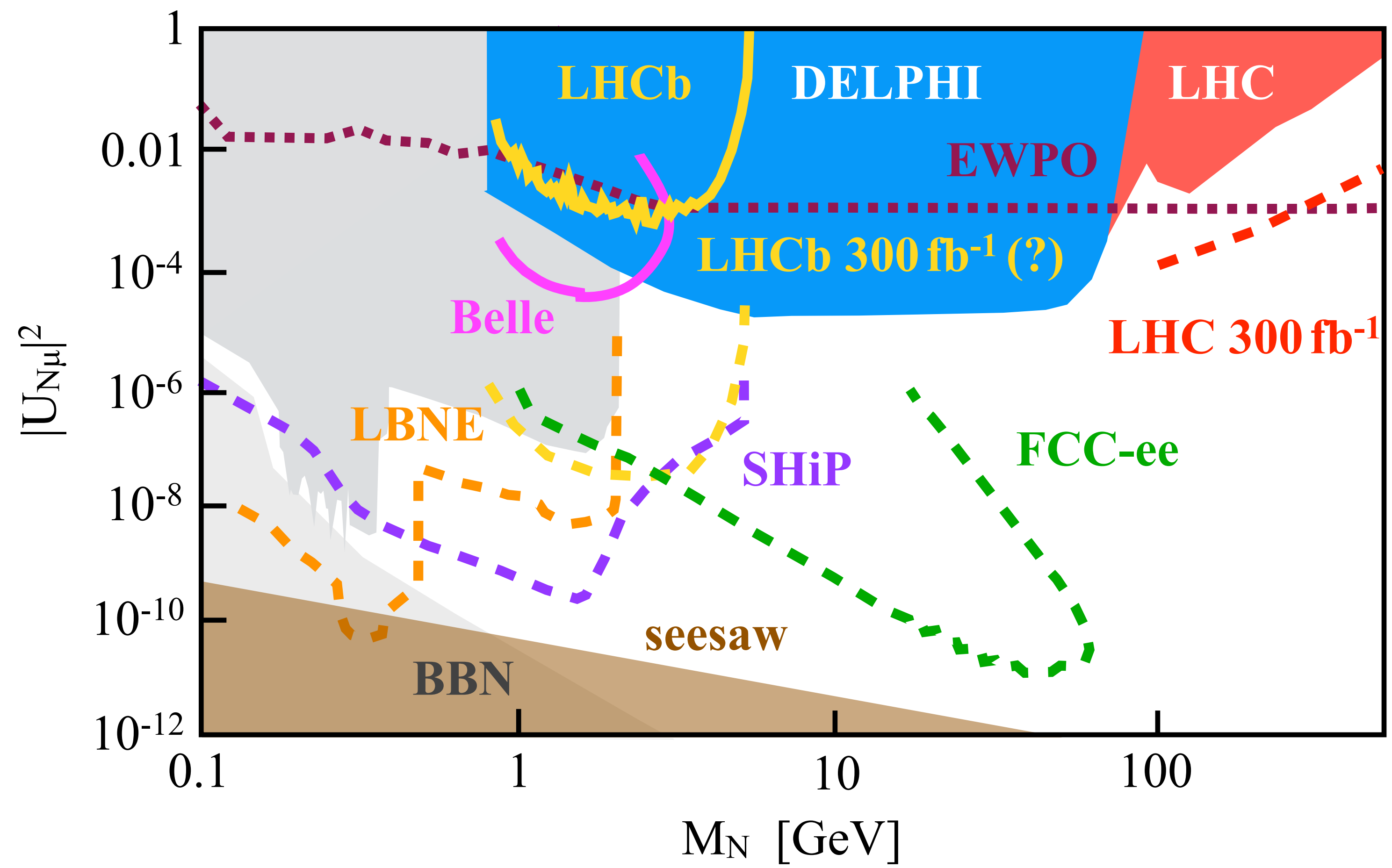

Di-muon spectrum can also be used to severely constrain GeV-mass scalar particles such as an inflaton if it mixes with SM Higgs boson

Batell, Pospelov & Ritz, 0911.4938; Bezrukov & Gorbunov, 0912.0390; 1303.4395

# Majorana neutrinos

UH update of SHiP physics case, 1504.04855

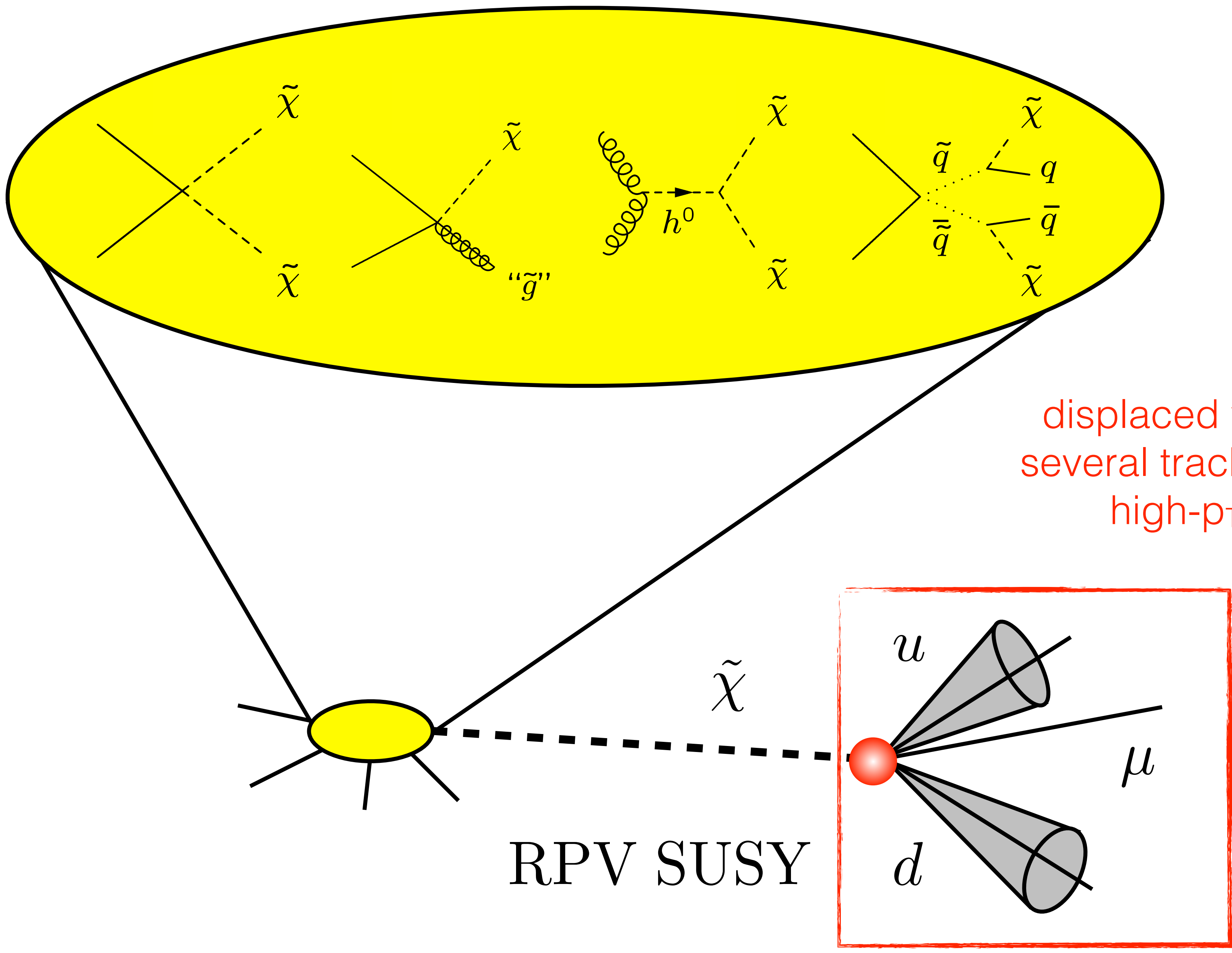



LHCb Run I search for $B^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$ allows to constrain mass & mixing angle of Majorana neutrinos. How does LHCb Phase-II Upgrade reach compare to SHiP prospects? Are other channels possible?

B flavour bounds from Shuve & Peskin, 1607.04258; see talk by Jessica Prisciandaro for LHCb prospects

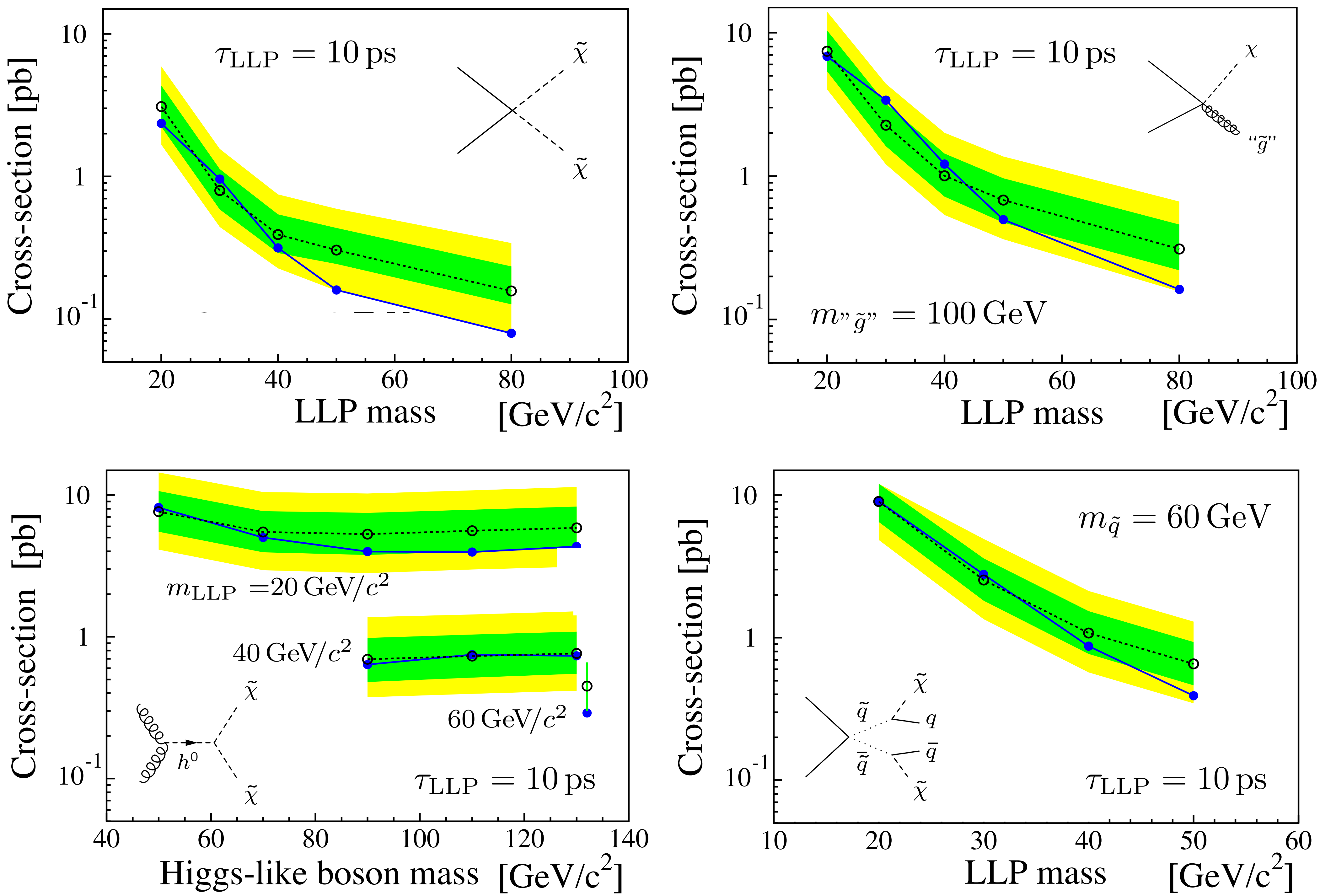
# LLPs in muon plus jets channel




displaced vertex with several tracks including high-$p_T$ muon

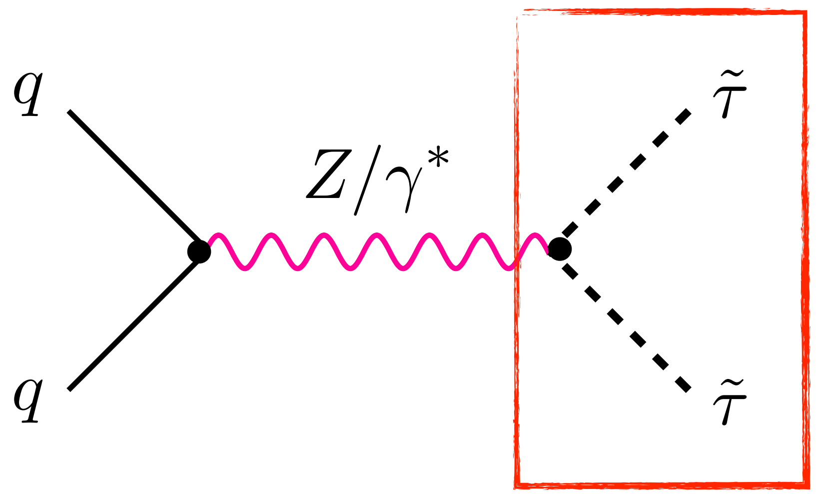
LHCb, 1612.00945

# LLPs in muon plus jets channel

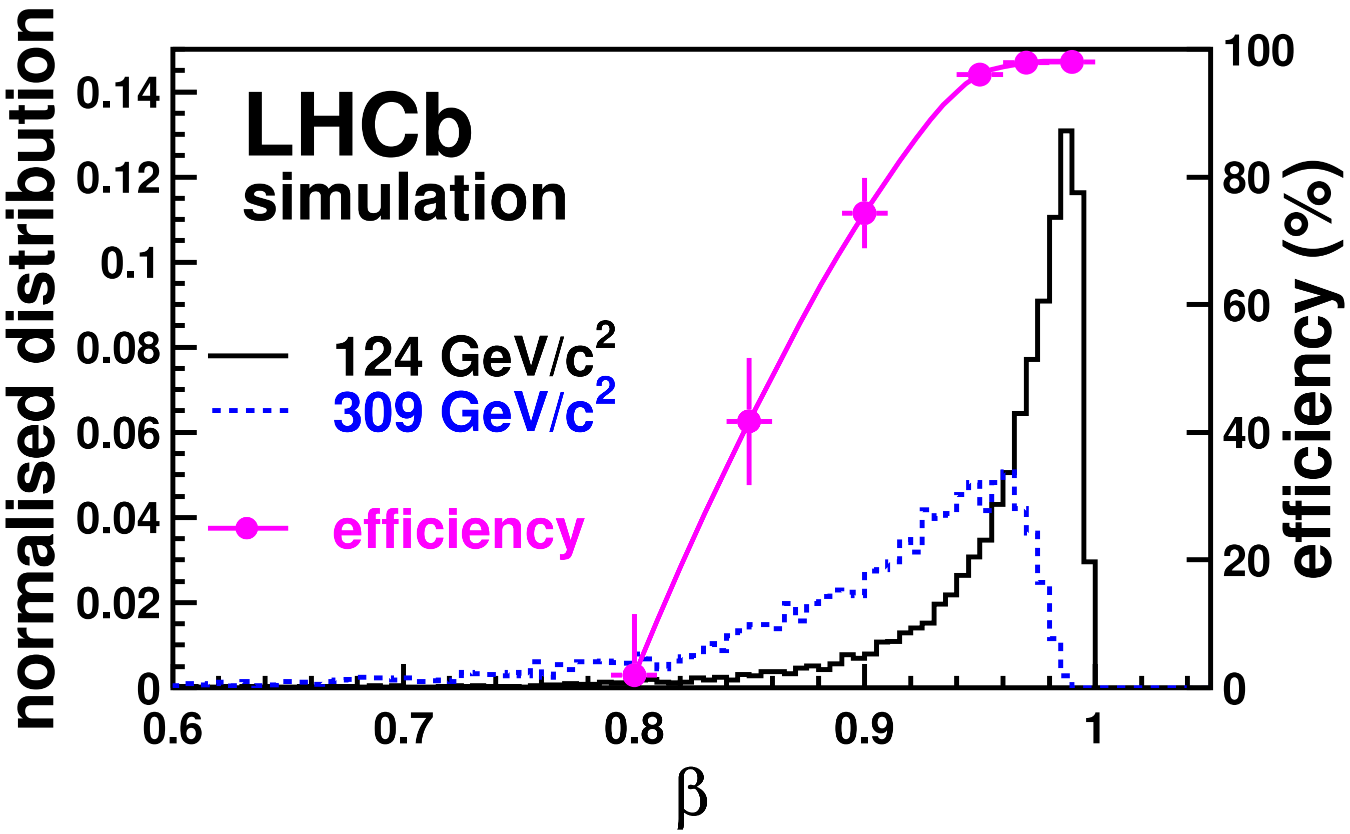



LHCb, 1612.00945

# Charged massive stable particles



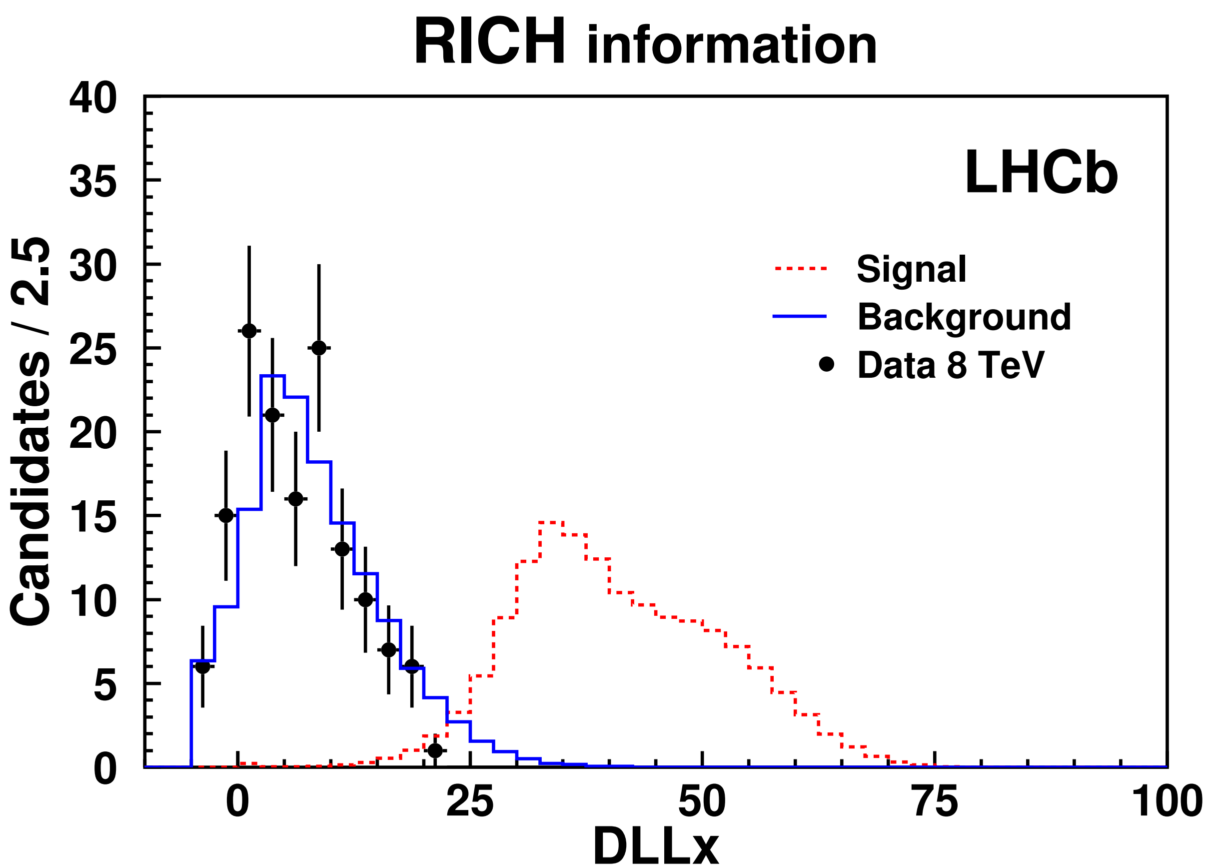

long-lived stau, possibly
NLSP in mGMSB

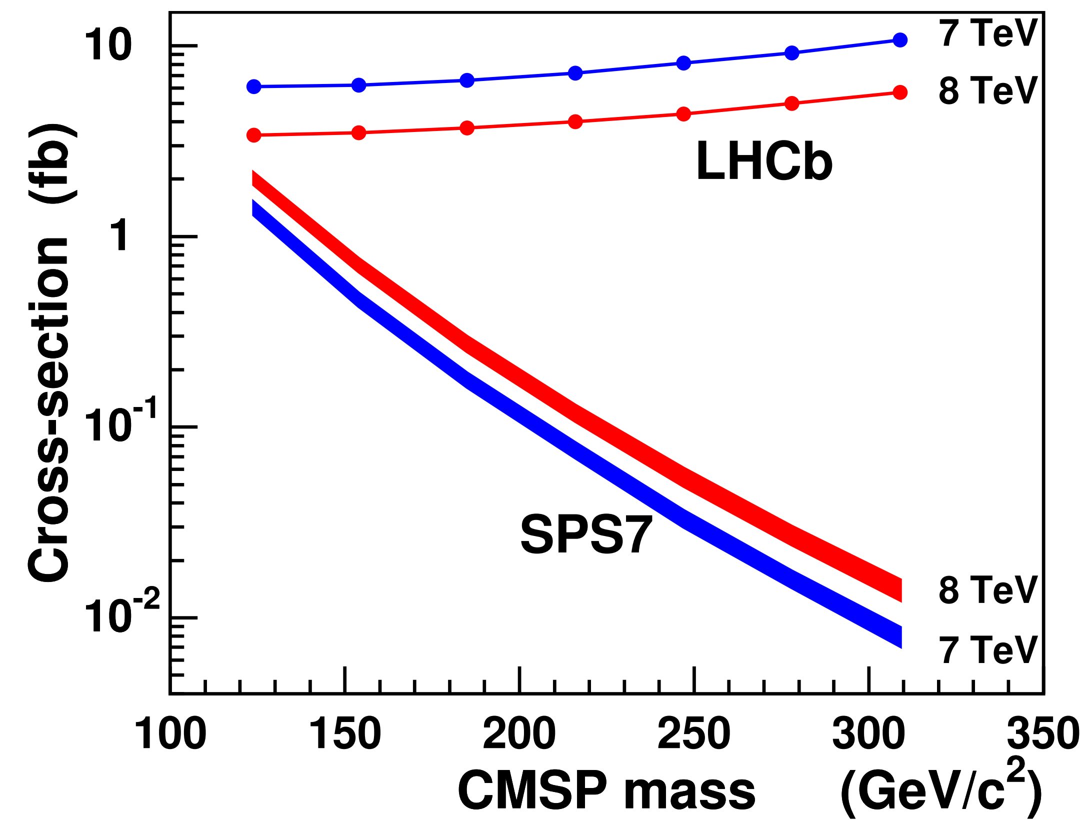



Charged massive stable particles produced with relatively low velocity & can be identified by their longer time-of-flight, their energy loss (ionisation) & absence of Cherenkov radiation

LHCb, 1506.09173

# Charged massive stable particles



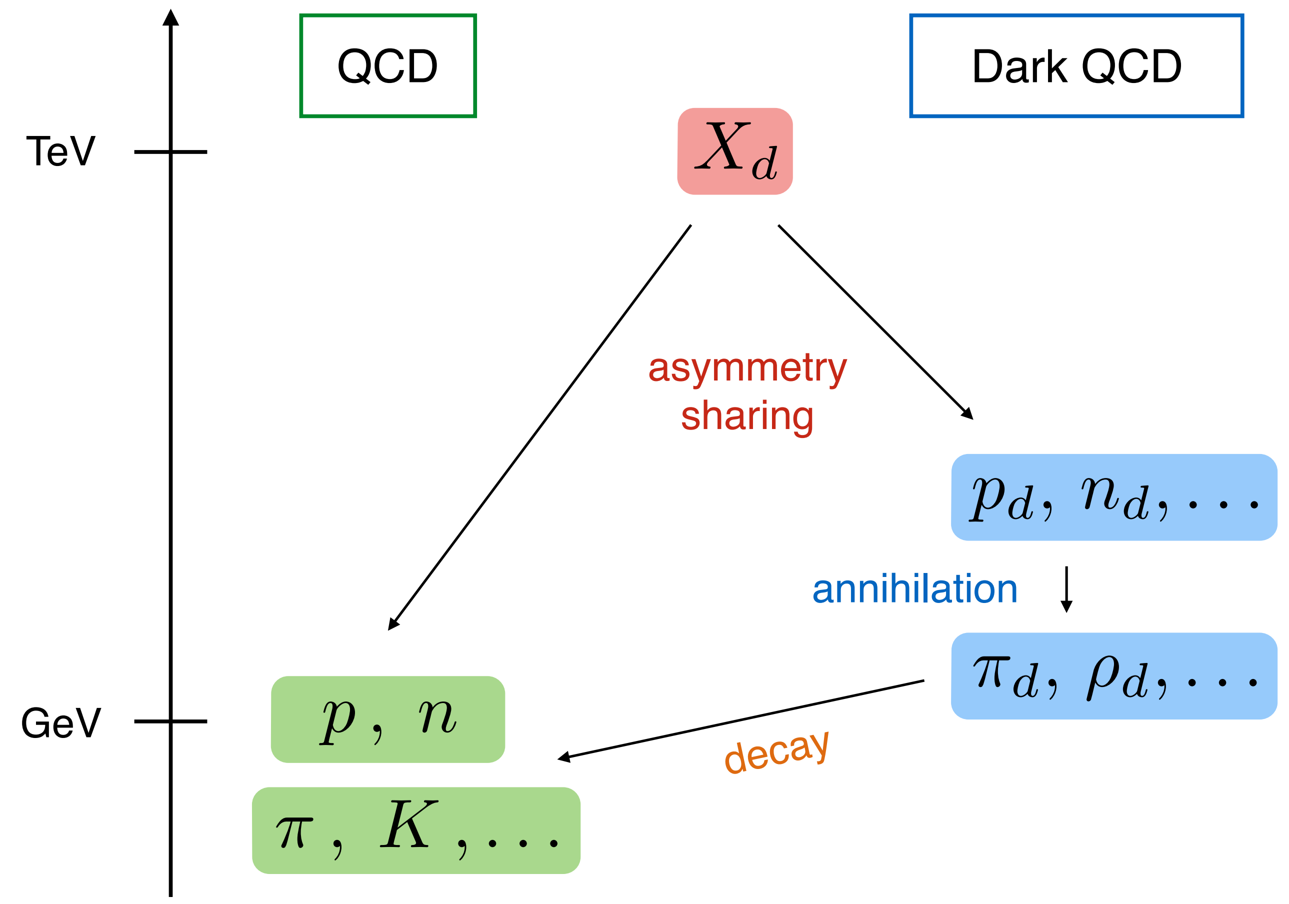

Select pair of muon-like tracks in mass range [120, 300] GeV. Neural network used to combine RICH information with energy loss from VELO & calorimeters. Existing LHCb limits not competitive with D0 (low mass) & ATLAS (high mass)

LHCb, 1612.00945

# Emerging jets: generalities

Requirements for appearance of emerging jets:

- large hierarchy between mediator mass & dark sector masses
- strong coupling in dark sector leading to large particle multiplicity
- macroscopic decay lengths of dark sector to visible particles




Schwaller, Stolarski & Weiler, 1502.05409

# Emerging jets: toy model

| Field | $SU(3)\times SU(2)\times U(1)$ | $SU(3)_{\text{dark}}$ | Mass | Spin |
|---|---|---|---|---|
| $Q_d$ | $(1,1,0)$ | $(3)$ | $m_d\ \mathcal{O}(\text{GeV})$ | Dirac Fermion |
| $X_d$ | $(3,1,\frac{1}{3})$ | $(3)$ | $M_{X_d}\ \mathcal{O}(\text{TeV})$ | Complex Scalar |

$$\mathcal{L}_\kappa = \kappa_{ij}\bar{Q}_{d_i} q_j X_d + \text{h.c.}$$

$$\mathcal{L} \supset \bar{Q}_{d_i}(\not{D} - m_{d_i})Q_{d_i} + (D_\mu X_d)(D^\mu X_d)^\dagger - M_{X_d}^2 X_d X_d^\dagger - \frac{1}{4} G_d^{\mu\nu} G_{\mu\nu,d} + \mathcal{L}_\kappa + \mathcal{L}_{\text{SM}}$$

Schwaller, Stolarski & Weiler, 1502.05409

# Emerging jets: dark pion decays

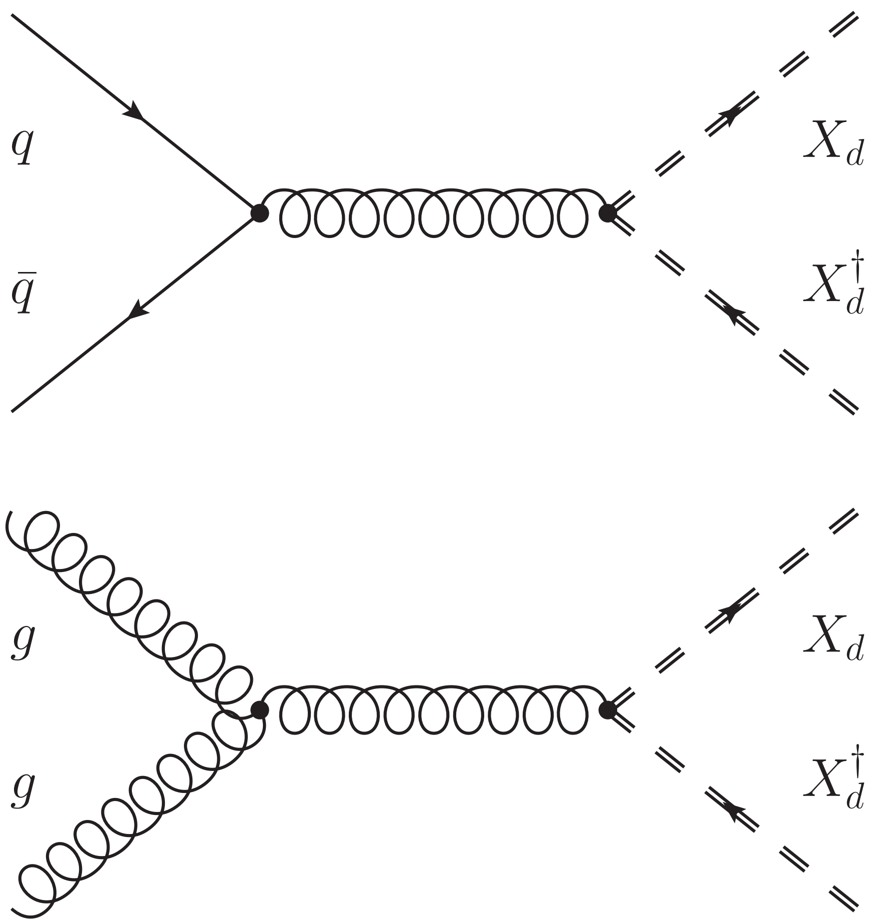
Dark pions are Goldstone bosons of $n_f \times n_f$ dark flavour symmetry. They decay to down-type quarks with centimeter to meter decay lengths:

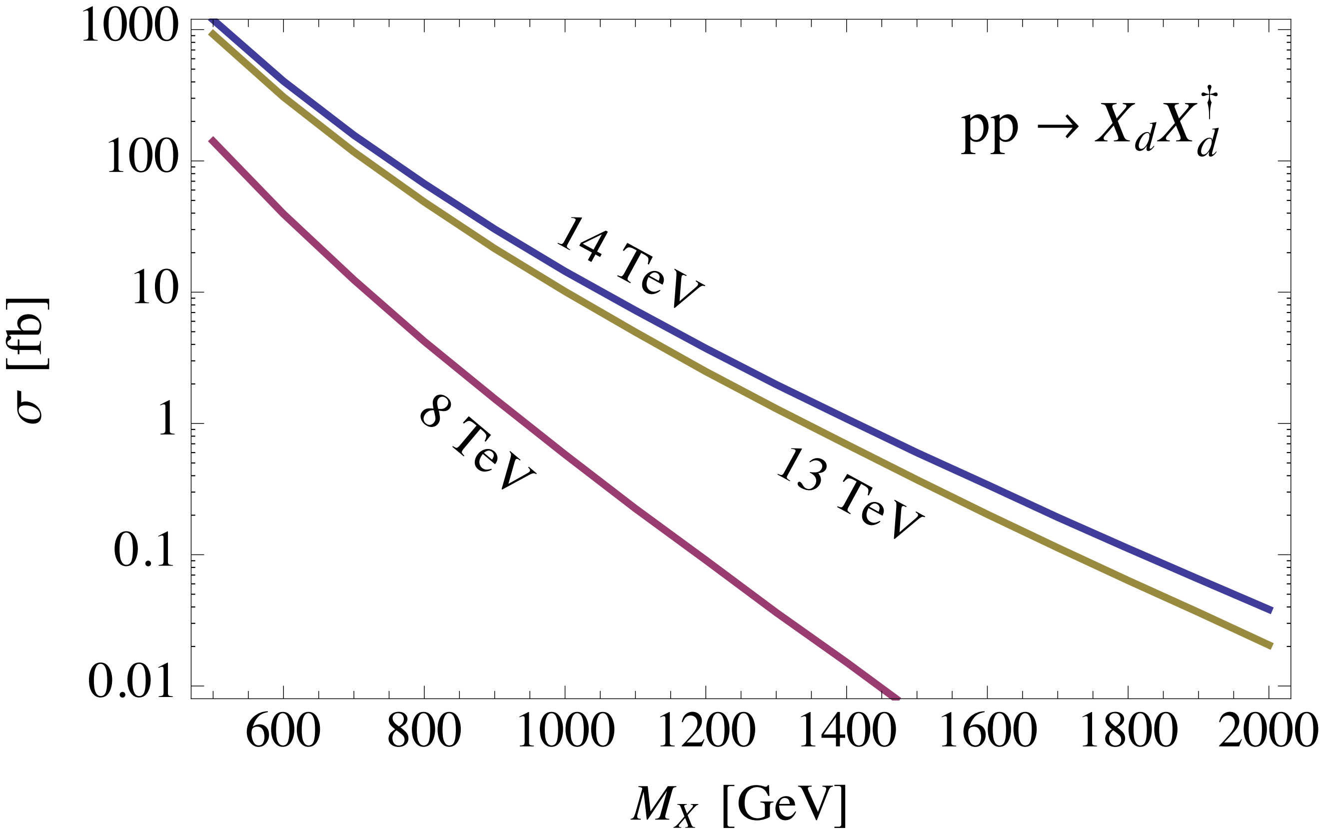
$$\Gamma(\pi_d \to \bar{d}d) = \frac{\kappa^4 N_c f_{\pi_d}^2 m_{\mathrm{down}}^2}{32\pi M_{X_d}^4} m_{\pi_d}$$

$$c\tau_0 = \frac{c\hbar}{\Gamma} \approx 80\,\mathrm{mm} \times \frac{1}{\kappa^4} \times \left(\frac{2\ \mathrm{GeV}}{f_{\pi_d}}\right)^2 \left(\frac{100\ \mathrm{MeV}}{m_{\mathrm{down}}}\right)^2 \left(\frac{2\ \mathrm{GeV}}{m_{\pi_d}}\right) \left(\frac{M_{X_d}}{1\ \mathrm{TeV}}\right)^4$$

Schwaller, Stolarski & Weiler, 1502.05409

# Emerging jets: mediator production

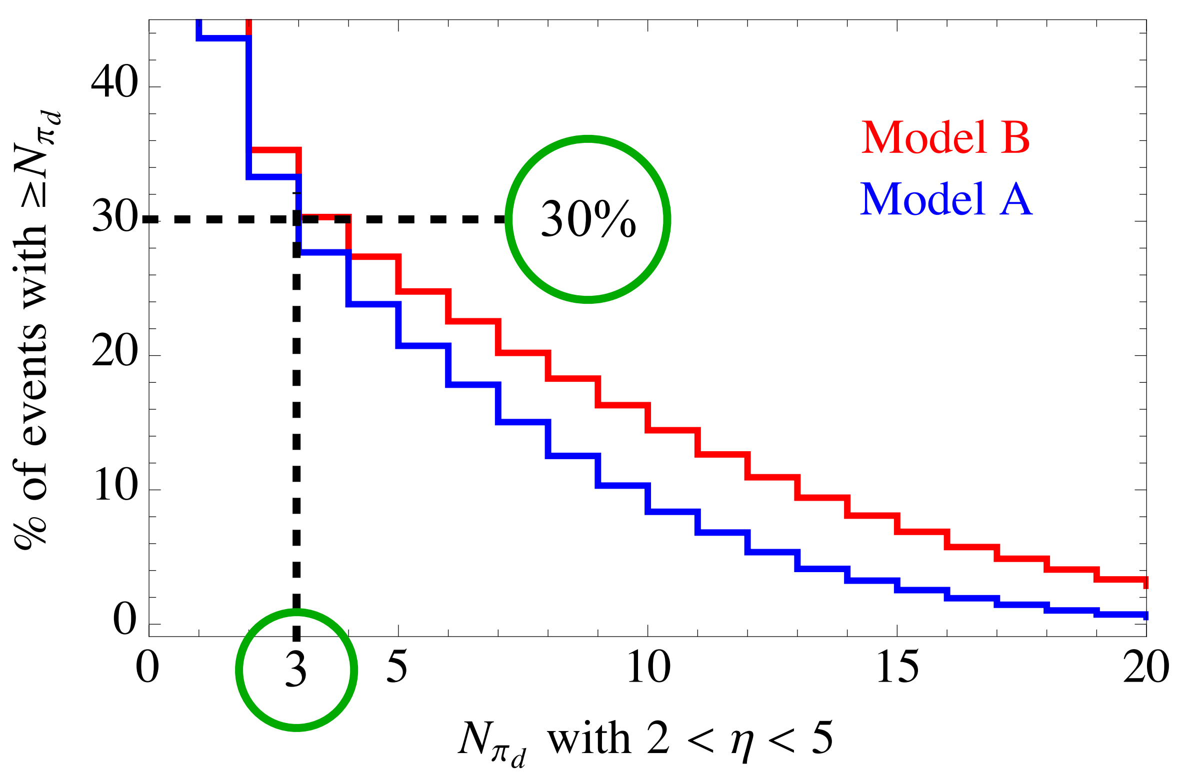


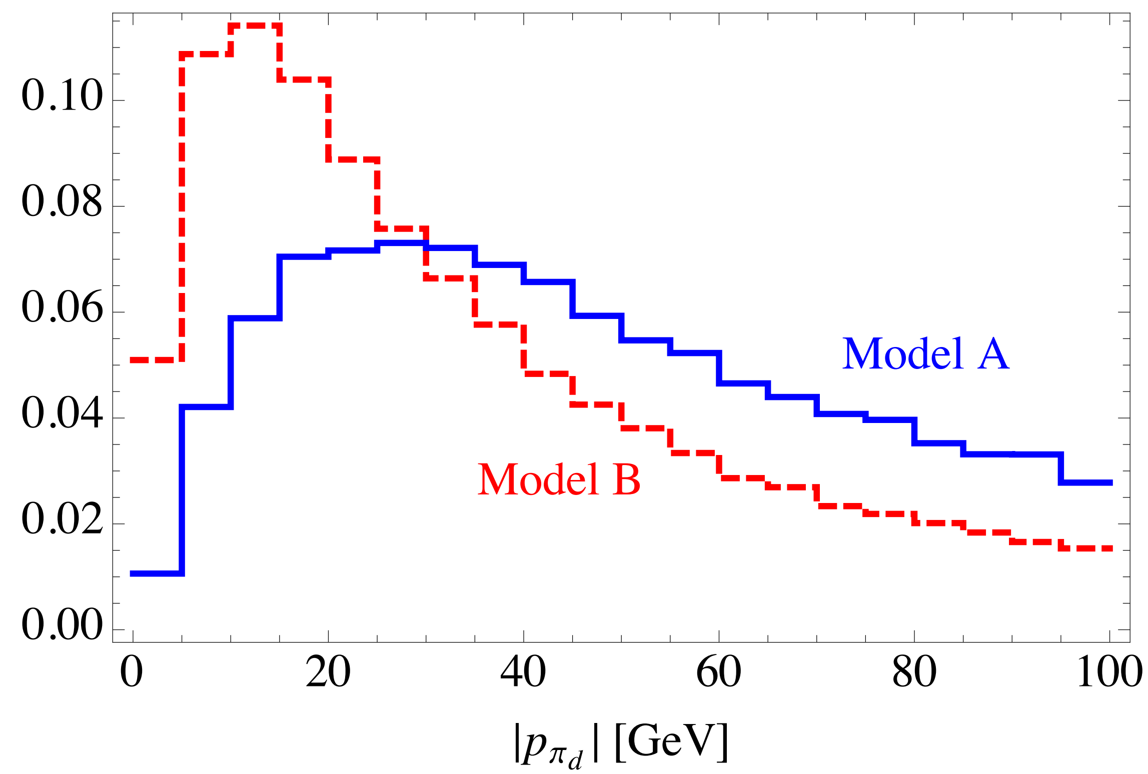




Schwaller, Stolarski & Weiler, 1502.05409

# Dark pion searches at LHCb

$$\sigma(pp \to \bar{Q}_d Q_d) \approx (8.2\ \mathrm{pb}) \times N_d \times n_f \times \left(\frac{\mathrm{TeV}}{\Lambda}\right)^4$$

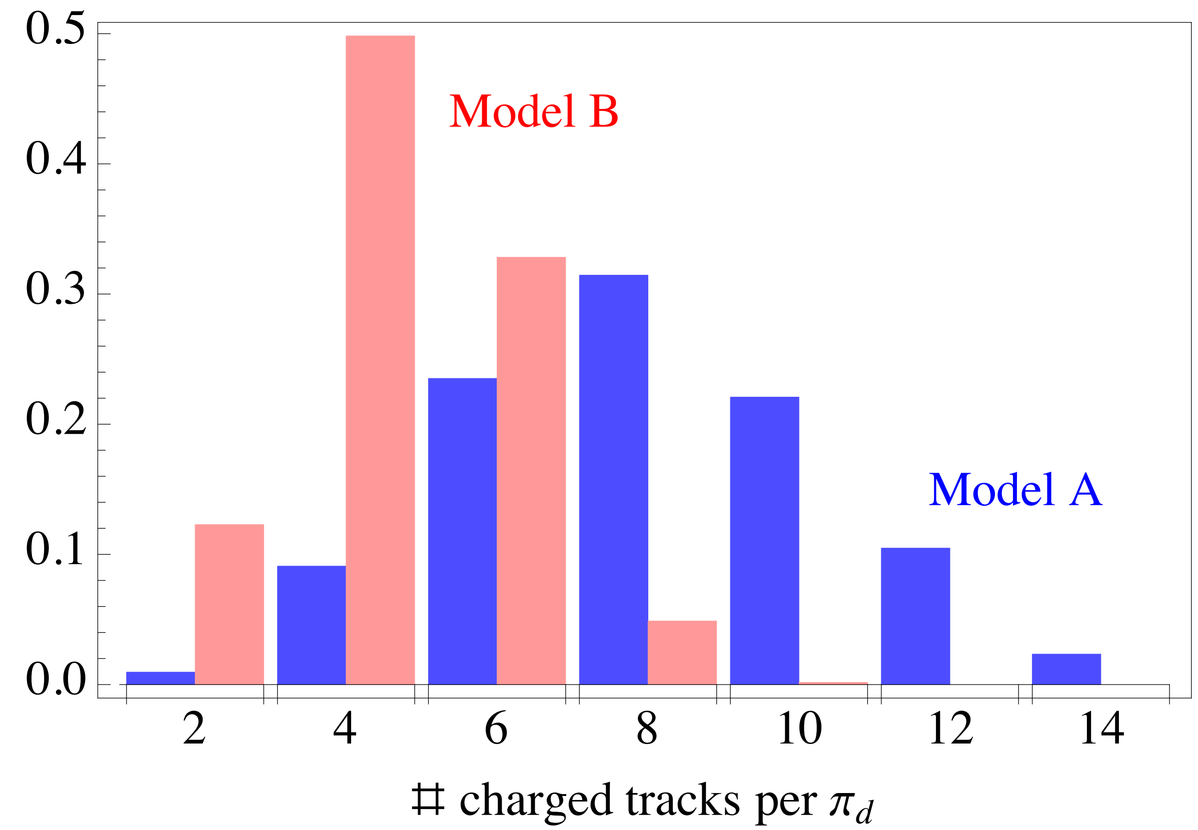



Schwaller, Stolarski & Weiler, 1502.05409

# Dark pion searches at LHCb

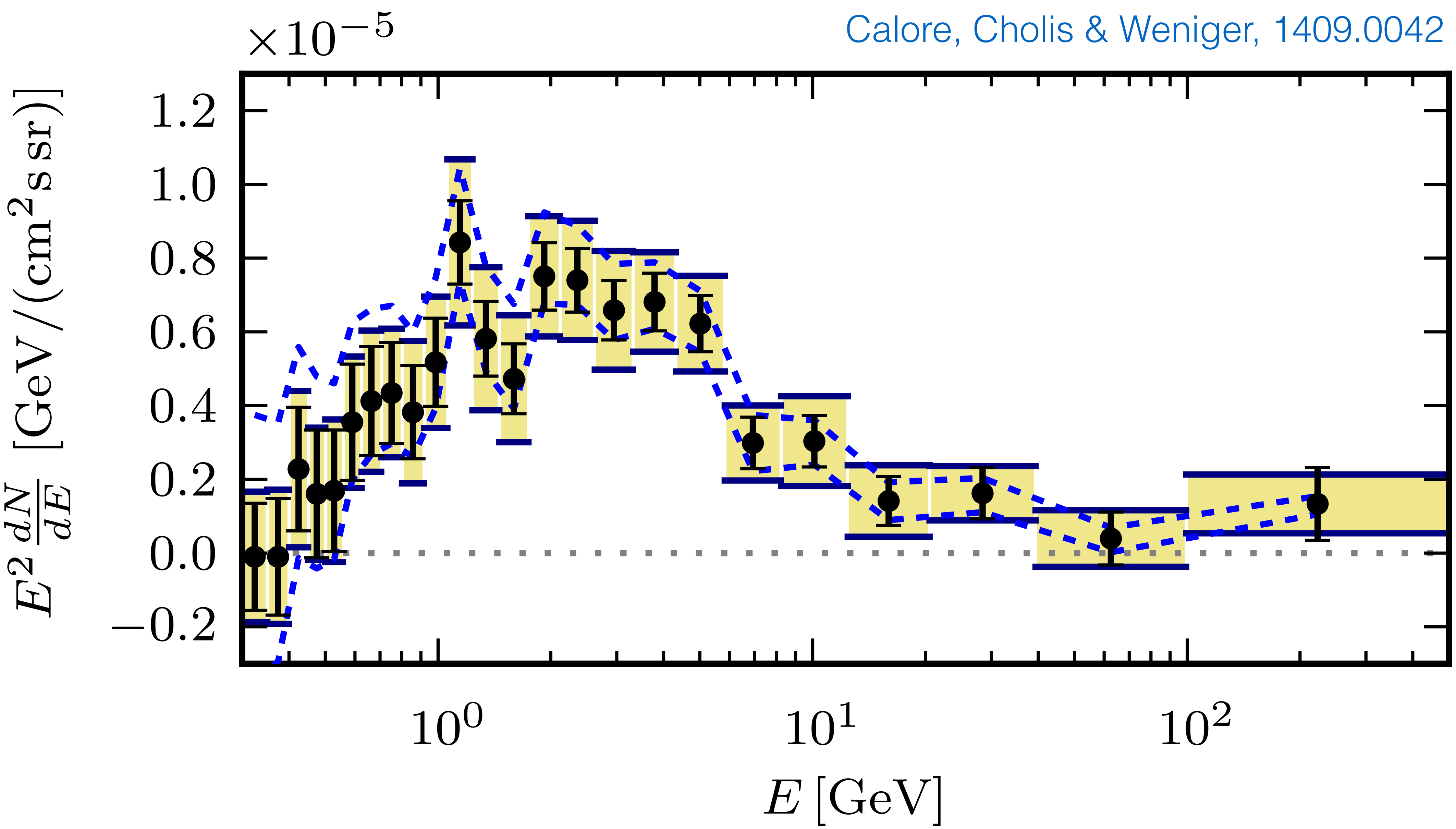
| | Model **A** | Model **B** |
|---|---|---|
| $\Lambda_d$ | 10 GeV | 4 GeV |
| $m_V$ | 20 GeV | 8 GeV |
| $m_{\pi_d}$ | 5 GeV | 2 GeV |
| $c\,\tau_{\pi_d}$ | 150 mm | 5 mm |




Number of tracks of O(10) for $m_{\pi_d}$ = 5 GeV. Events with three or more dark pions may look sufficiently different than background. Assuming a reconstruction efficiency of 10% with 15 $fb^{-1}$ should be possible to test 10 fb cross sections, corresponding to scales of O(5 TeV)

Schwaller, Stolarski & Weiler, 1502.05409

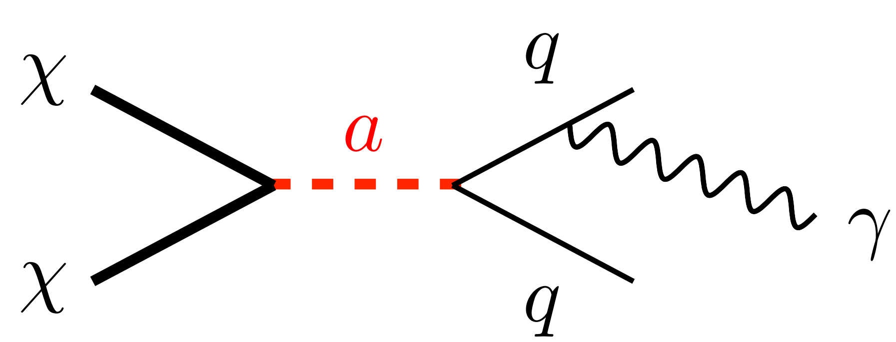
# Fermi-LAT excess

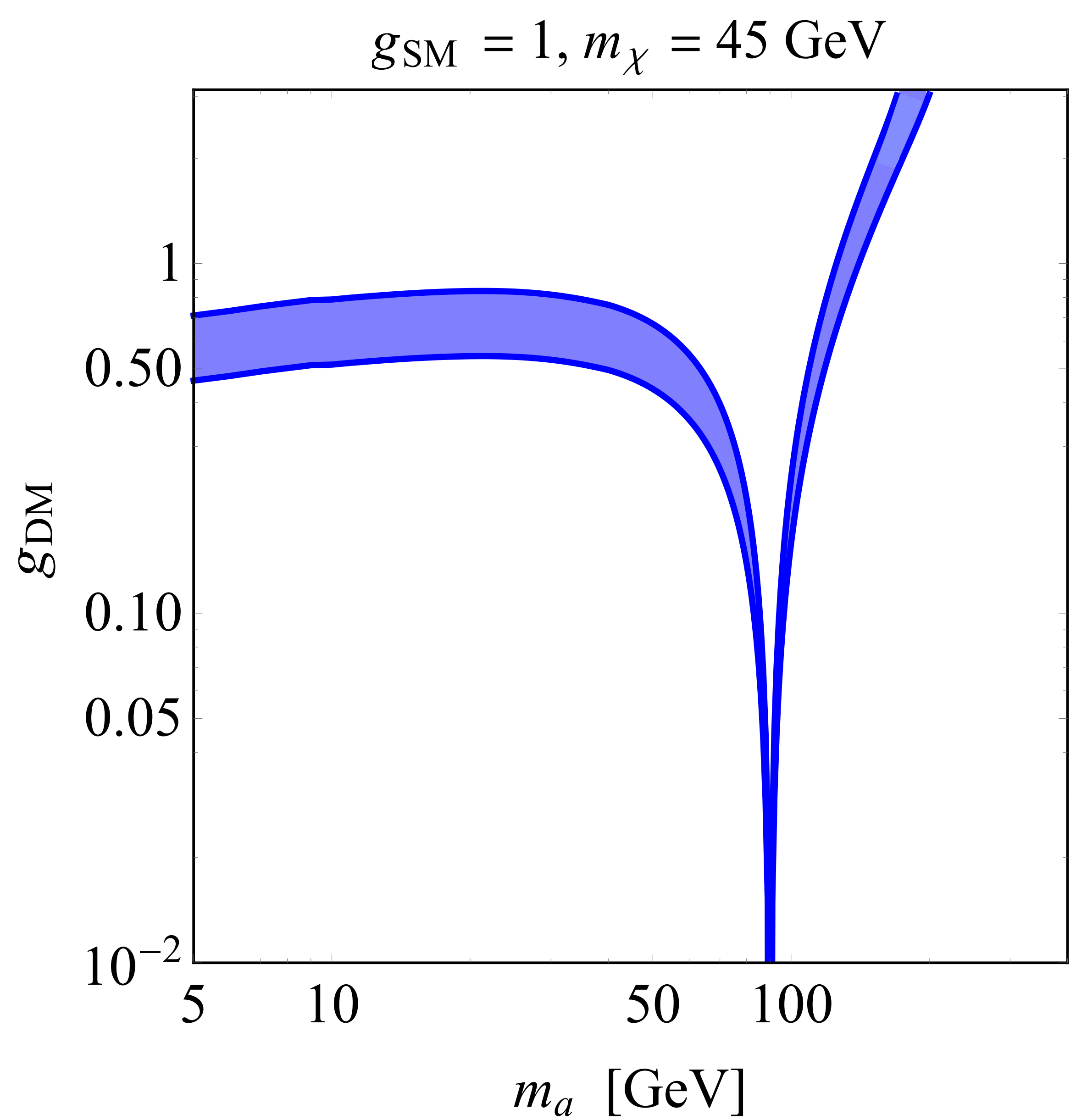



Fermi-LAT observes an excess at a few GeV in γ-ray emission data from galactic center & inner galaxy

# Fermi-LAT excess

$$\mathcal{L} \supset -\, i g_{\mathrm{DM}}\, a\, \bar{\chi}\gamma_5\chi$$
$$-\, i g_{\mathrm{SM}} \sum_q \frac{m_q}{v}\, a\, \bar{q}\gamma_5 q$$

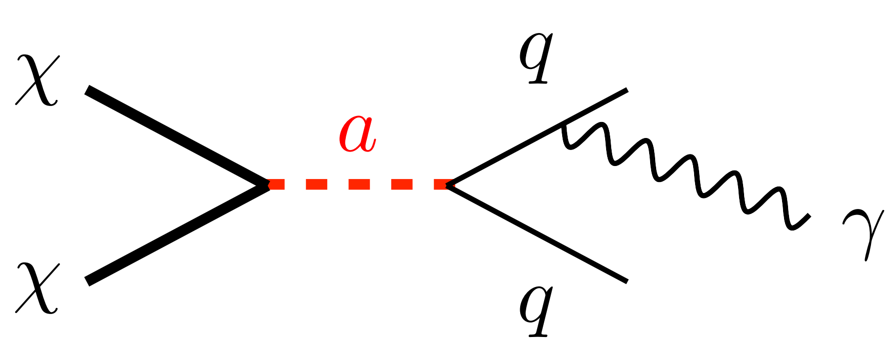


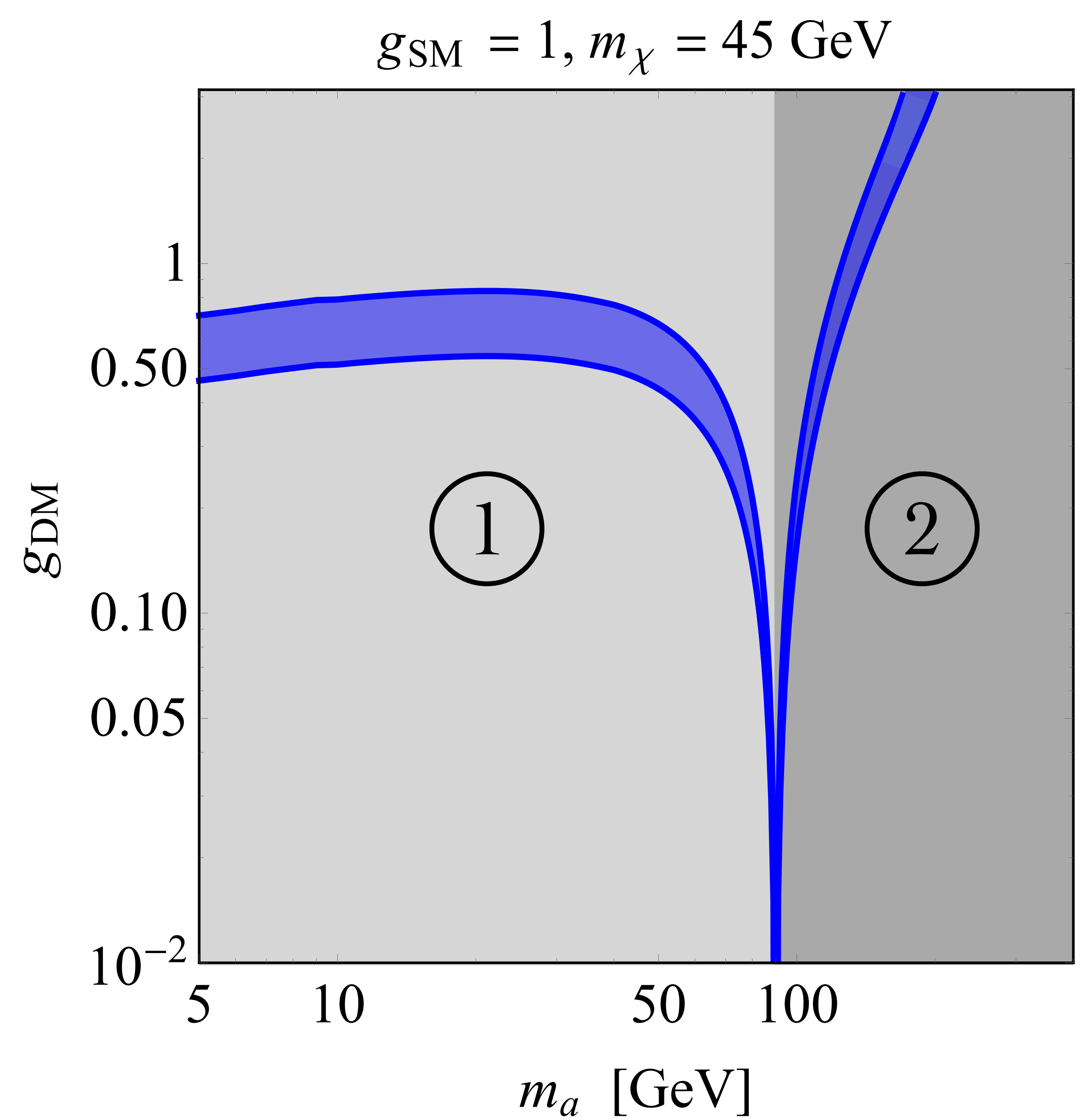




Simplified model with Dirac dark matter, pseudoscalar mediator & Higgs-like couplings fits excess with reasonable parameters

# Fermi-LAT excess

$$\mathcal{L} \supset -ig_{\rm DM}\, a\,\bar{\chi}\gamma_5\chi - ig_{\rm SM}\sum_q \frac{m_q}{v}\, a\,\bar{q}\gamma_5 q$$



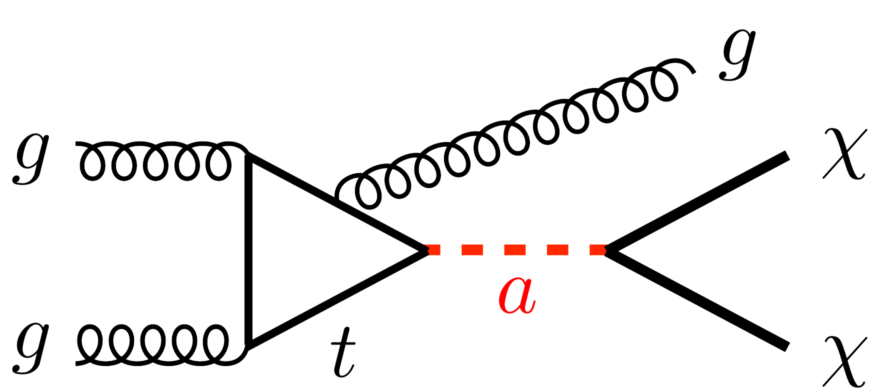



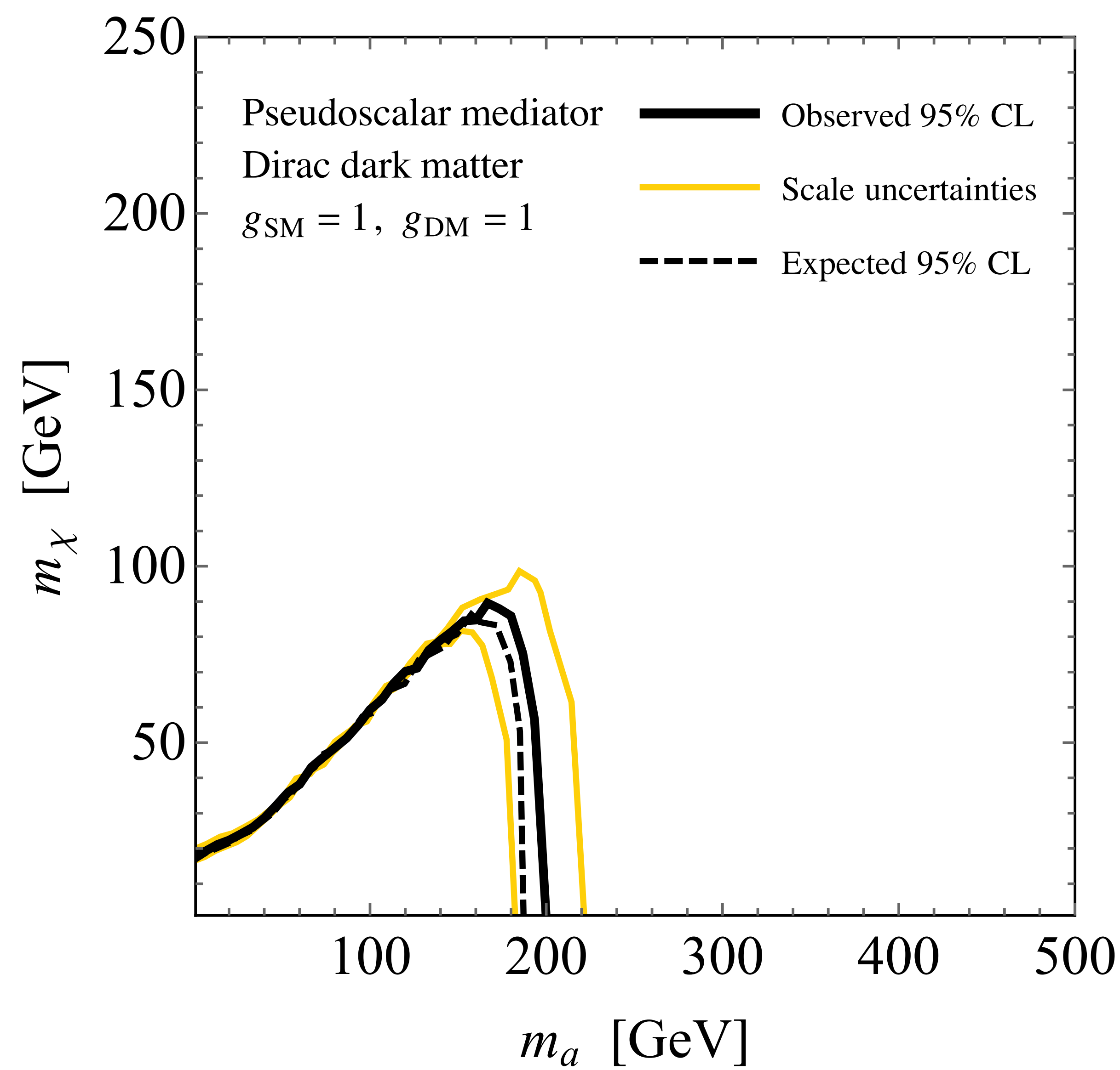

In fact, allowed parameter space can be divided into two parts. One where $m_a < 2m_\chi$ & another one where $m_a > 2m_\chi$

# LHC dark matter searches

Boveia et al., 1603.04156

$$\mathcal{L} \supset -\, i g_{\rm DM}\, a\, \bar{\chi}\gamma_5\chi$$
$$-\, i g_{\rm SM} \sum_q \frac{m_q}{v}\, a\, \bar{q}\gamma_5 q$$

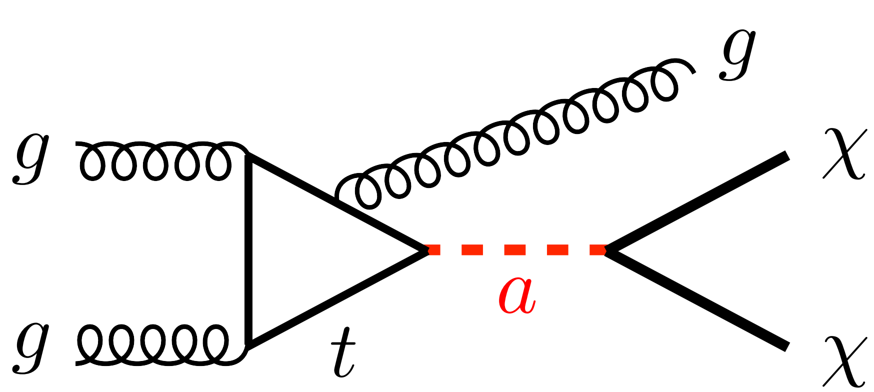


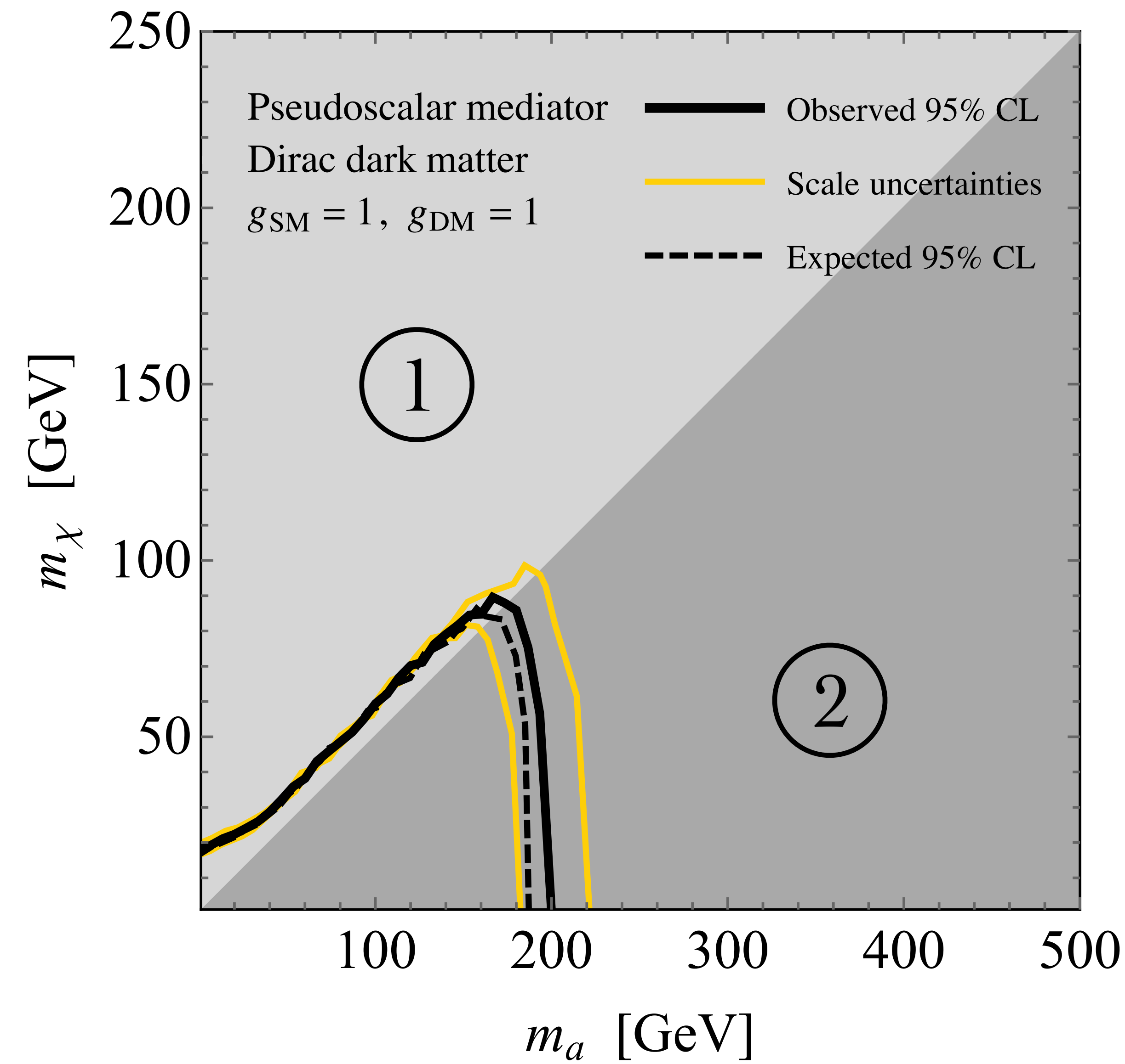

Simplified model that allows to explain Fermi-LAT excess can be tested by ATLAS & CMS for instance via mono-jet searches

# LHC dark matter searches

$$\mathcal{L} \supset -\, i g_{\rm DM}\, a\, \bar{\chi}\gamma_5\chi$$
$$-\, i g_{\rm SM} \sum_q \frac{m_q}{v}\, a\, \bar{q}\gamma_5 q$$



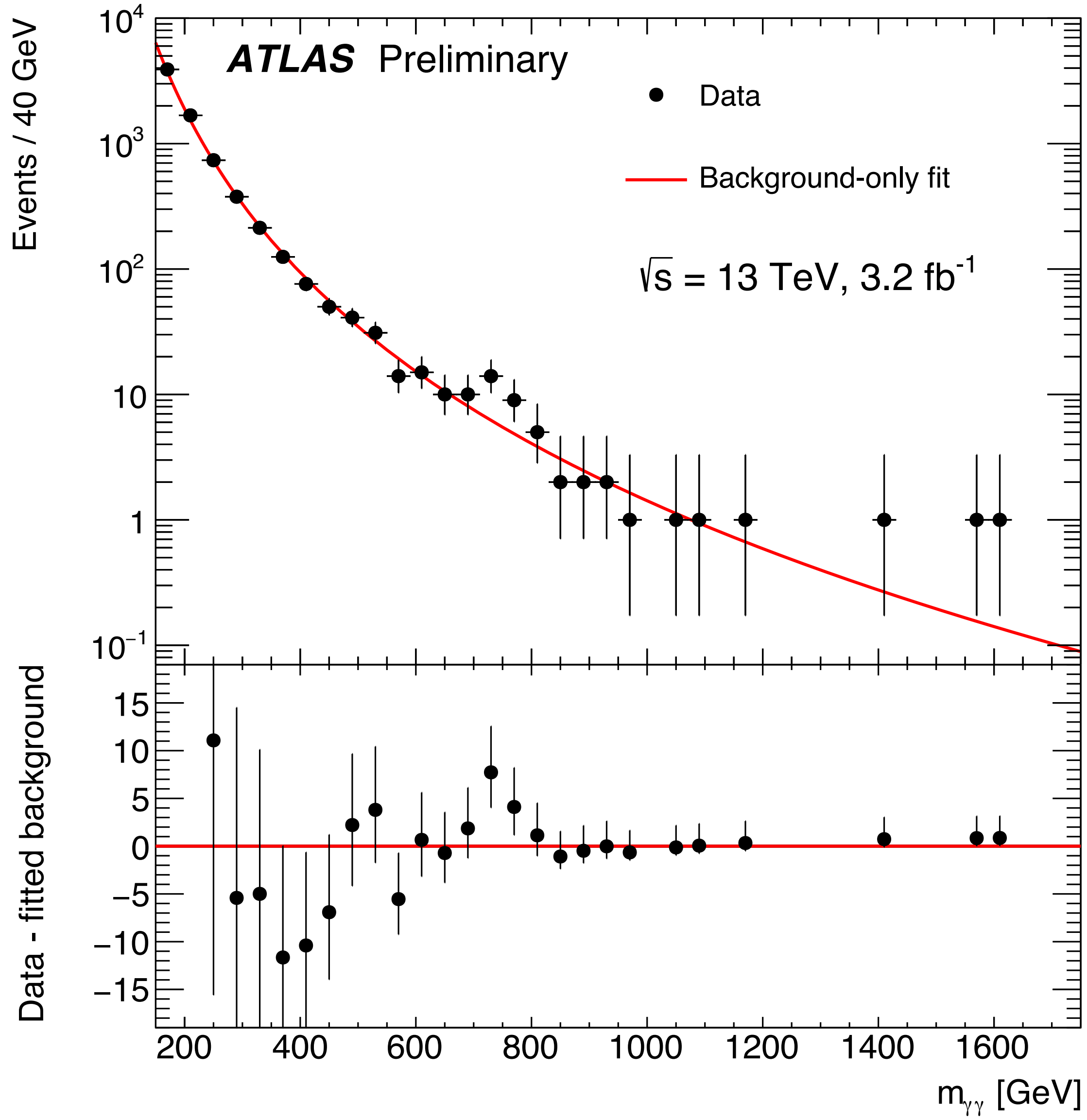

Boveia et al., 1603.04156




Existing & future constraints are however only strong in on-shell region (i.e. $m_a > 2m_\chi$), while weak in off-shell region (i.e. $m_a < 2m_\chi$)

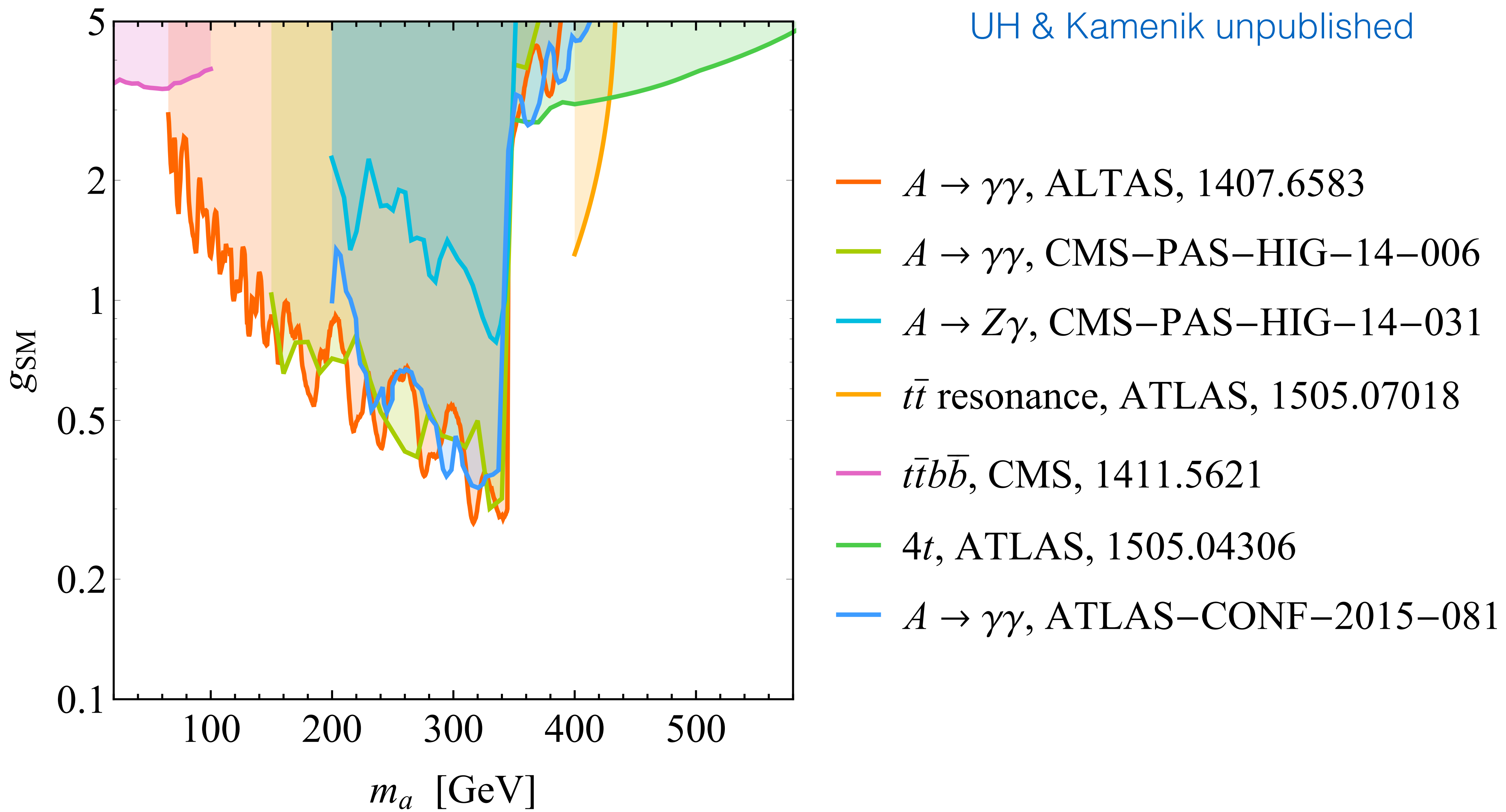
# LHC standard model searches

ATLAS-CONF-2015-081




For $m_a < 2m_\chi$, mediators will dominantly decay back to standard model states & searches typically focus on high invariant masses

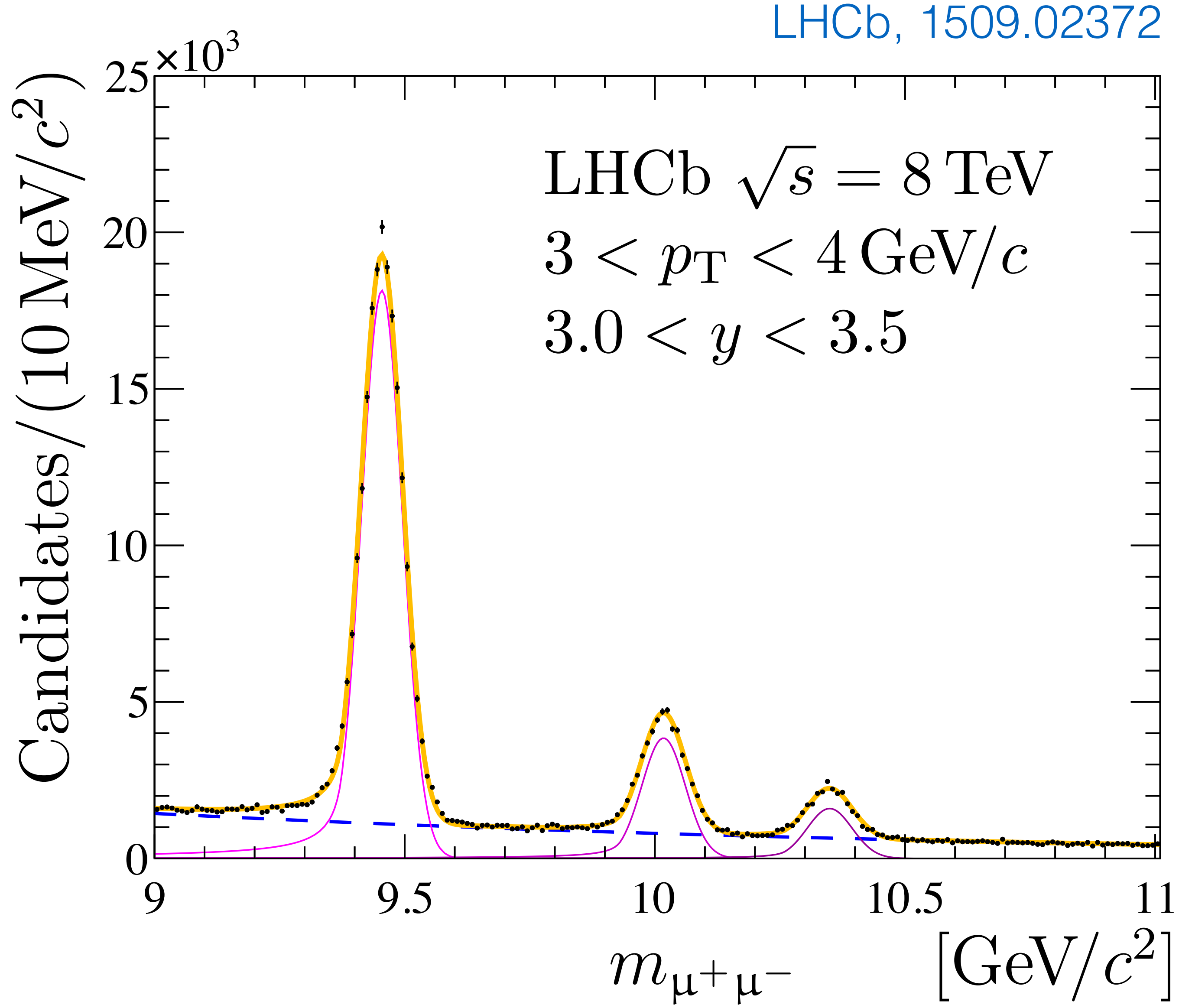
# LHC standard model searches




If they have masses around [10, 50] GeV, new spin-0 states may have escaped detection even for moderately large couplings $g_{SM}$

# $\Upsilon$ production at LHCb

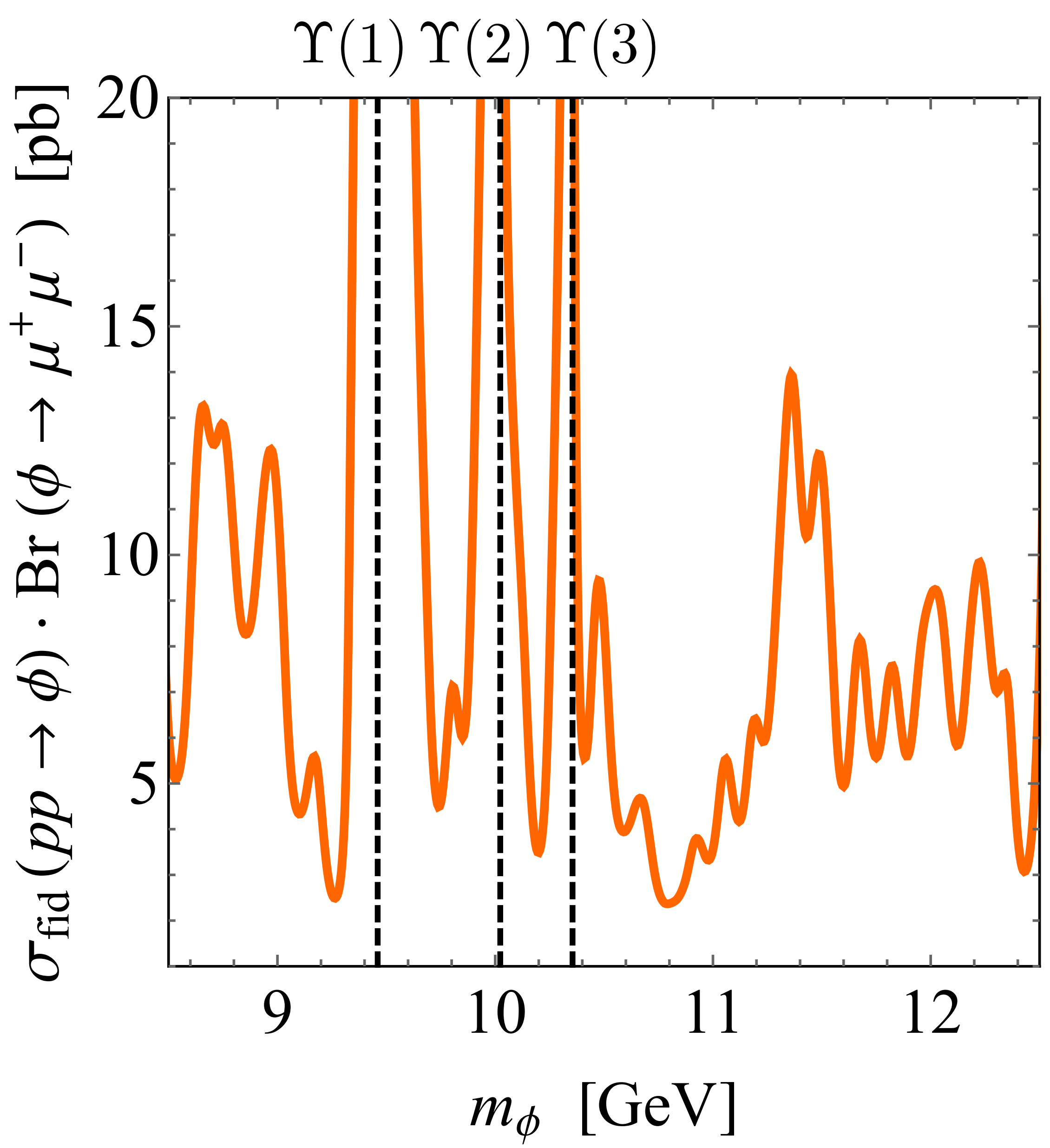
LHCb, 1509.02372




Precision measurement of di-muon spectrum for invariant masses in $\Upsilon$ region with only 3% of 8 TeV data set

# Bound on $\sigma_{fid}(pp \to \phi) \cdot Br(\phi \to \mu^+\mu^-)$

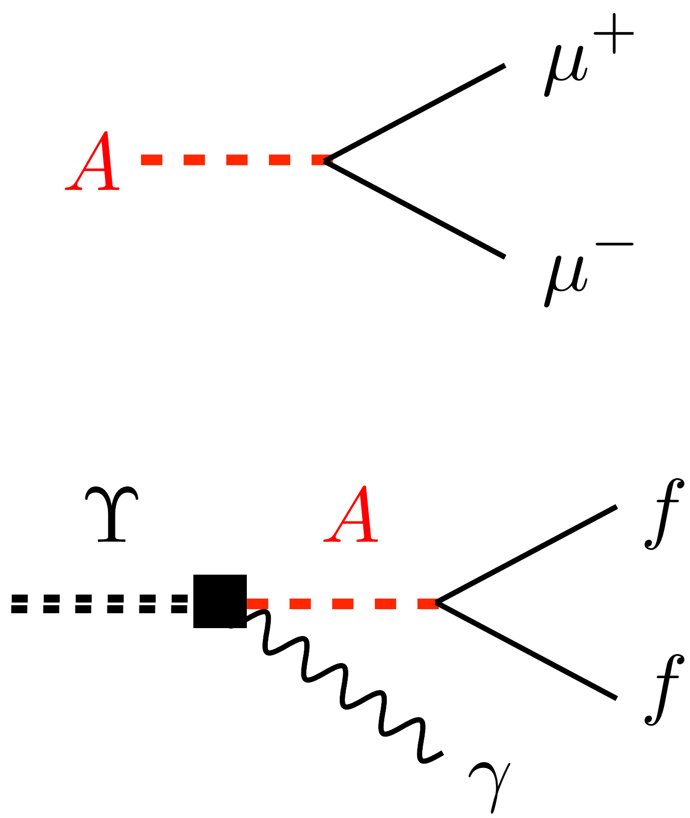
- Signal: light spin-0 dimuon resonance $\phi$
- Acceptances: A = 0.23 for $|\eta| \in [2, 4.5]$ & $p_T < 30$ GeV independent of $\phi$ mass; final acceptance $A_f$ in $|\eta| \in [3, 3.5]$ & $p_T \in [3, 4]$ GeV depends mildly on $m_\phi$
- Recast: inject $\phi$ signal & refit LHCb data on $\Upsilon$ production

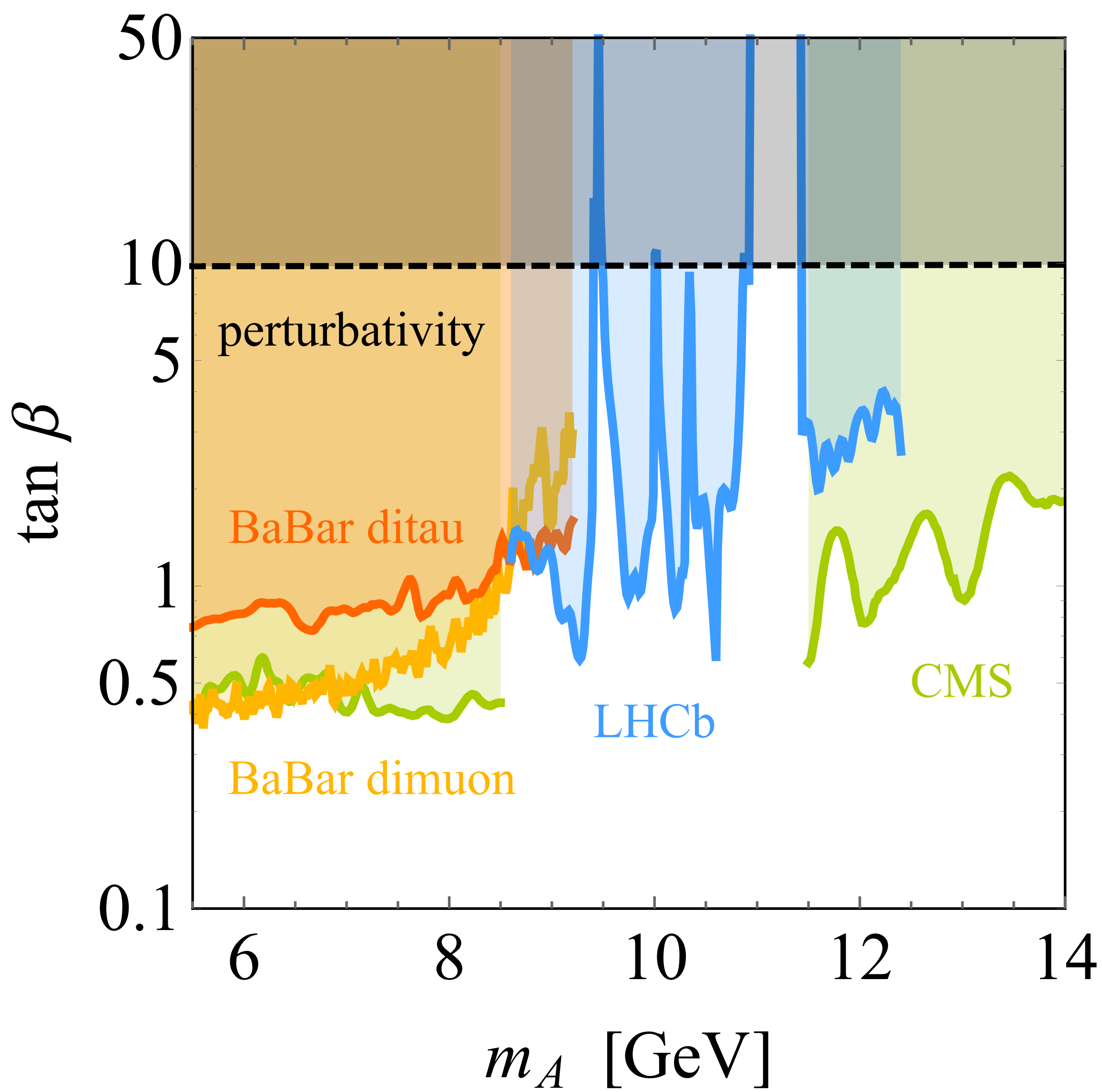



UH & Kamenik, 1601.05110

# Type II two-Higgs doublet model

UH & Kamenik, 1601.05110



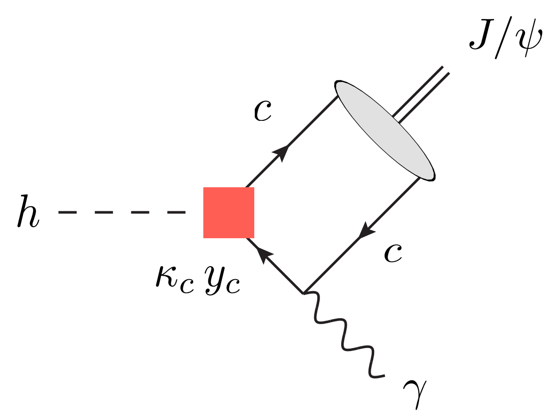

LHCb provides best bound for $m_A \in [8.6, 11]$ GeV. Mass region [11,11.5] GeV remains unexplored, due to strong mixing effects

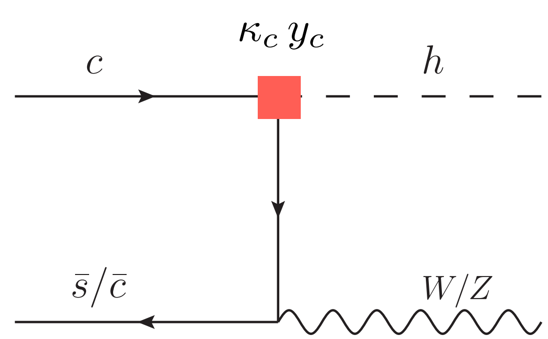
# Charm Yukawa coupling

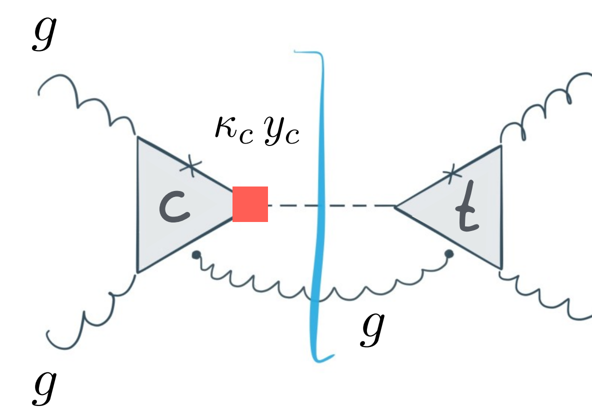
Literature:

- Bodwin et al., 1306.5770 & 1407.6695
- Perez, Soreq, Stamou & Tobioka, 1503.00290 & 1505.06689
- König & Neubert, 1505.03870
- Brivio, Goertz & Isidori, 1507.02916
- Bishara, UH, Monni & Re, 1606.09253
- Soreq, Zhu & Zupan, 1606.09621
- LHCb collaboration, LHCb-CONF-2016-006
- Tao Han & Xing Wang, 1704.00790

# Assortment of bounds on $\kappa_c$



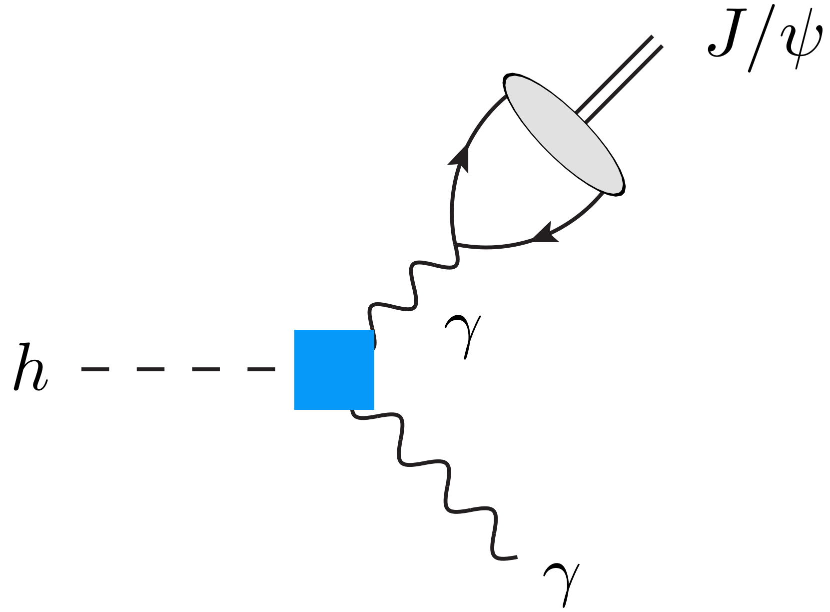



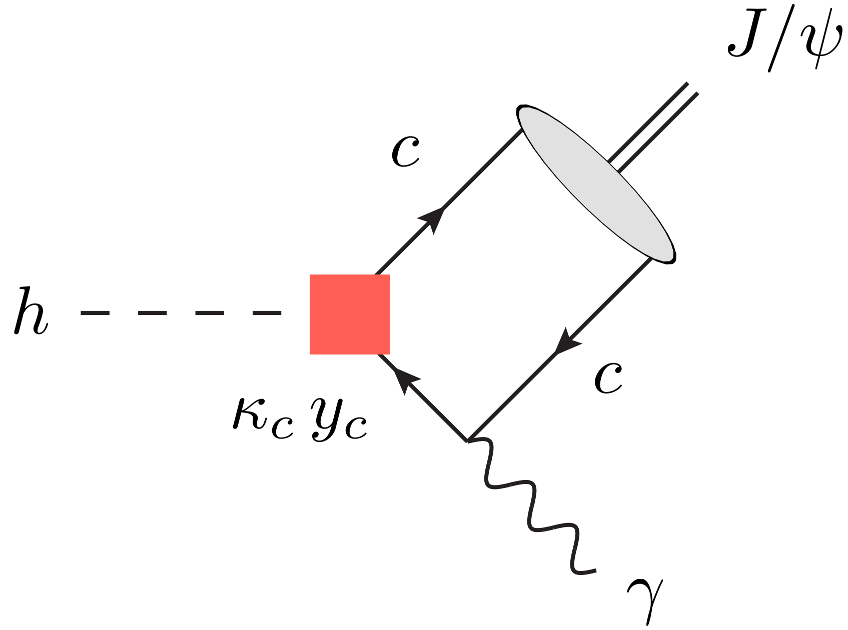

| | | | |
|---|---|---|---|
| LHC Run I | $\lvert\kappa_c\rvert < 429$ | $\lvert\kappa_c\rvert < 234$ | $\kappa_c \in [-16, 18]$ |
| LHC Run II | $\lvert\kappa_c\rvert \lesssim 80$ | $\lvert\kappa_c\rvert < 21$ | $\kappa_c \in [-1.4, 3.8]$ |
| HL-LHC | $\lvert\kappa_c\rvert \lesssim 45$ | $\lvert\kappa_c\rvert < 3.7$ | $\kappa_c \in [-0.6, 3.0]$ |

Sensitivity of LHC to $y_c$ higher than anticipated. Complementary strategies exit that should be combined to tighten bounds on $\kappa_c$

Perez et al., 1503.00290, 1505.06689; König & Neubert, 1505.03870; Bishara et al., 1606.09253

# Exclusive Higgs decays: h→J/ψγ




$$\mathrm{Br}\left(h \to J/\psi\gamma\right) = 2.95 \cdot 10^{-6}\,\left(1.07 - 0.07\,\kappa_c\right)^2$$

Bodwin et al., 1306.5770 & 1407.6695; König & Neubert, 1505.03870

# Exclusive Higgs decays: h→J/ψγ

$$\mathrm{Br}\left(h \to J/\psi\gamma\right) < 1.5 \cdot 10^{-3}$$

ATLAS, 1501.03276; CMS, 1507.03031

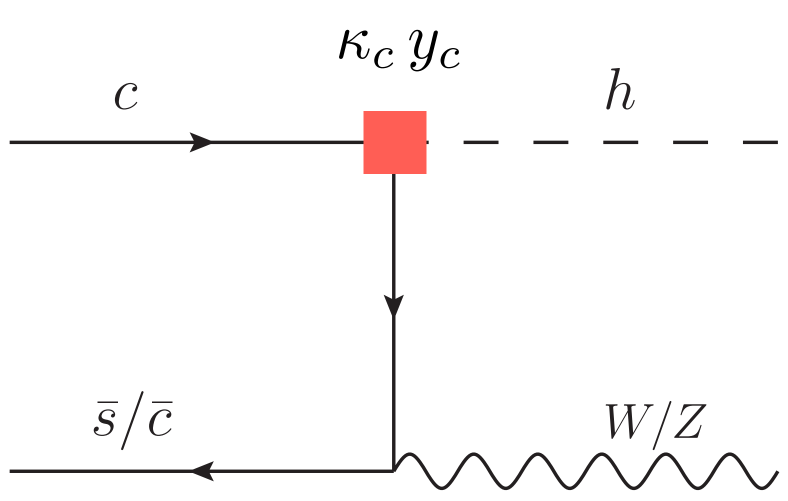
$$\longrightarrow \quad |\kappa_c| < 429$$

$$\mathrm{Br}\left(h \to J/\psi\gamma\right) = 2.95\left(1 \pm 0.2\right) \cdot 10^{-6}$$

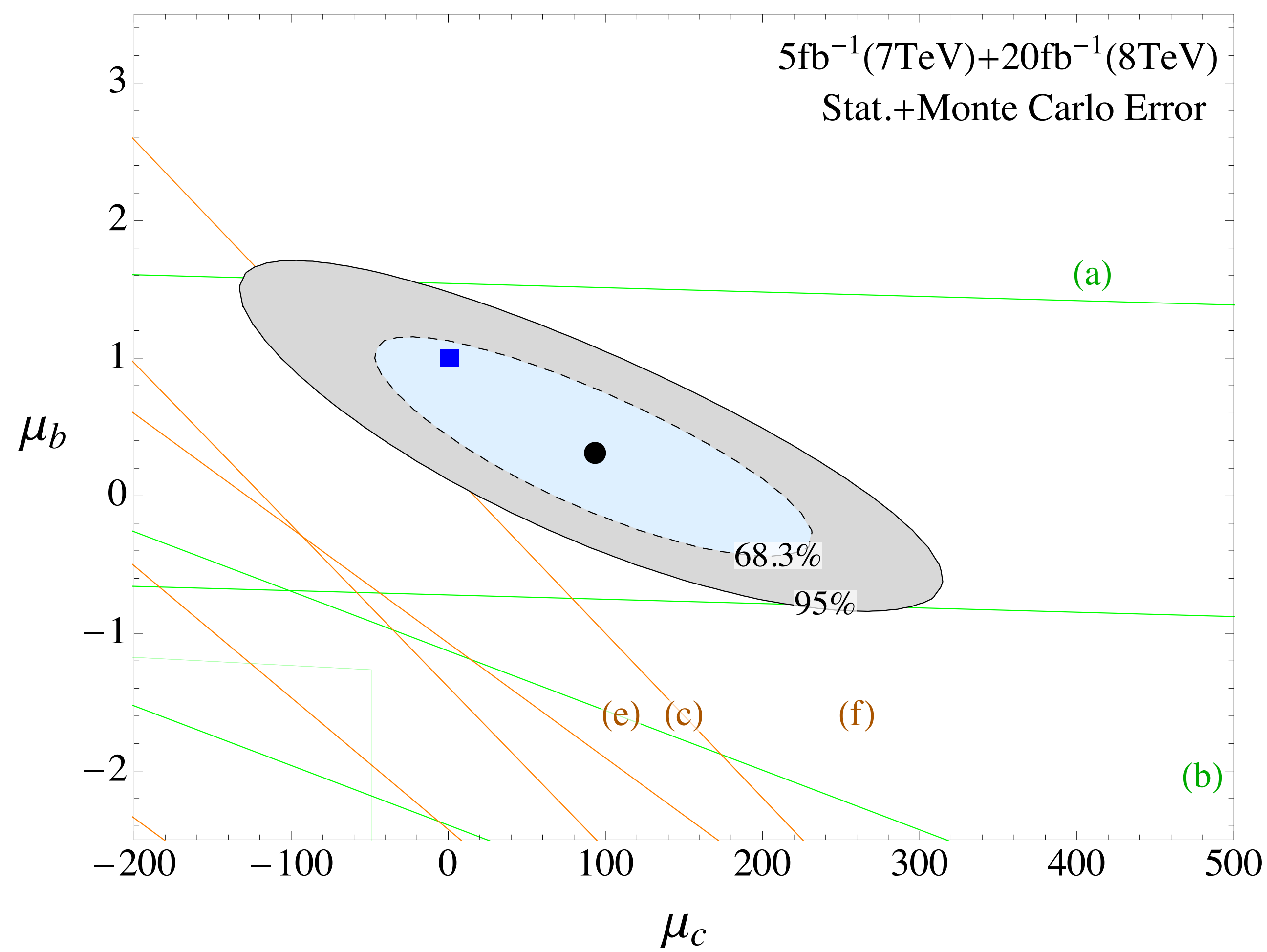
$$\longrightarrow \quad \kappa_c \in \left[-0.51, 3.07\right]$$

König & Neubert, 1505.03870

# Vh production & flavour tagging

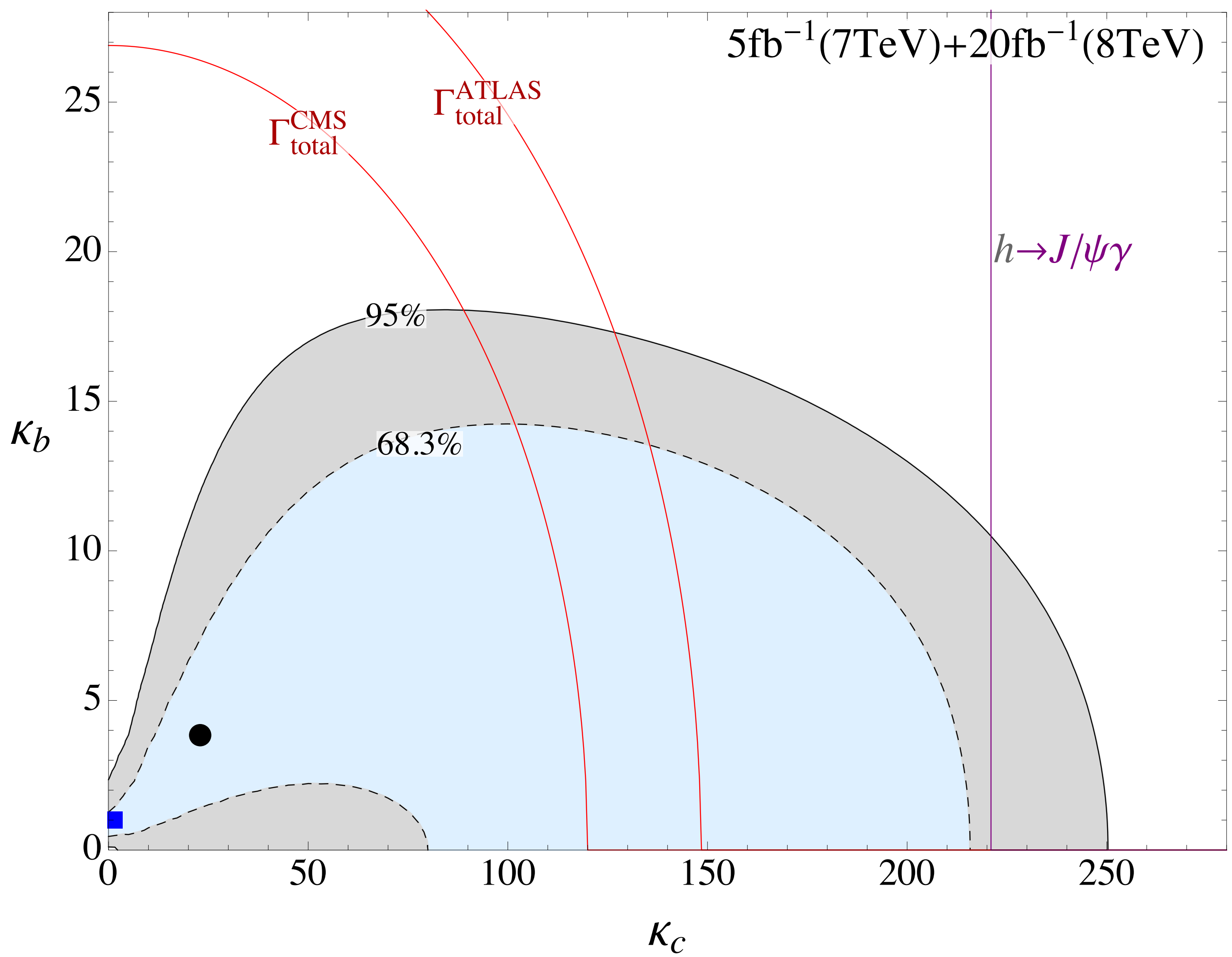



Perez, Soreq, Stamou & Tobioka, 1503.00290




By using different working points for heavy-flavour tagging can recast $h \to b\bar{b}$ analyses to constrain $h \to c\bar{c}$ rate

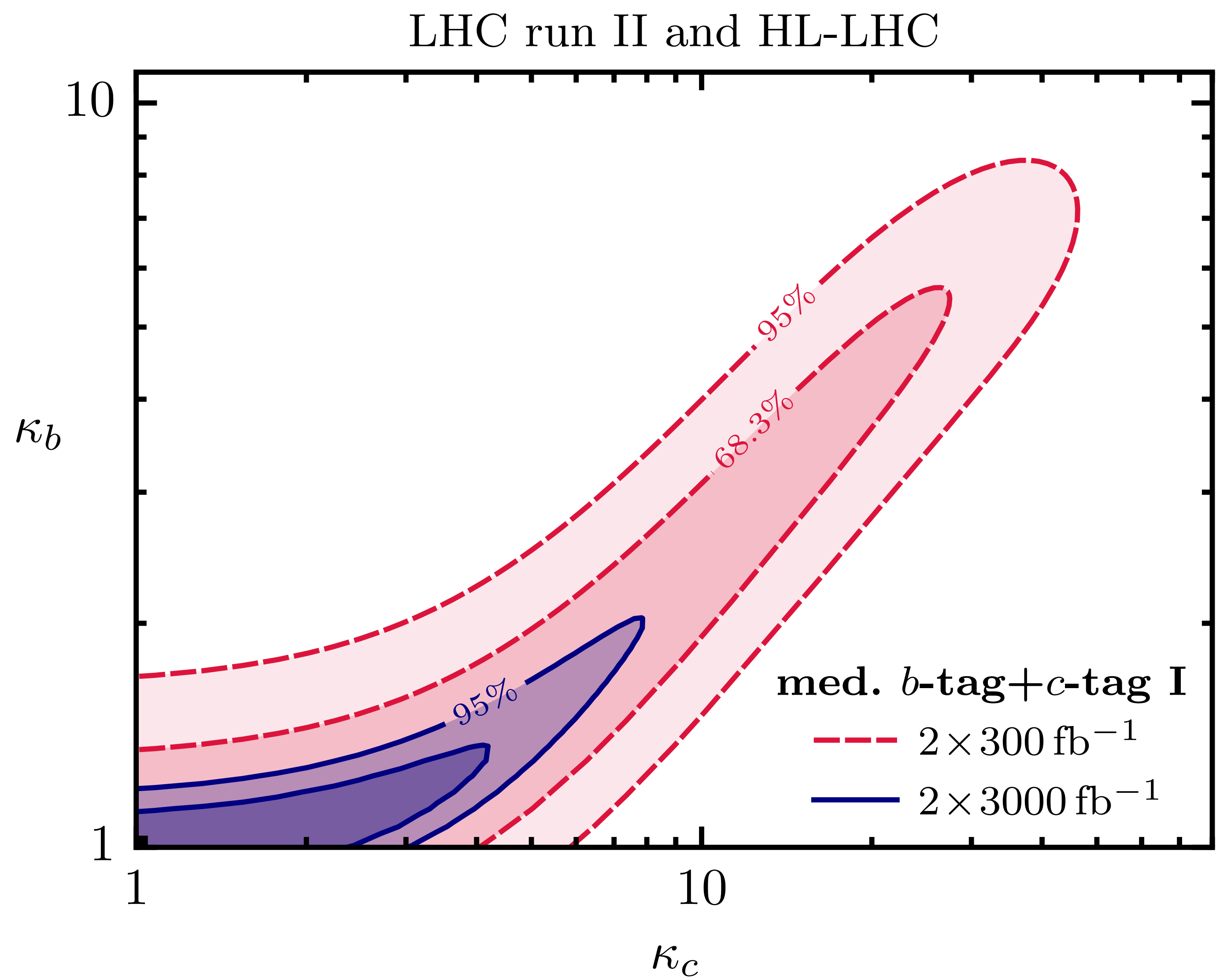
# Vh production & flavour tagging




$\longrightarrow \quad \kappa_c \lesssim 234$

Perez, Soreq, Stamou & Tobioka, 1503.00290

# Vh production & flavour tagging




$\longrightarrow$ $\kappa_c < \{38, 5.6\}$

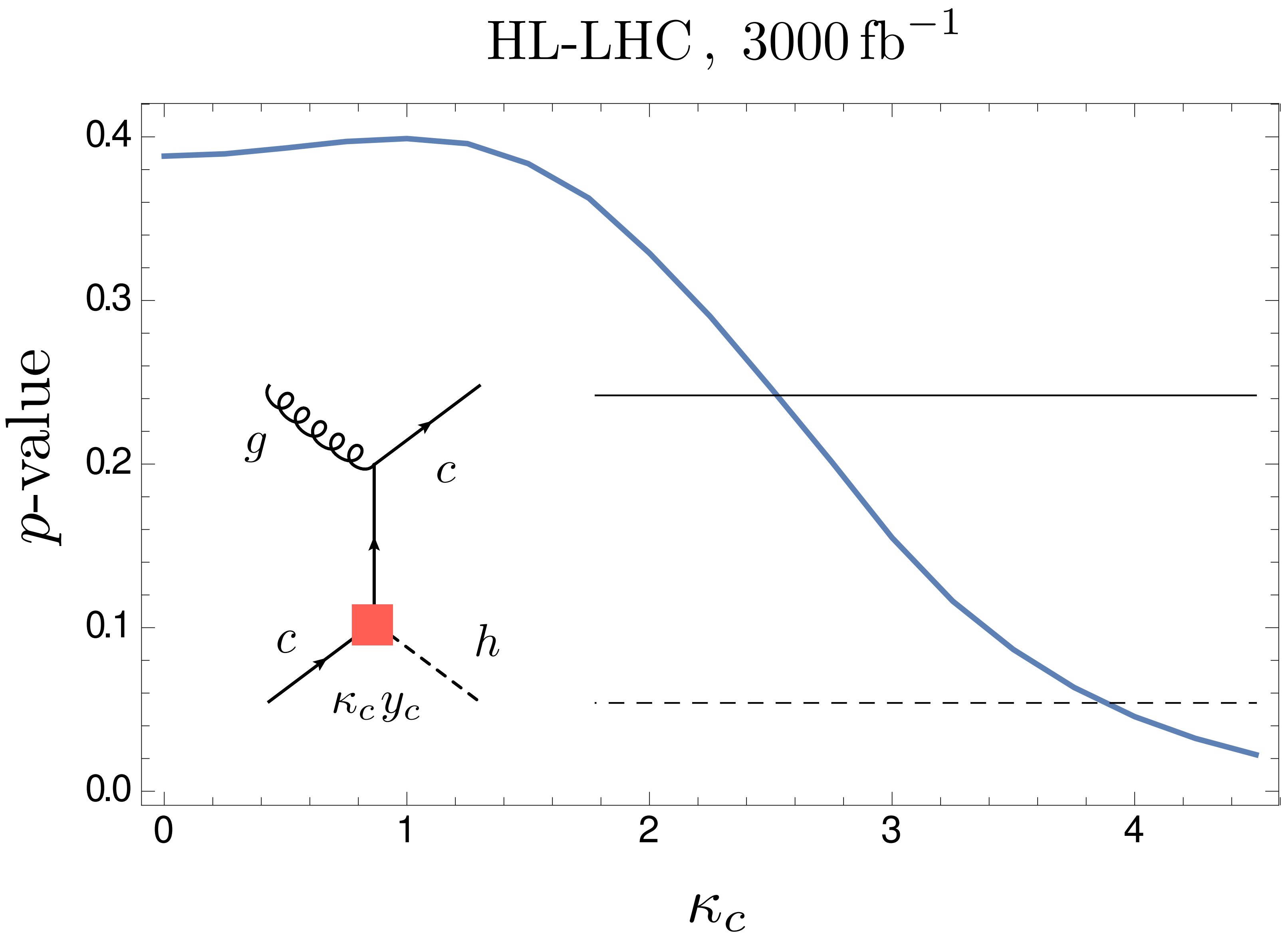
Perez, Soreq, Stamou & Tobioka, 1505.06689

# Vh production & flavour tagging

| $\mathcal{L}$ | $\sqrt{s} = 14\,\mathrm{TeV}$ | $\kappa_b$ @ 95% CL | $\lvert\kappa_c\rvert$ @ 95% CL |
|---|---|---|---|
| $2 \times 300\,\mathrm{fb}^{-1}$ | correlated $c$-tagging I | $[0.67, 7.07]$ | $< 37$ |
| | uncorrelated $c$-tagging I | $[0.69, 7.16]$ | $< 38$ |
| | uncorrelated $c$-tagging II | $[0.70, 4.70]$ | $< 21$ |
| | uncorrelated $c$-tagging III | $[0.70, 1.90]$ | $< 6.0$ |
| $2 \times 3000\,\mathrm{fb}^{-1}$ | correlated $c$-tagging I | $[0.84, 1.57]$ | $< 5.5$ |
| | uncorrelated $c$-tagging I | $[0.85, 1.60]$ | $< 5.6$ |
| | uncorrelated $c$-tagging II | $[0.86, 1.30]$ | $< 3.7$ |
| | uncorrelated $c$-tagging III | $[0.87, 1.18]$ | $< 2.5$ |

Perez, Soreq, Stamou & Tobioka, 1505.06689

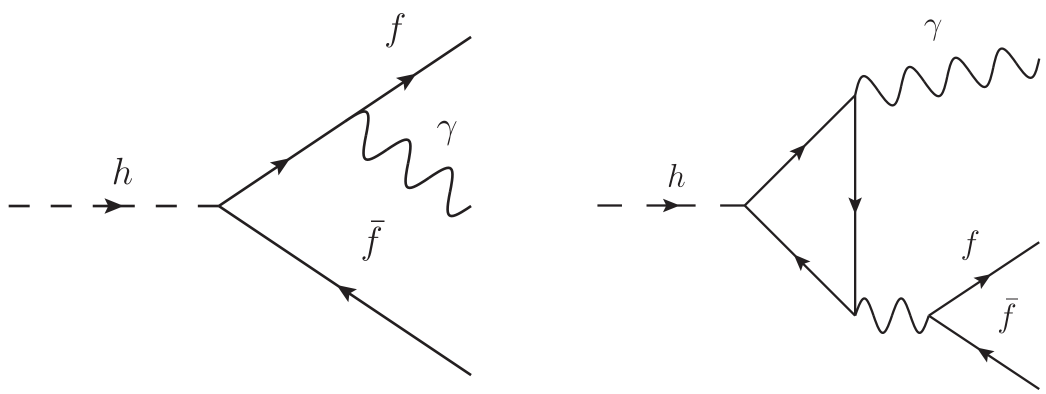
# Higgs & charm production

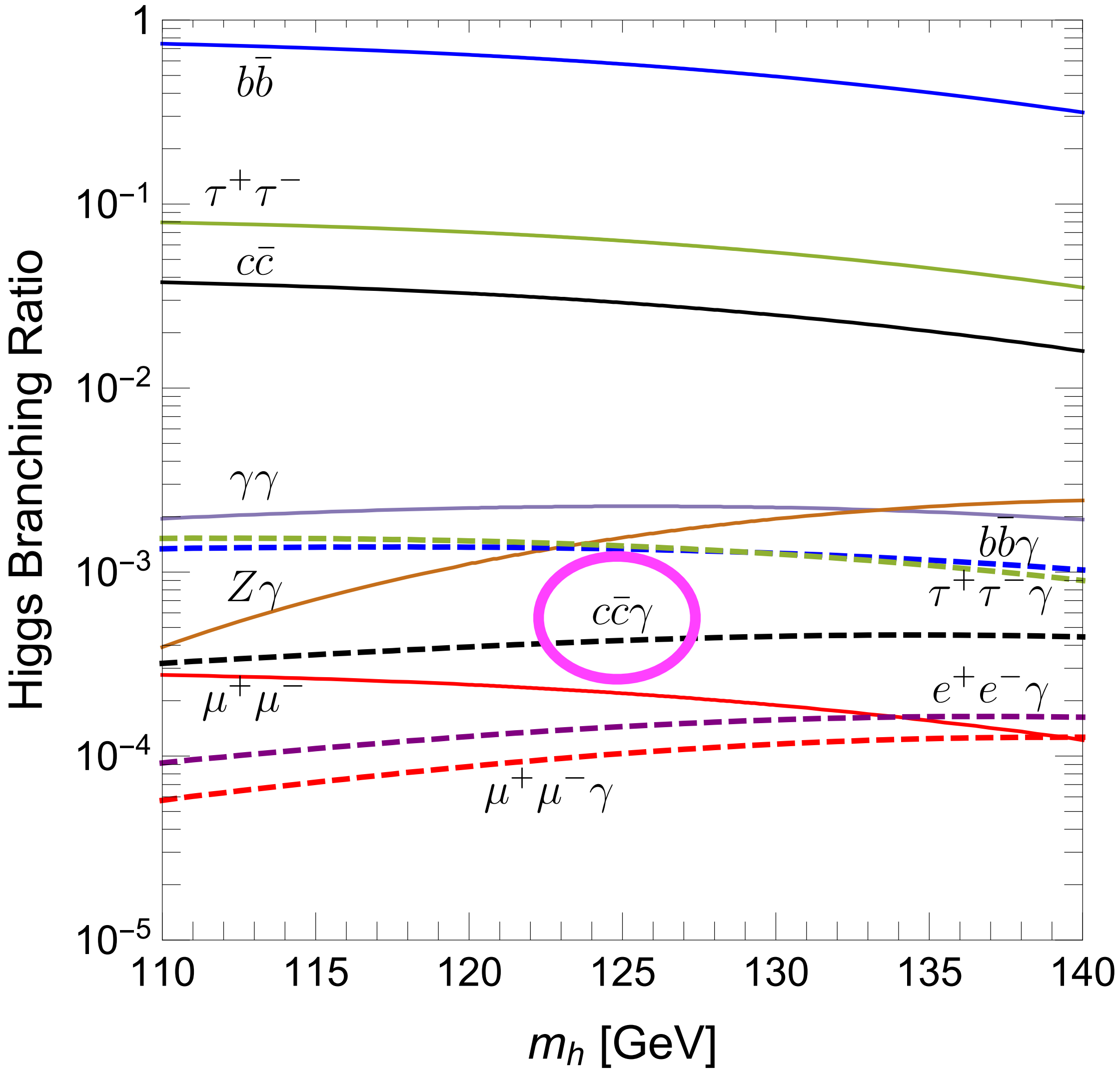



$\longrightarrow$ $\kappa_c < 3.9$

Brivio, Goertz & Isidori, 1507.02916

# Charm Yukawa from h→cc̄γ



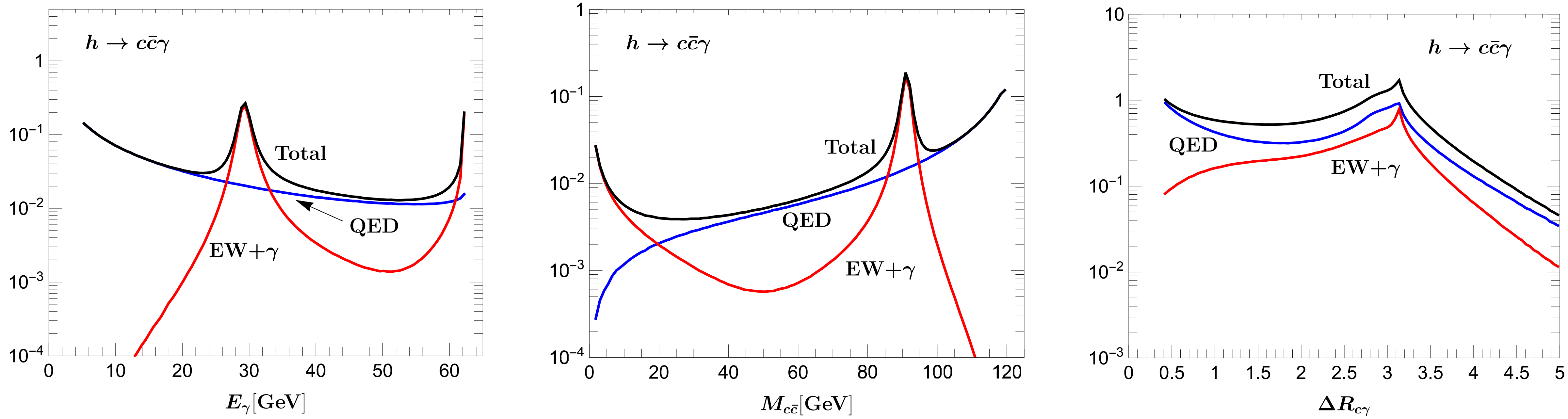




$$\mathrm{Br}(h \to J/\psi\gamma) \simeq 3 \cdot 10^{-6}$$

$$\mathrm{Br}(h \to c\bar{c}\gamma) \simeq 4 \cdot 10^{-4}$$

Han & Wang, 1704.00790

# Charm Yukawa from h→cc̄γ




$$|\kappa_c| < 6.3 \quad \text{(HL-LHC)}$$

Han & Wang, 1704.00790

# A simple observation

ATLAS & CMS, 1606.02266

| Production | Loops | Interference | Effective scaling factor | Resolved scaling factor |
|---|---|---|---|---|
| $\sigma(ggF)$ | ✓ | $t$–$b$ | $\kappa_g^2$ | $1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t\kappa_b$ |
| $\sigma(\mathrm{VBF})$ | – | – | | $0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$ |
| $\sigma(WH)$ | – | – | | $\kappa_W^2$ |
| $\sigma(qq/qg \to ZH)$ | – | – | | $\kappa_Z^2$ |
| $\sigma(gg \to ZH)$ | ✓ | $t$–$Z$ | | $2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z\kappa_t$ |
| $\sigma(ttH)$ | – | – | | $\kappa_t^2$ |
| $\sigma(gb \to tHW)$ | – | $t$–$W$ | | $1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t\kappa_W$ |
| $\sigma(qq/qb \to tHq)$ | – | $t$–$W$ | | $3.40 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t\kappa_W$ |
| $\sigma(bbH)$ | – | – | | $\kappa_b^2$ |
| Partial decay width | | | | |
| $\Gamma^{ZZ}$ | – | – | | $\kappa_Z^2$ |
| $\Gamma^{WW}$ | – | – | | $\kappa_W^2$ |
| $\Gamma^{\gamma\gamma}$ | ✓ | $t$–$W$ | $\kappa_\gamma^2$ | $1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W\kappa_t$ |
| $\Gamma^{\tau\tau}$ | – | – | | $\kappa_\tau^2$ |
| $\Gamma^{bb}$ | – | – | | $\kappa_b^2$ |
| $\Gamma^{\mu\mu}$ | – | – | | $\kappa_\mu^2$ |
| Total width ($B_{\mathrm{BSM}} = 0$) | | | | |
| $\Gamma_H$ | ✓ | – | $\kappa_H^2$ | $0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 +$ $0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 +$ $0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{(Z\gamma)}^2 +$ $0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$ |

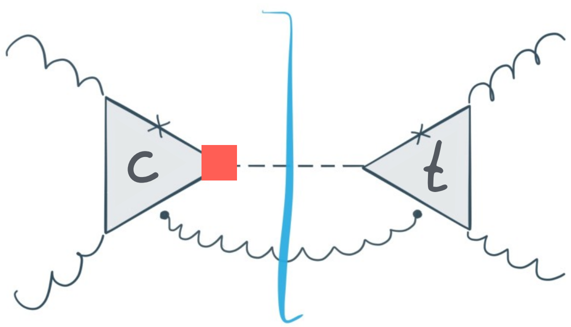
$$- 0.07 \cdot \kappa_t \kappa_b$$

# A simple observation

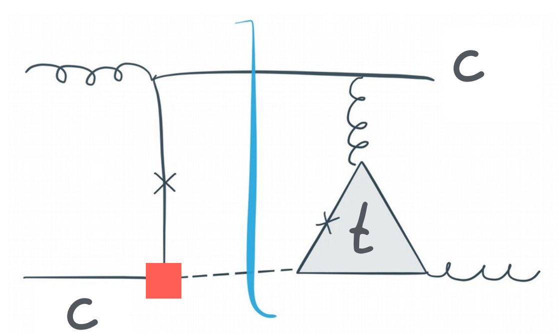
- In SM, interference between top & bottom loops does not only change total Higgs production cross section but also distributions in $pp \to hj$ such as $p_{T,h}$, $y_h$, $p_{T,j}$, …
- Measurements of shape of distributions at low to moderate $p_T$ should allow to constrain modifications $\kappa_c = y_c/y_c^{SM}$
- At HL-LHC with $3\,ab^{-1}$ of luminosity, $p_{T,h}$ measurements not statistics limited. Future bounds on $\kappa_c$ from Higgs spectra thus depend sensitively on size of systematic uncertainties

Bishara, UH, Monni & Re, 1606.09253; Soreq, Zhu & Zupan, 1606.09621

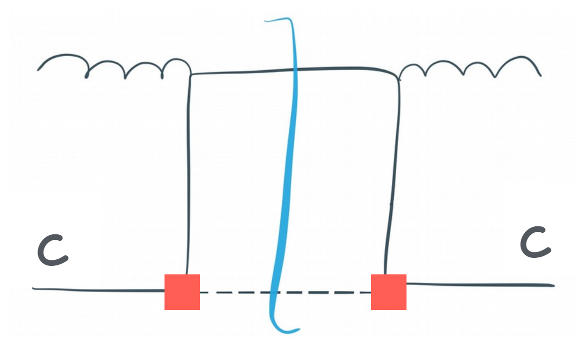
# Charm contributions to pp→hj




$$\sim \alpha_s^3 \boxed{\kappa_c} \frac{m_c^2}{m_h^2} \ln^2\left(\frac{p_T^2}{m_c^2}\right)$$

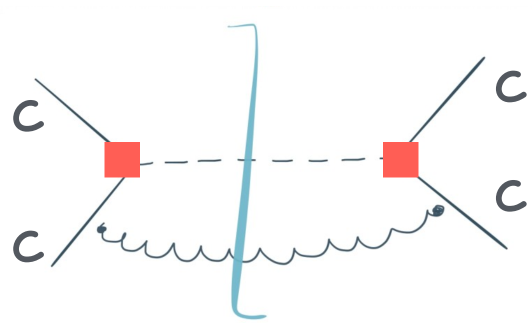



$$\sim \boxed{\alpha_s} \alpha_s^2 \boxed{\kappa_c} \frac{m_c^2}{m_h^2} \qquad (= 0 \;\text{ in 4, 5 flavour scheme})$$



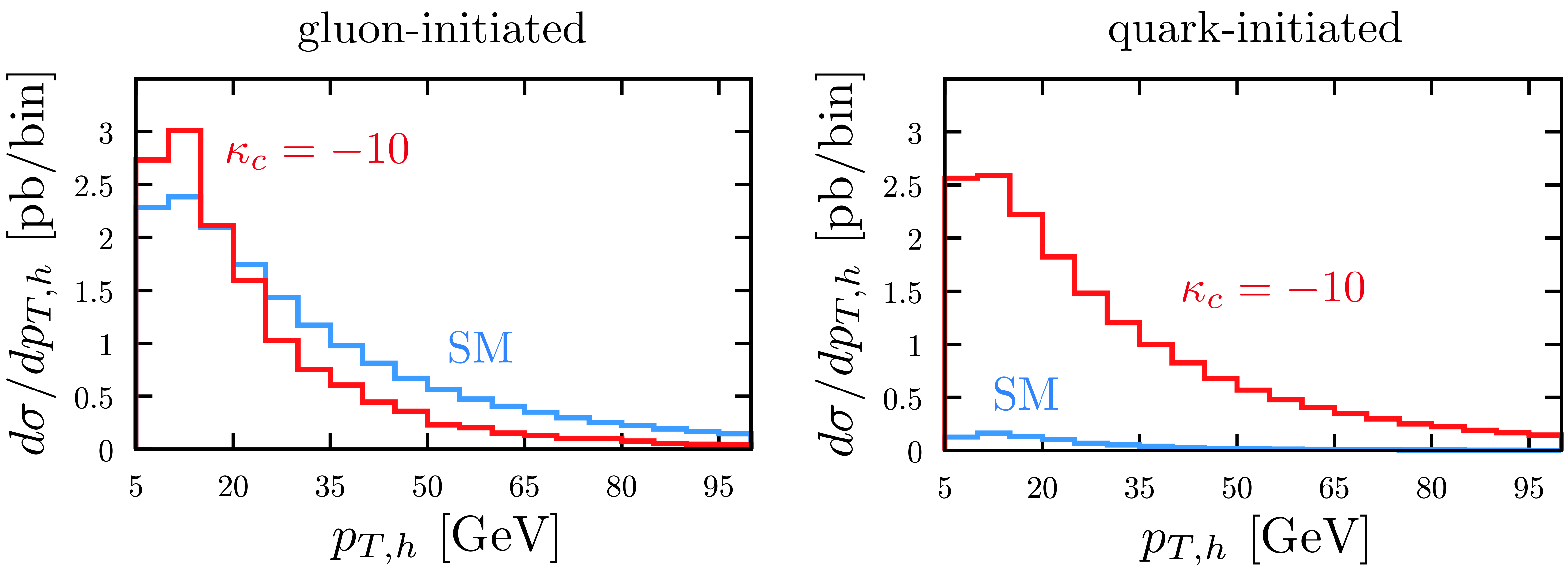

$$\sim \boxed{\alpha_s} \alpha_s \boxed{\kappa_c^2} \frac{m_c^2}{m_h^2}$$

extra powers of $\alpha_s$ from charm PDF




$$\sim \boxed{\alpha_s^2} \alpha_s \boxed{\kappa_c^2} \frac{m_c^2}{m_h^2}$$

# Charm contributions to pp→hj

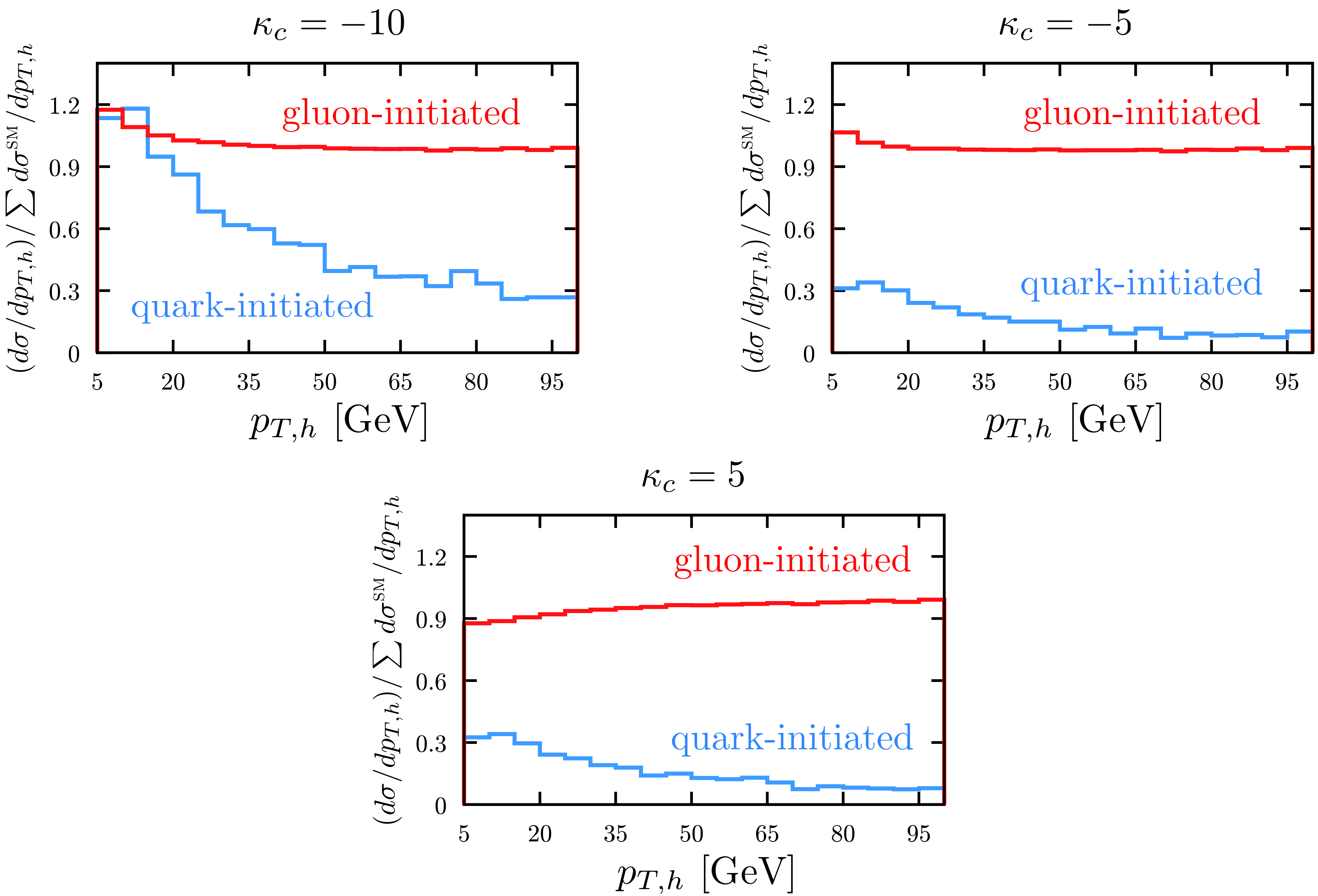



Bishara, unpublished

For $|\kappa_c| < O(10)$ gg-channel dominates, while for $|\kappa_c| > O(10)$ gq- & $\bar{q}q$-production becomes as relevant. For $y_{s,d,u}$ quark-channels dominate given LHC sensitivities of $|\kappa_{s,d,u}| \gg 10$

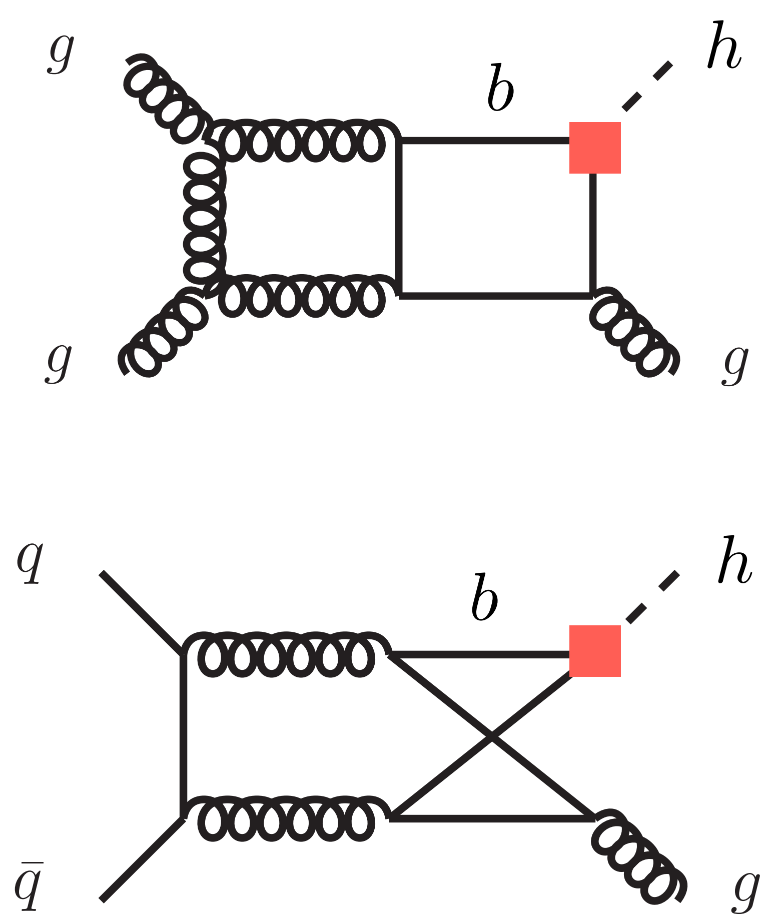
Bishara, UH, Monni & Re, 1606.09253; Soreq, Zhu & Zupan, 1606.09621

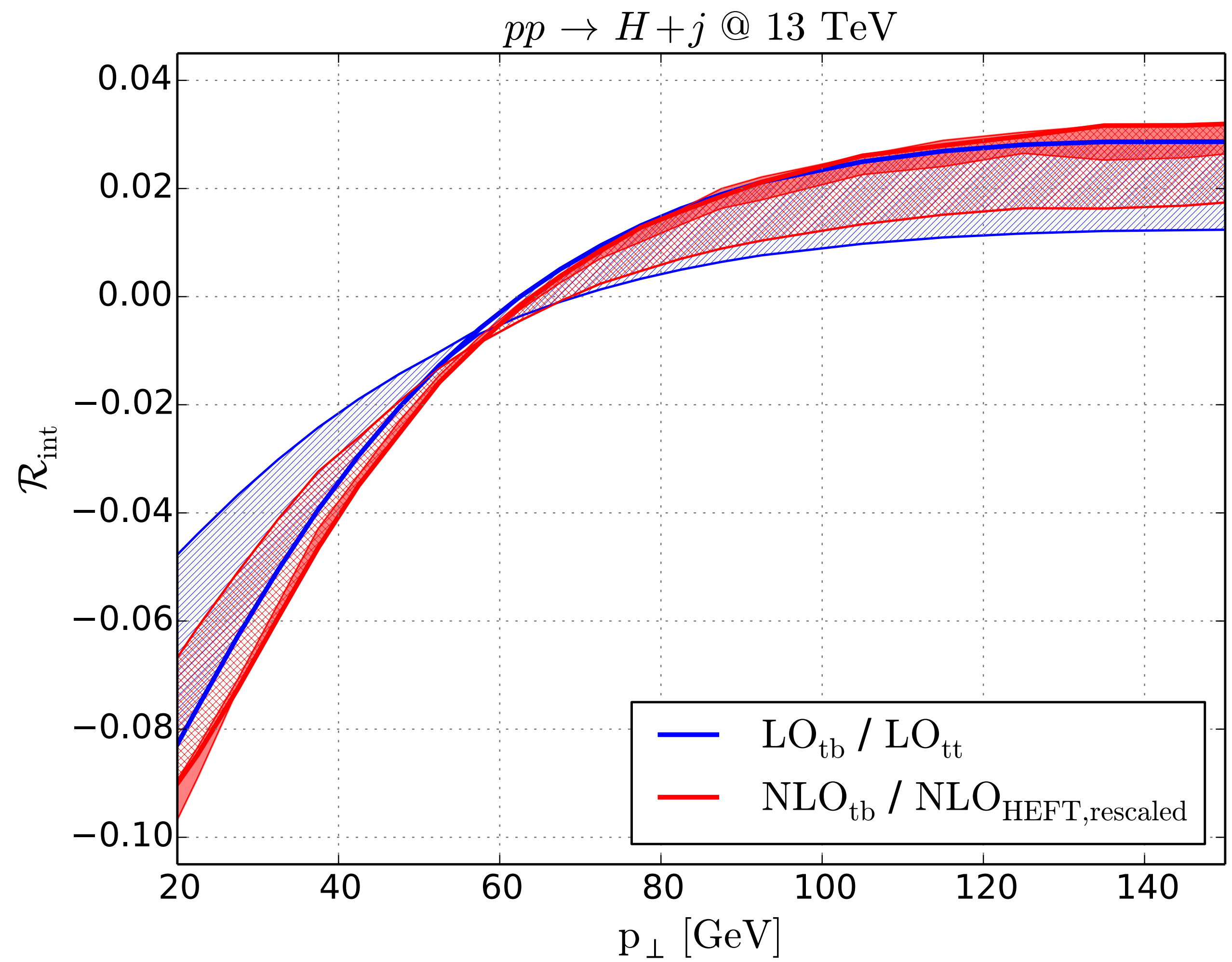
# Charm contributions to pp→hj




Bishara, unpublished

# Top-bottom interference at NLO



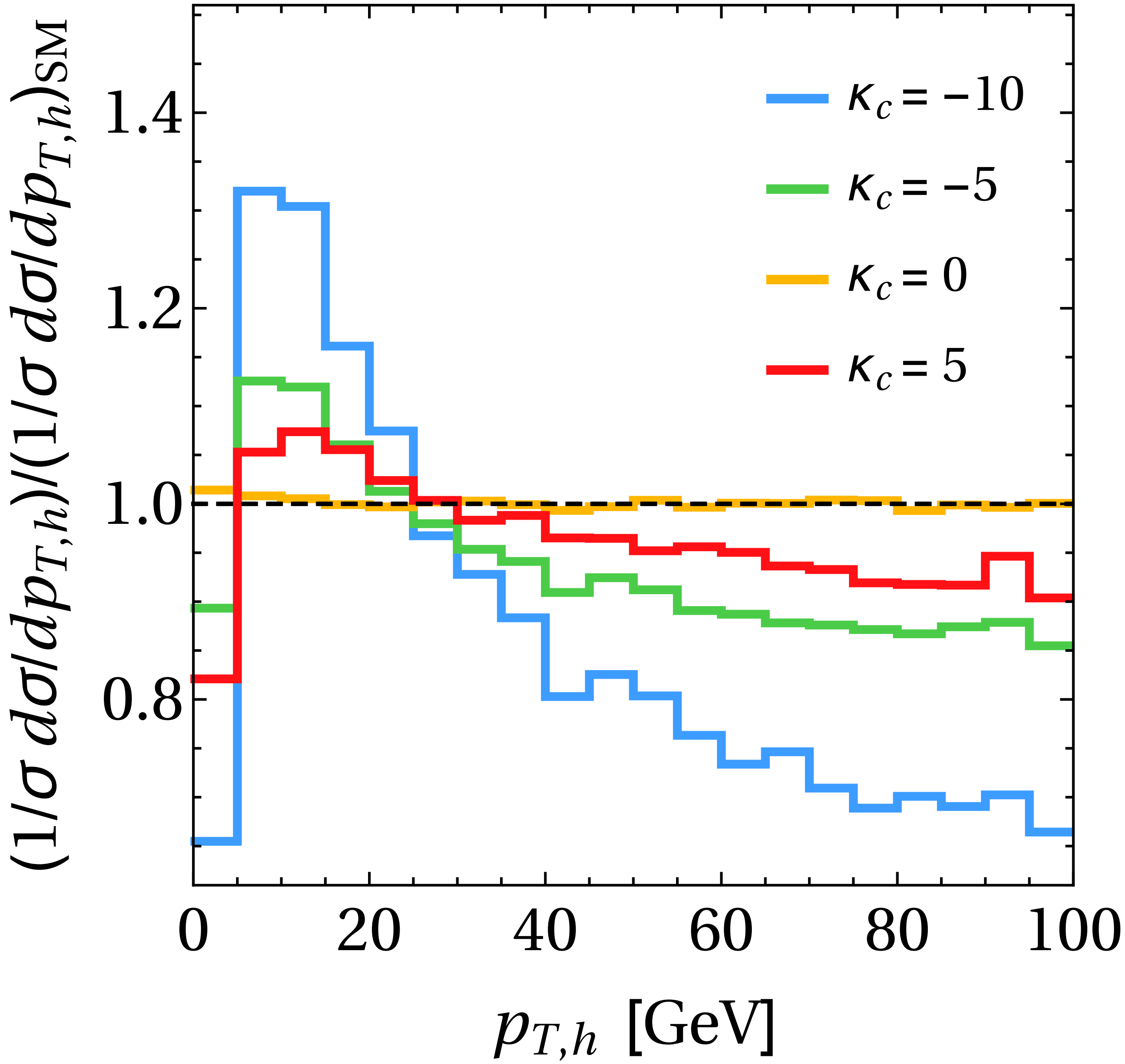




NLO corrections of O(50%) but closely track QCD effects to top-mediated contribution. For $p_T$ < 30 GeV inclusion of NLO effects lead to a O(2) reduction of scheme ambiguity related to $m_b$

Melnikov, Tancredi & Wever, 1610.03747; 1702.00426; Lindert, Melnikov, Tancredi & Wever, 1703.03886

# Normalised $p_{T,h}$ spectra at 8 TeV

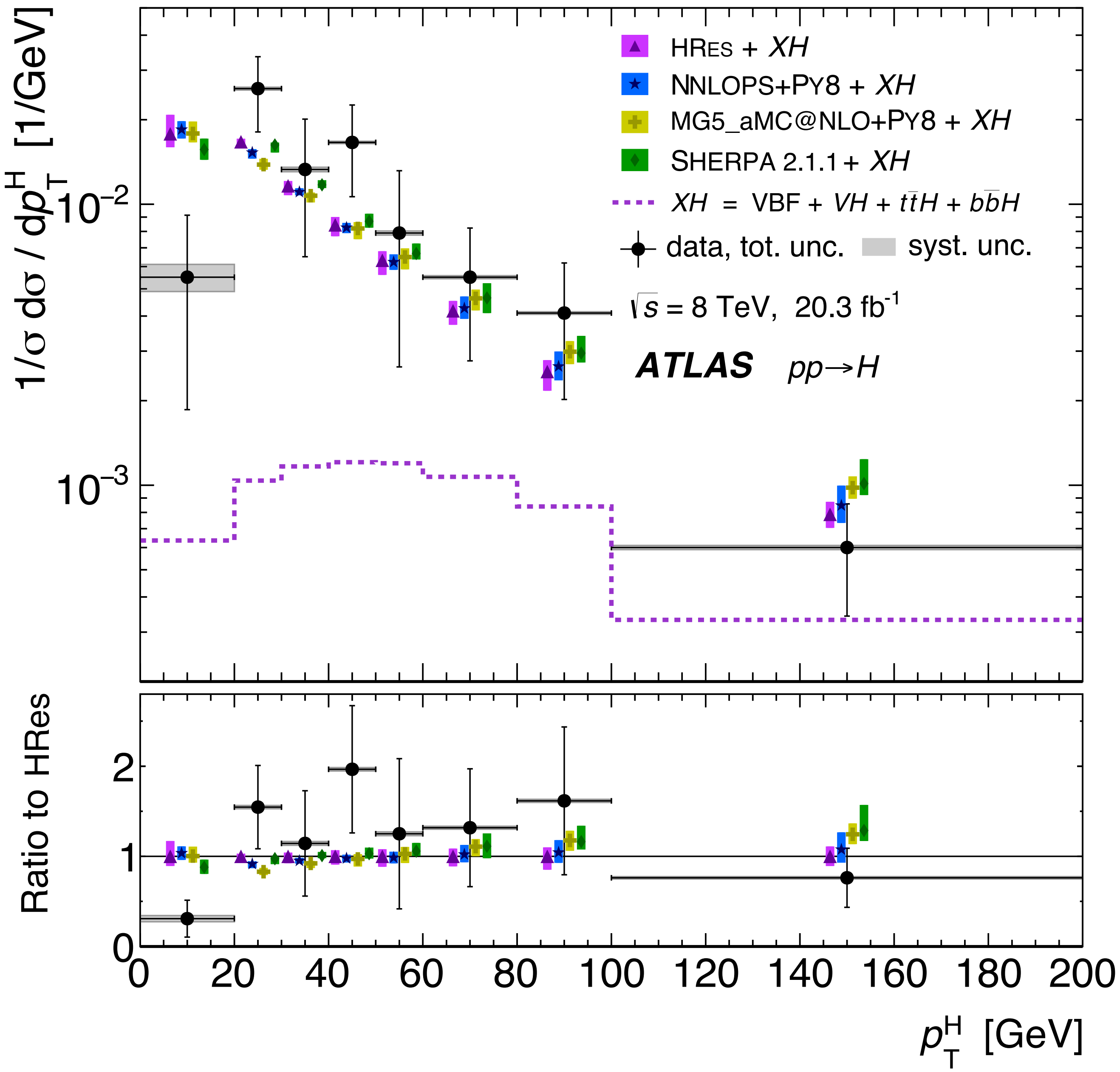
Bishara, UH, Monni & Re, 1606.09253




O(1) deviations in $\kappa_c$ lead to few % effects in $p_{T,h}$ distribution

# Measured $p_{T,h}$ spectrum at 8 TeV

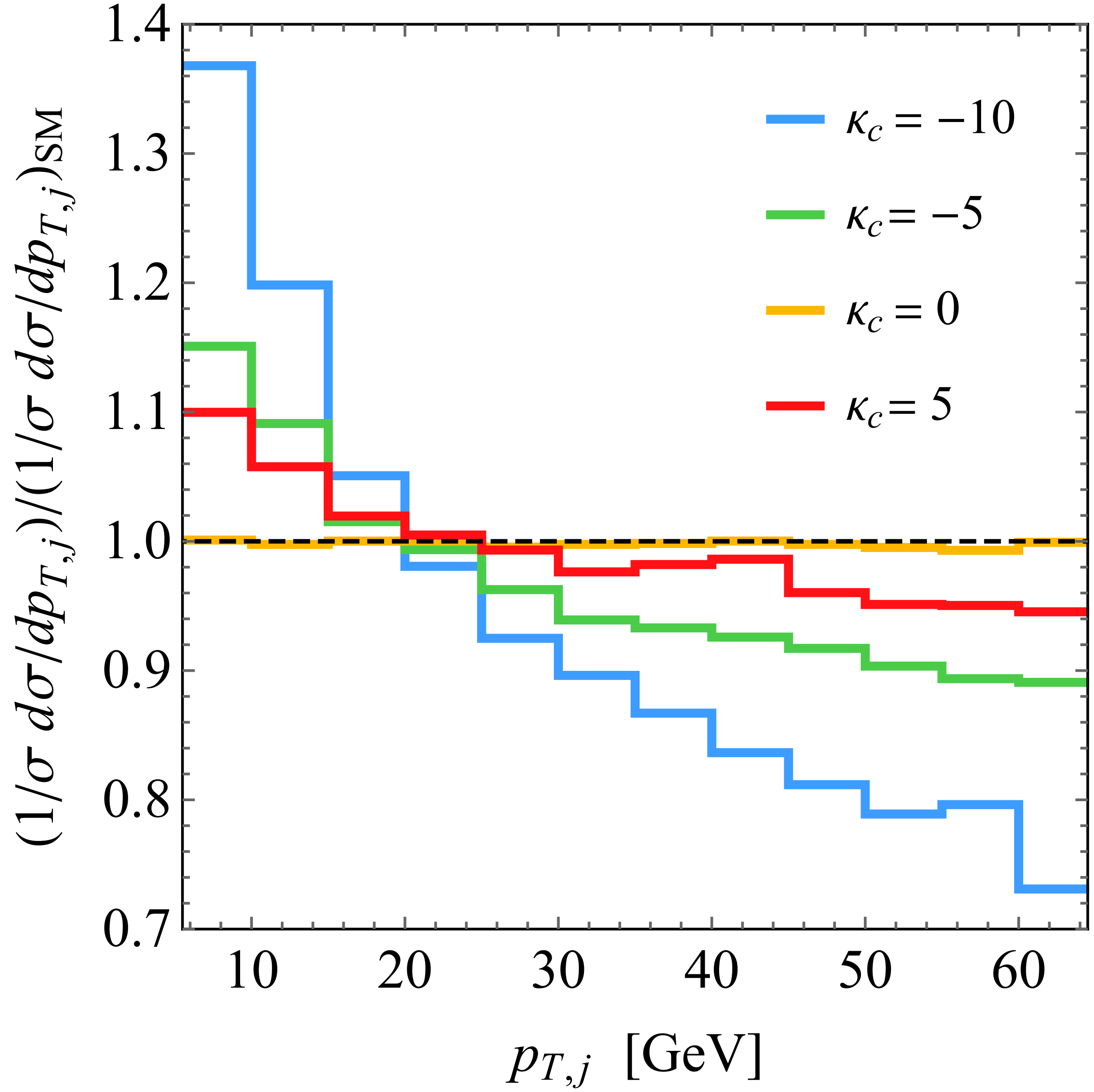
ATLAS, 1504.05833




Statistics limited & not in full agreement with theory predictions

# Normalised $p_{T,j}$ spectra at 8 TeV

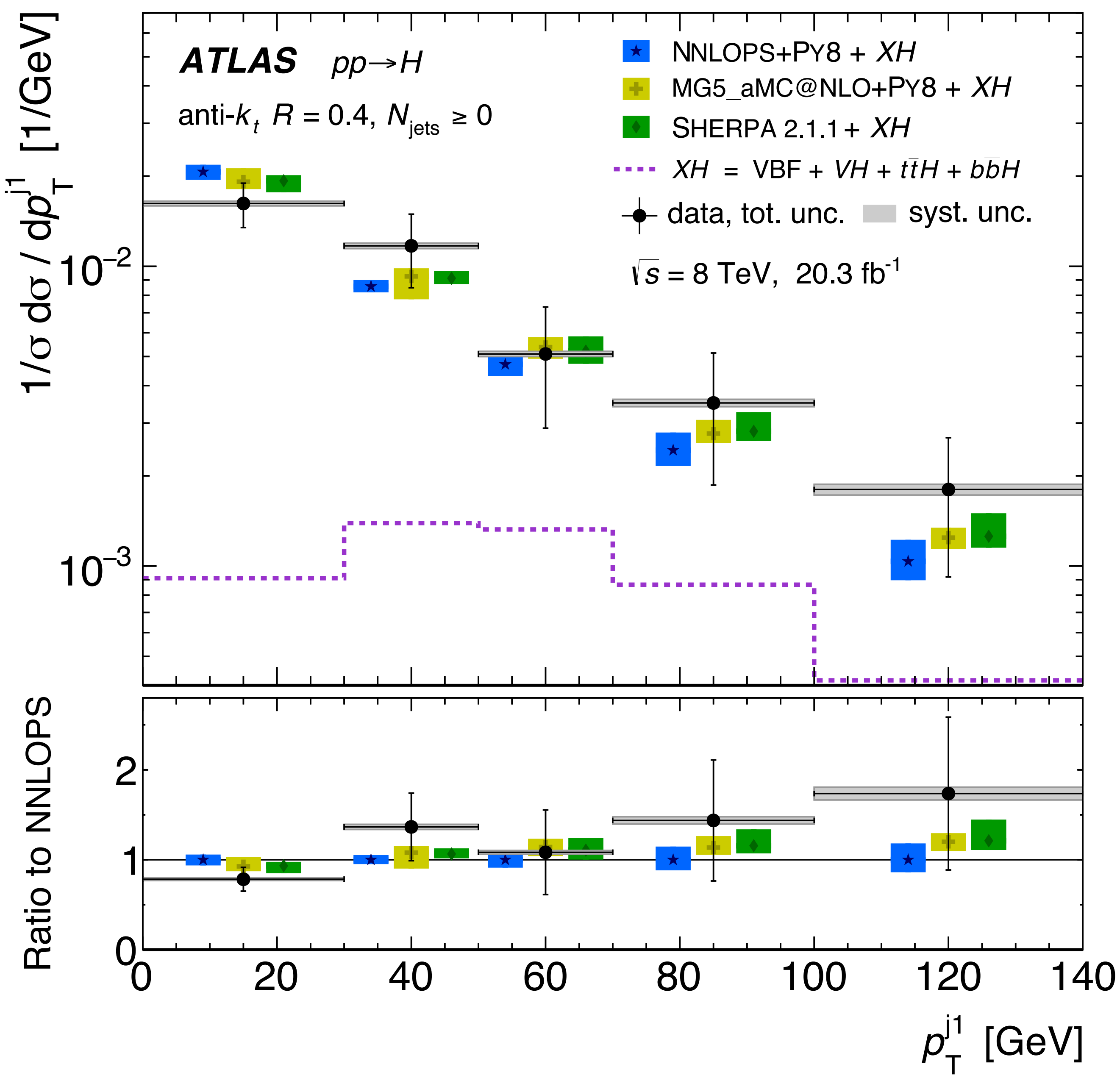
Bishara, UH, Monni & Re, 1606.09253




O(1) deviations in $\kappa_c$ lead to few % effects in $p_{T,j}$ distribution

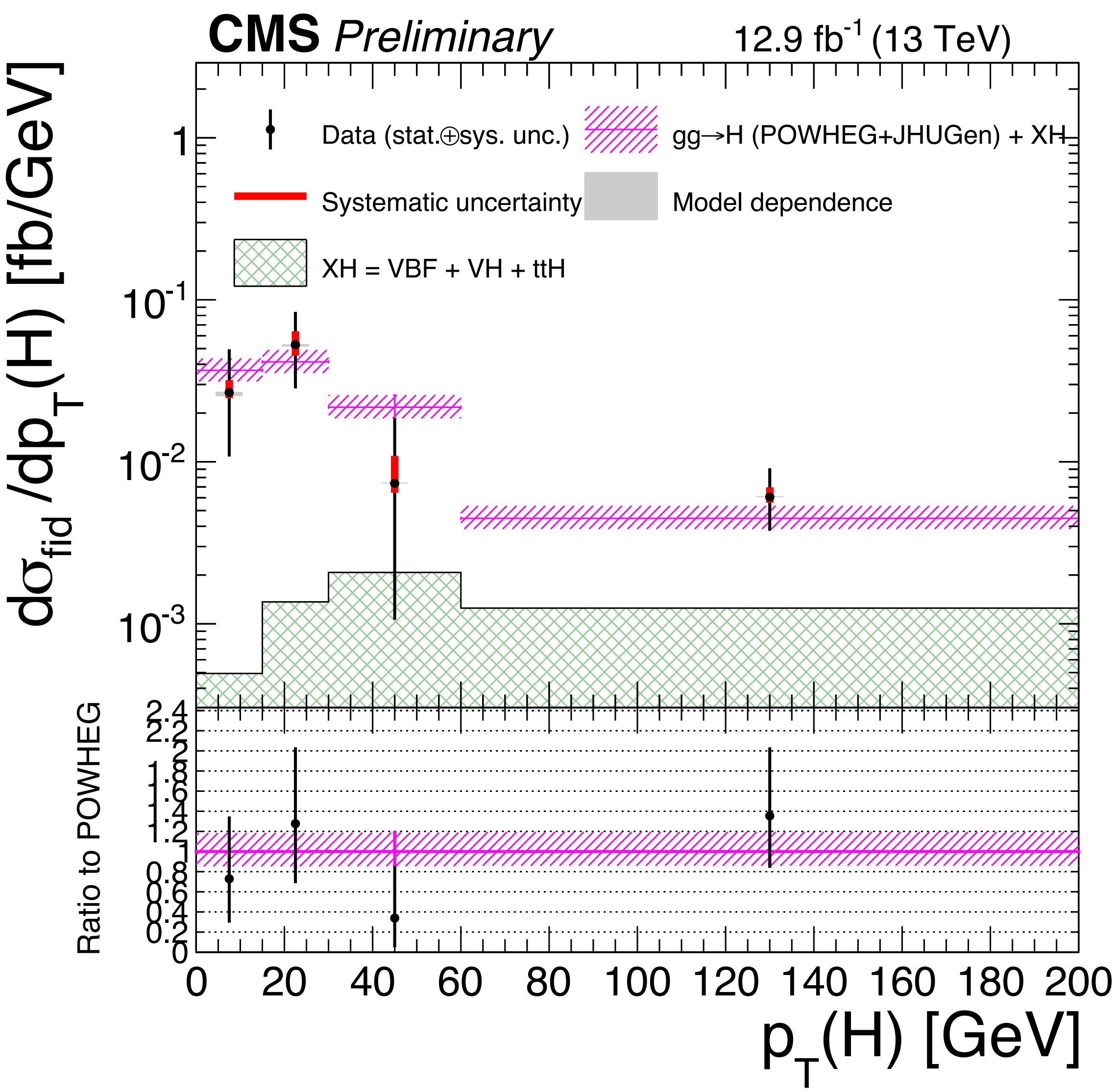
# Measured $p_{T,j}$ spectrum at 8 TeV

ATLAS, 1504.05833

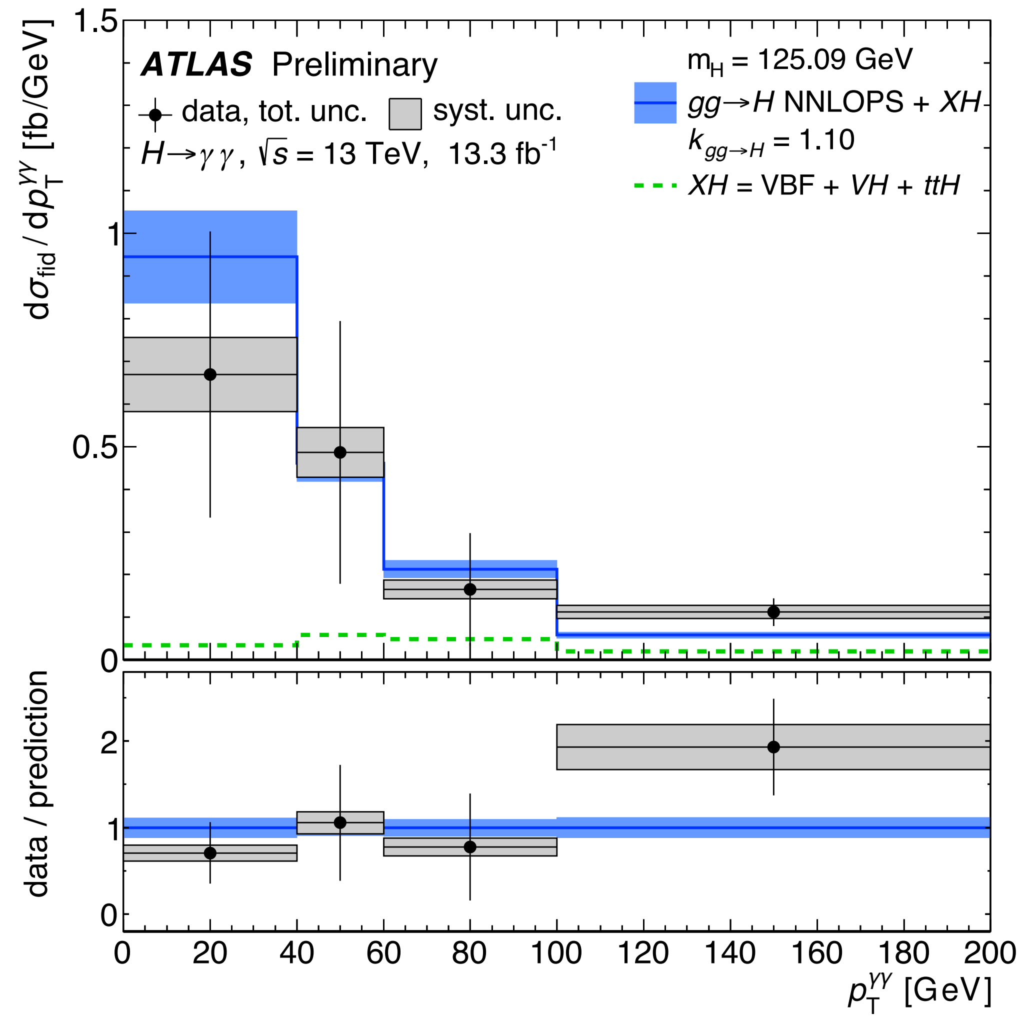



Statistics limited & in full agreement with theory predictions

# Measured $p_{T,h}$ spectra at 13 TeV

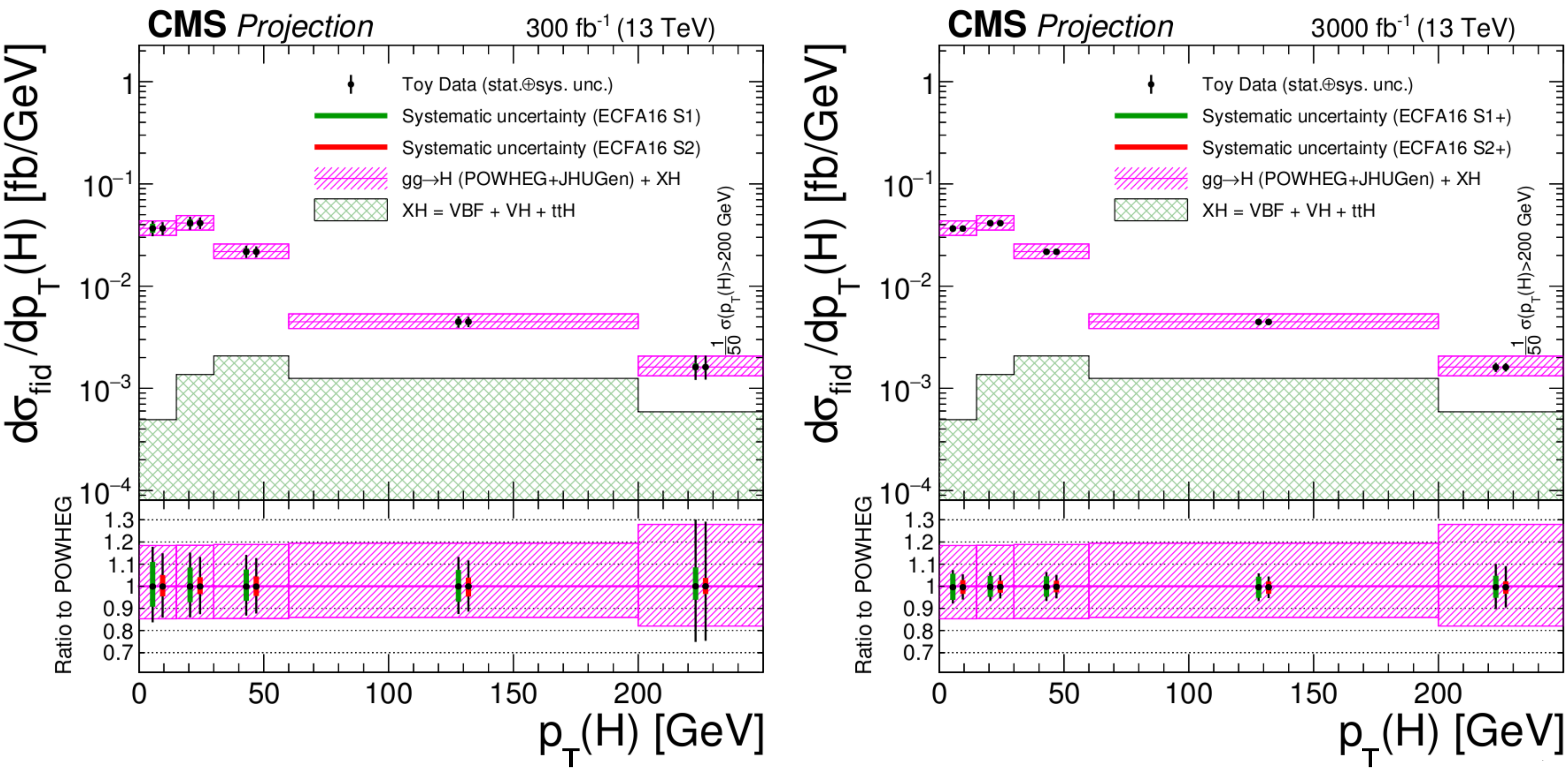



CMS PAS HIG-16-033




ATLAS-CONF-2016-067

# $p_{T,h}$ spectra at future LHC runs

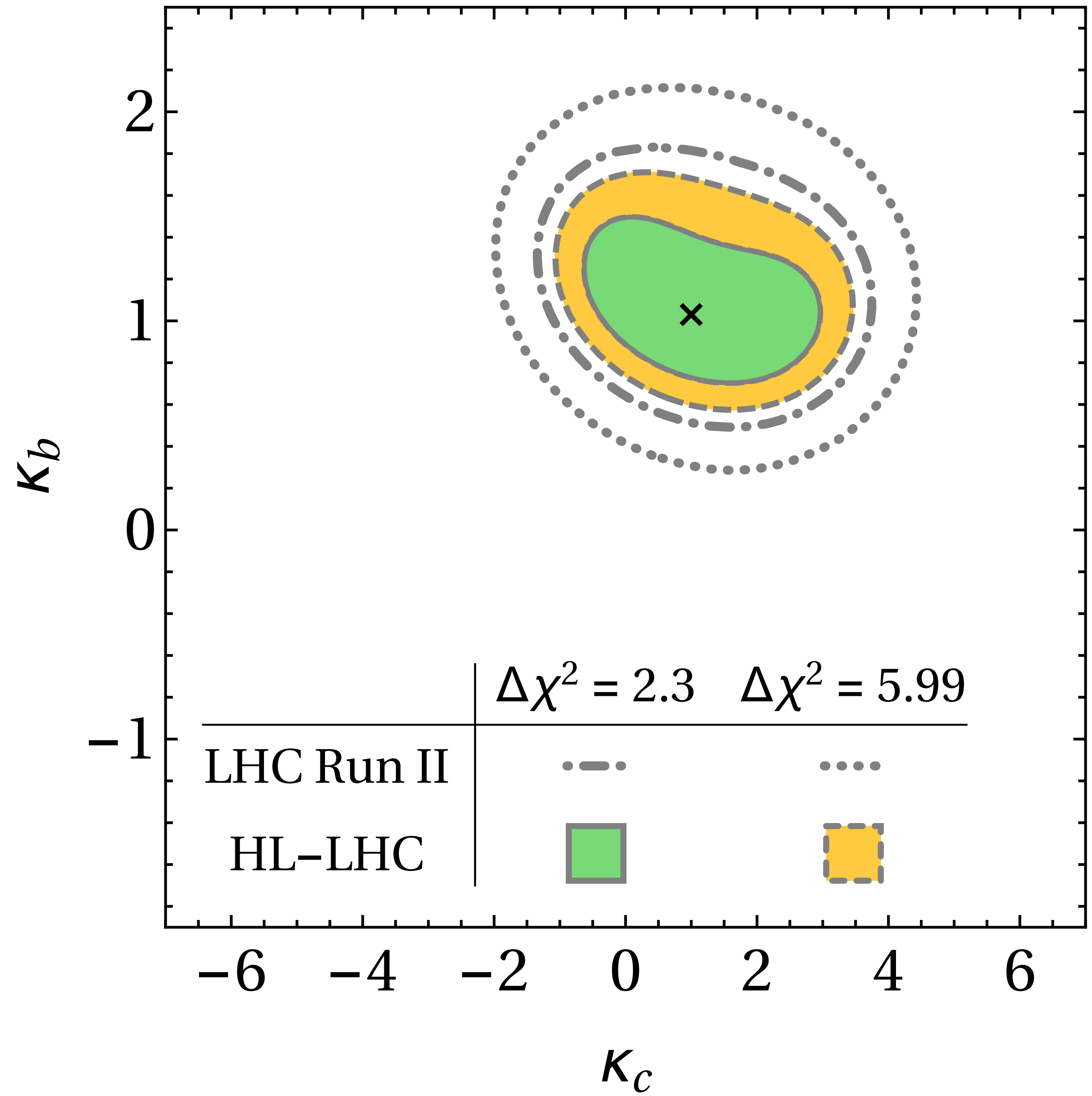



CMS-DP-2016-064

Systematic errors of a few % should be achievable at HL-LHC

# Constraints on $\kappa_{c,b}$: prospects

Bishara, UH, Monni & Re, 1606.09253




$$\kappa_c \in [-1.4, 3.8]^\dagger$$

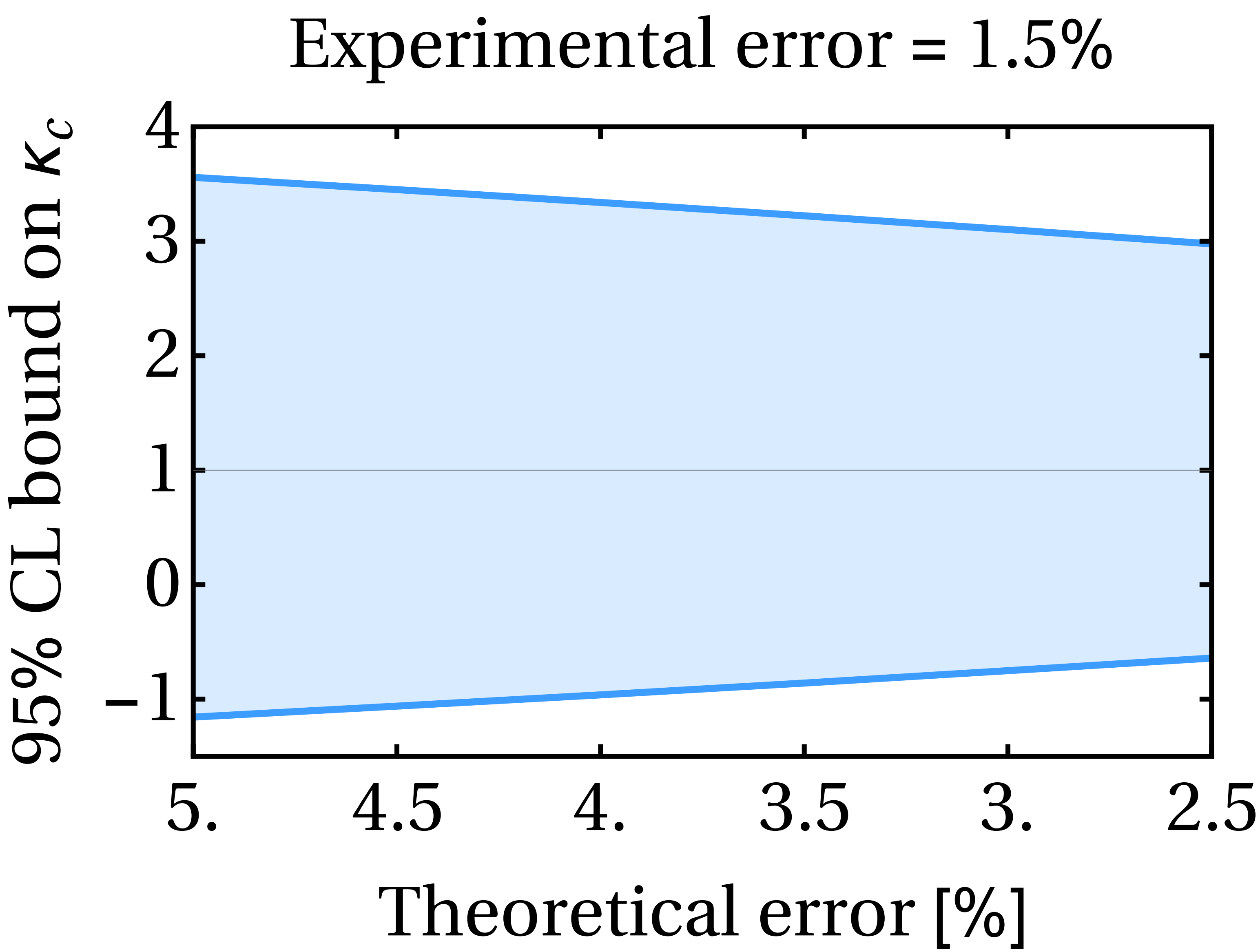
(LHC Run II)

$$\kappa_c \in [-0.6, 3.0]^\dagger$$

(HL-LHC)

† 95% CL after profiling over $\kappa_b$

# Impact of theory error at HL-LHC




Bishara, UH, Monni & Re, supplemental material to 1606.09253