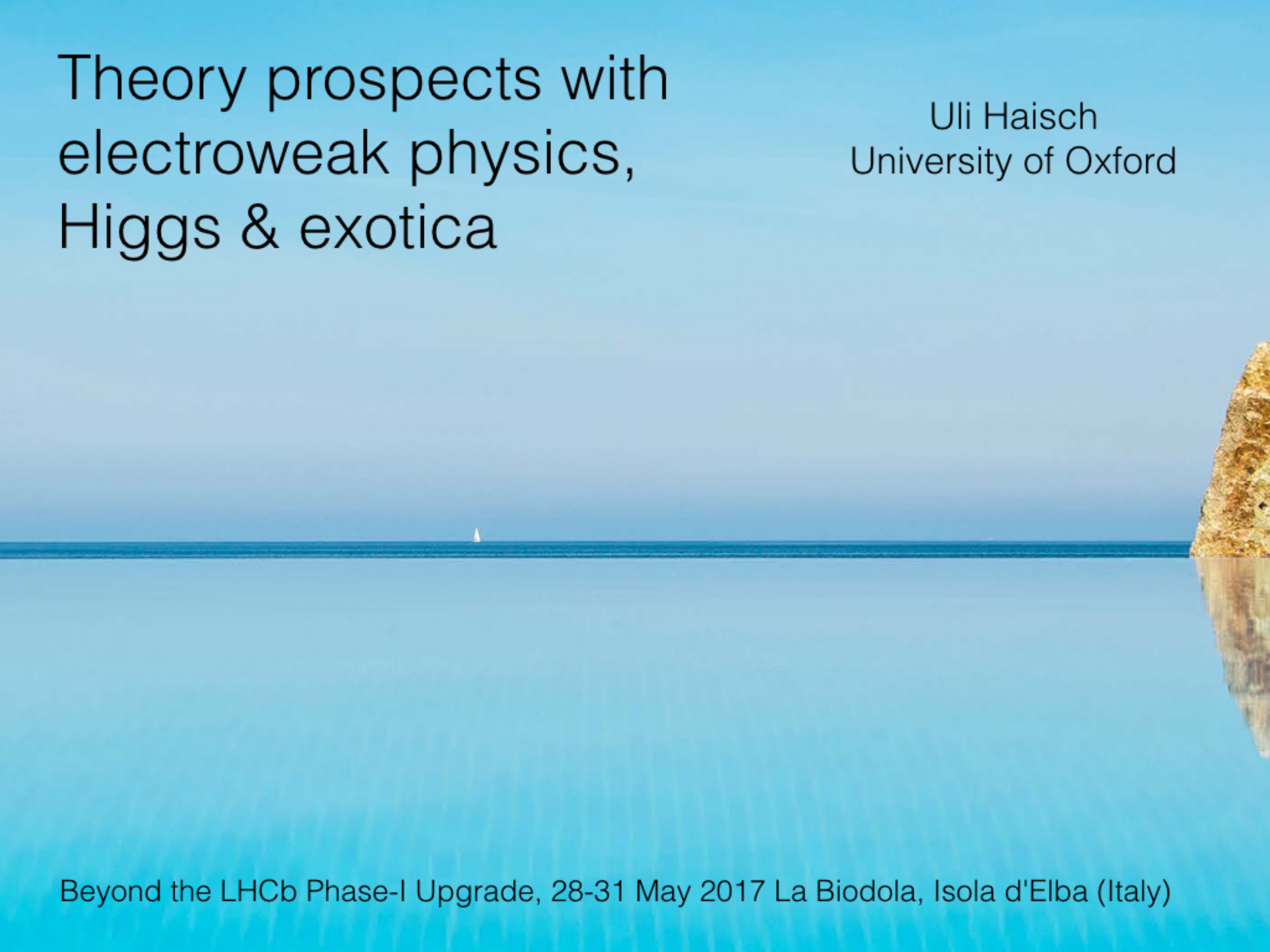
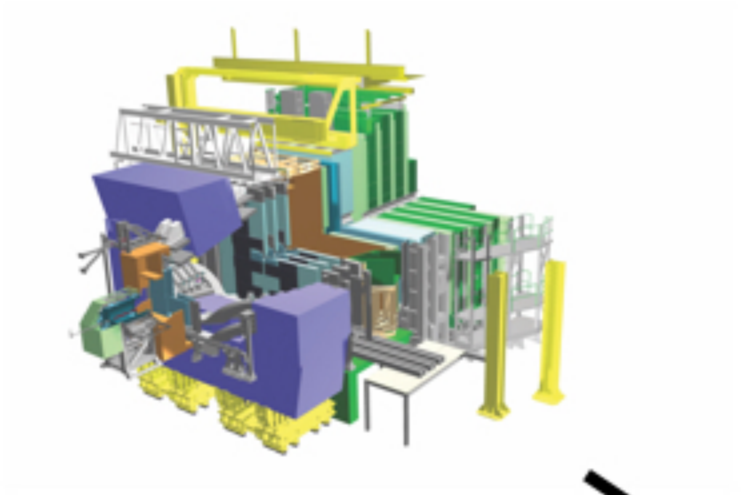


Theory prospects with electroweak physics, Higgs & exotica

Uli Haisch
University of Oxford

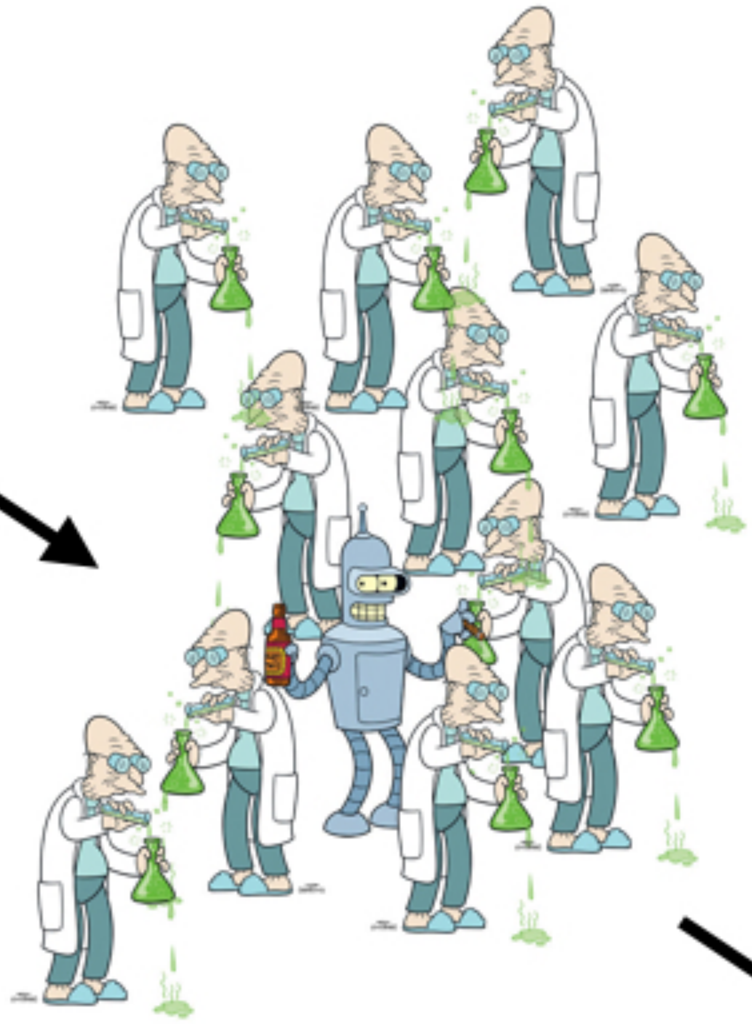
Beyond the LHCb Phase-I Upgrade, 28-31 May 2017 La Biodola, Isola d'Elba (Italy)

So far …



LHCb

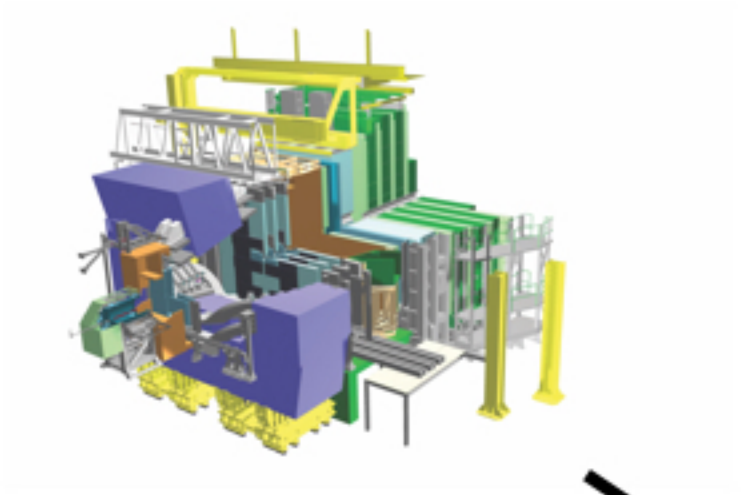
$P_i', R_K,$
$R_{K^*}, \ldots$



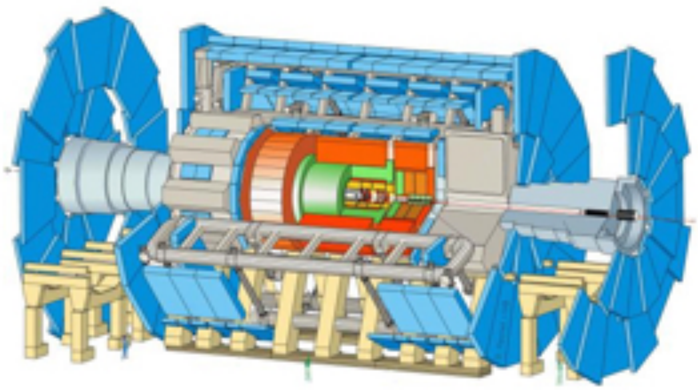
theory

$C_9 \simeq -1$

while in this talk …

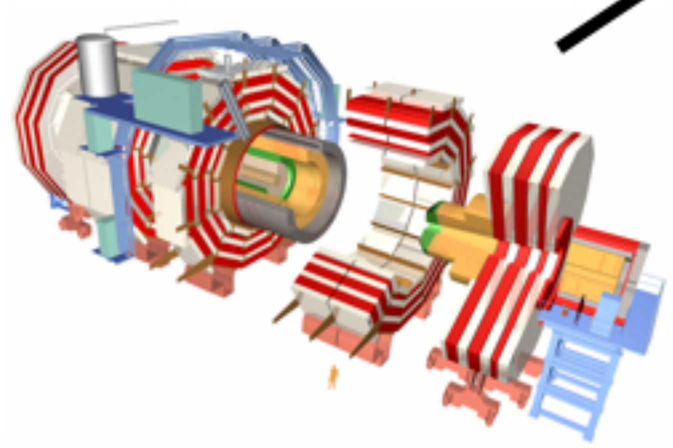


LHCb



ATLAS

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



CMS

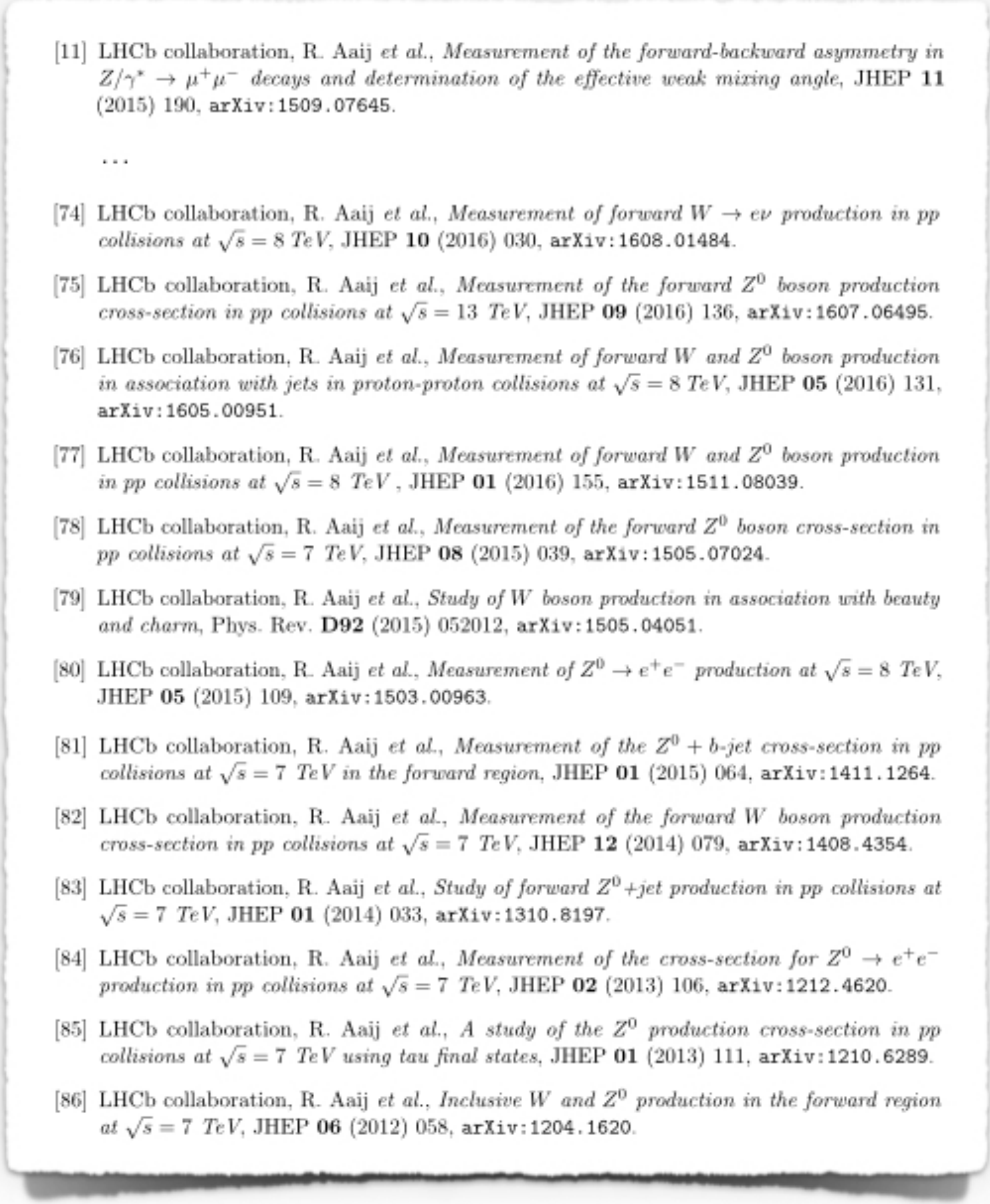
theory

?

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`.

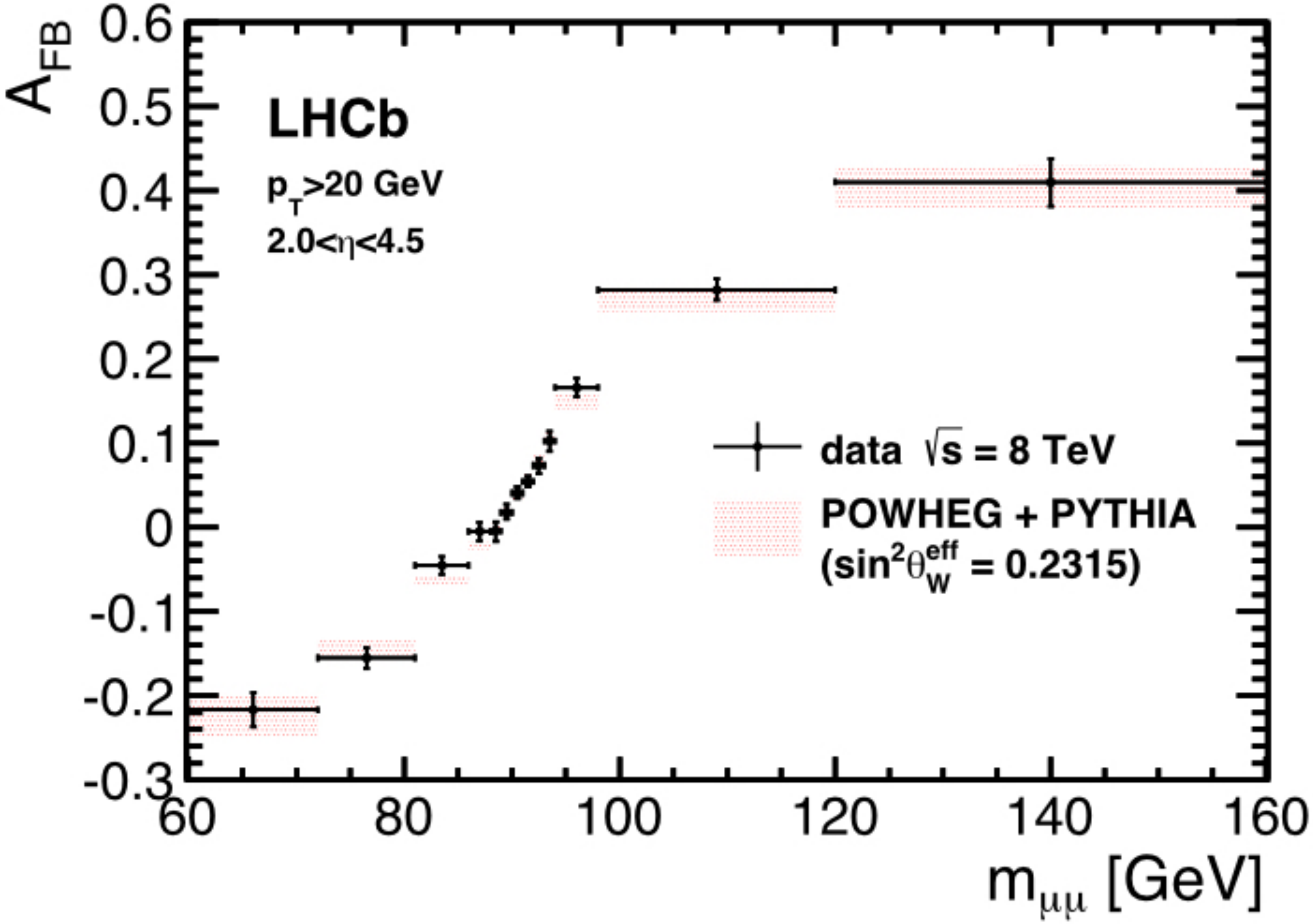
[85] LHCb collaboration, R. Aaij *et al.*, *A study of the Z^0 production cross-section in pp collisions at $\sqrt{s} = 7$ TeV using tau final states*, JHEP **01** (2013) 111, `arXiv:1210.6289`.

[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`.

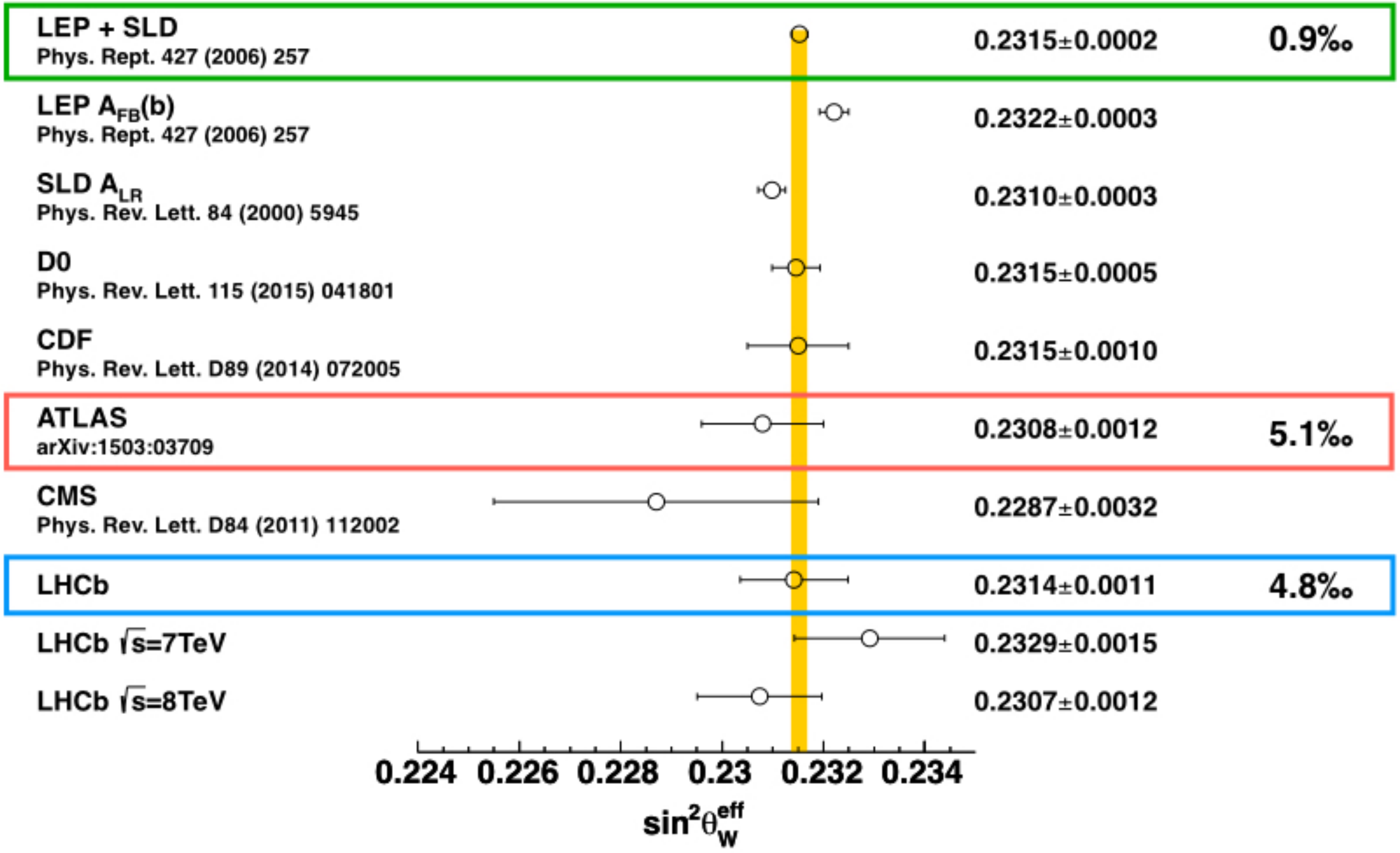
CERN-LHCC-2017-003

Drell-Yan (DY) production

LHCb, 1509.07645



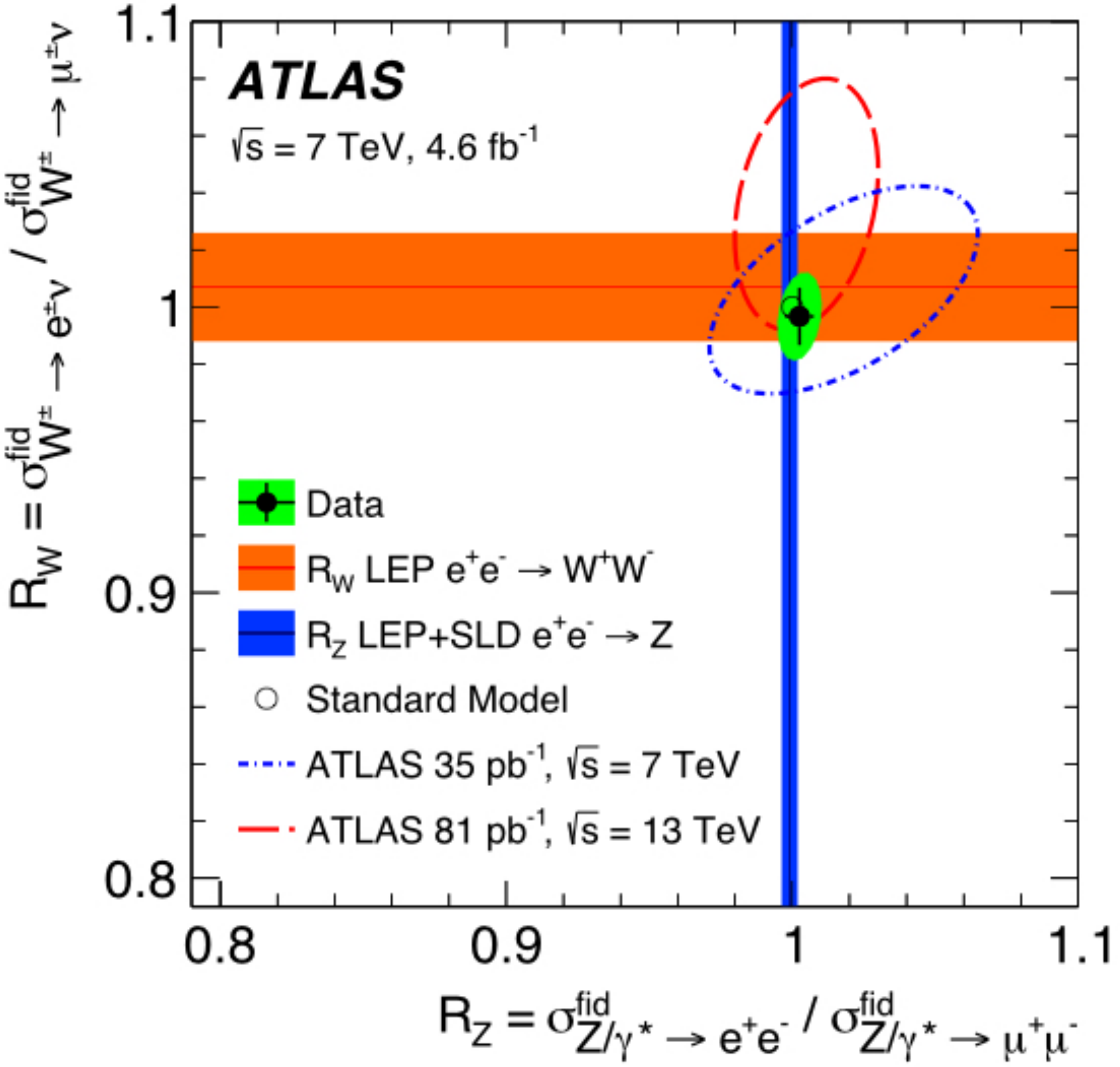
Weak mixing angle



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

Lepton flavour universality in DY

ATLAS, 1612.03016



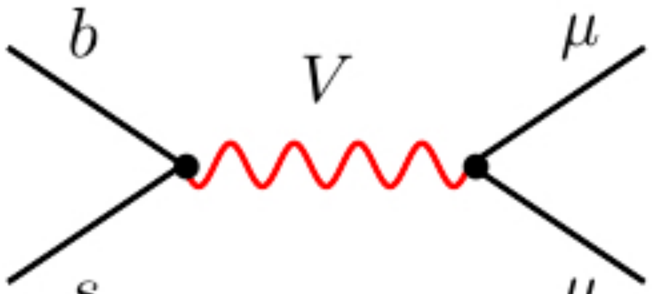
$$R_Z^{\text{ATLAS}} = 1.0026\,(1 \pm \boxed{5.0\text{‰}})$$

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

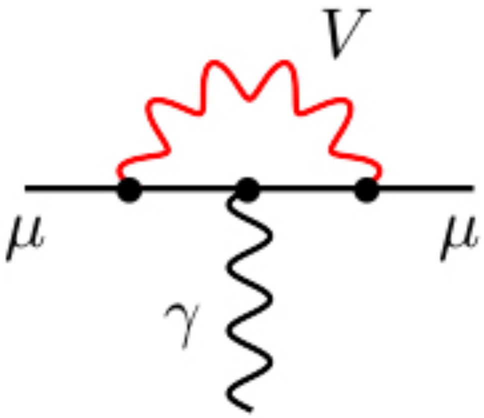
1‰ DY measurements $\longrightarrow ?$

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

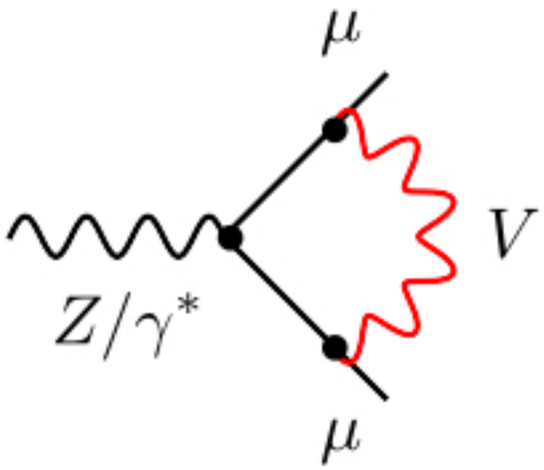
$$\mathcal{L} \supset \left(g_L^{sb}\, \bar{s}_L \not{V} b_L + \text{h.c.}\right) + \bar{\mu}\left(g_V^{\mu} - g_A^{\mu}\gamma_5\right) \not{V} \mu$$



P_5', R_K, R_{K^*}



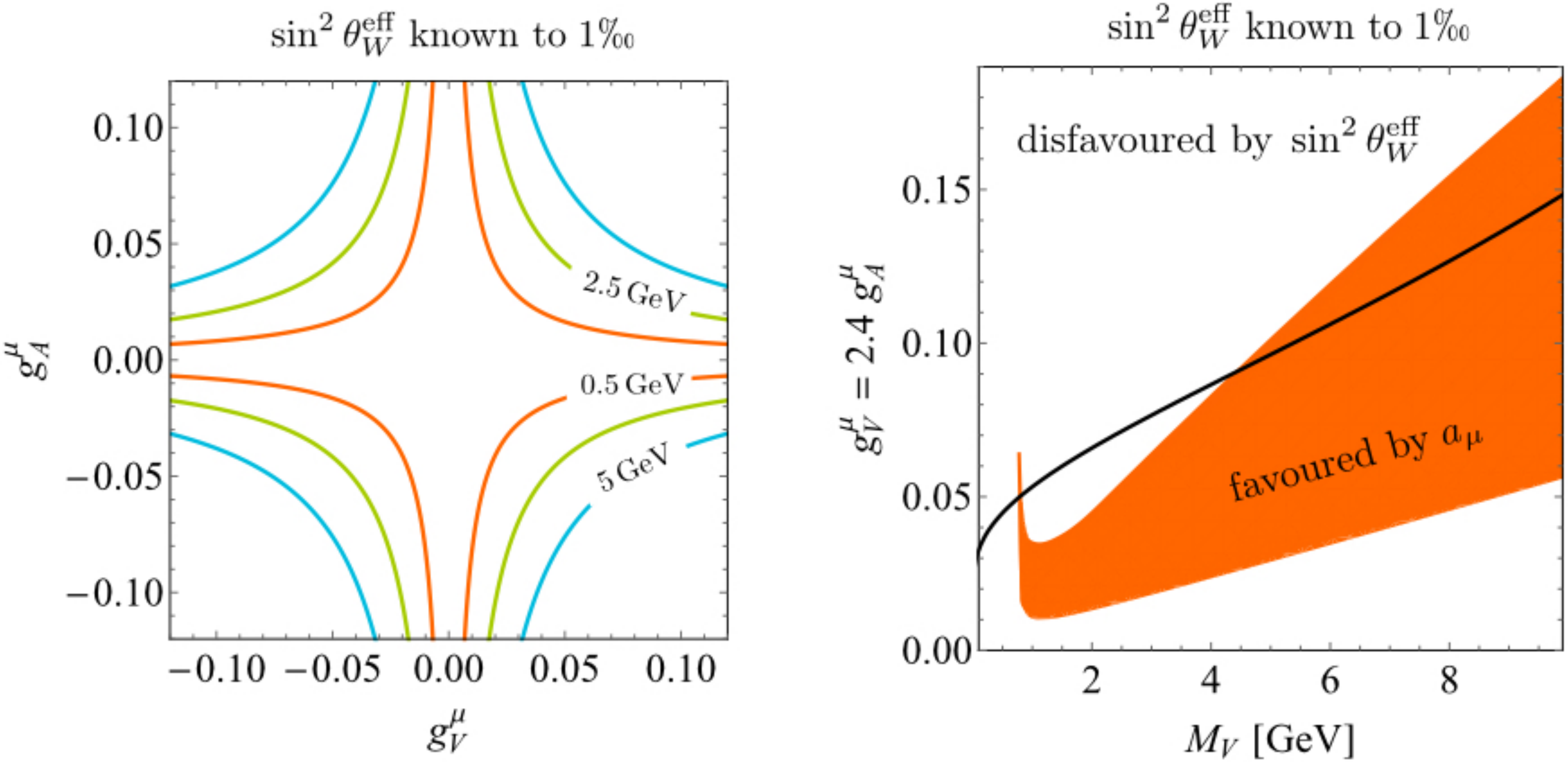
$a_\mu = ((g-2)/2)_\mu$



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_μ

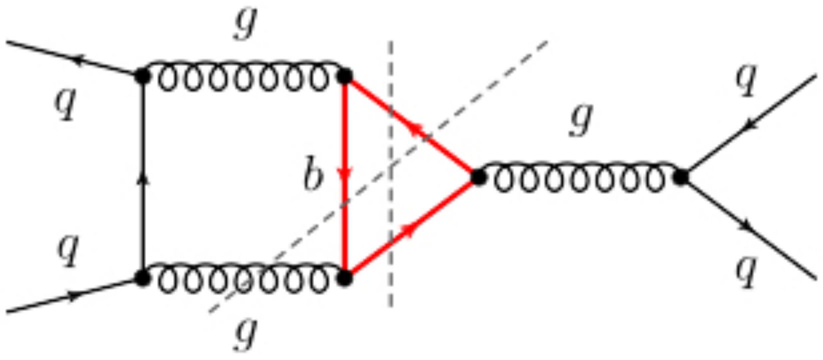
Precision on Z/W couplings

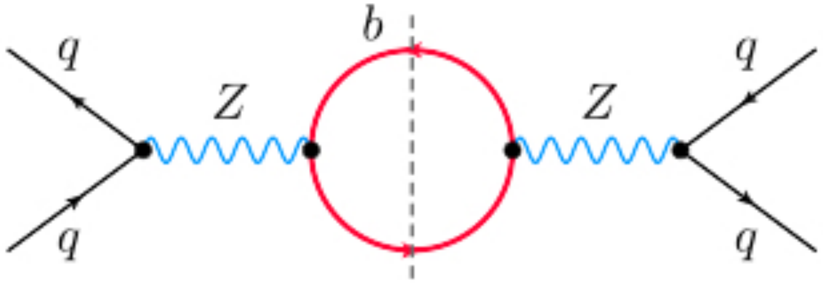
Ze^+e^- couplings	$(0.1\%)_L, (0.1\%)_R$
$Zc\bar{c}$ couplings	$(1.0\%)_L, (3.2\%)_R$
$Zb\bar{b}$ couplings	$(0.4\%)_L, (6.5\%)_R$
$Zt\bar{t}$ couplings	$> 100\%$
WWZ coupling	2.3%
$WW\gamma$ coupling	3.4%

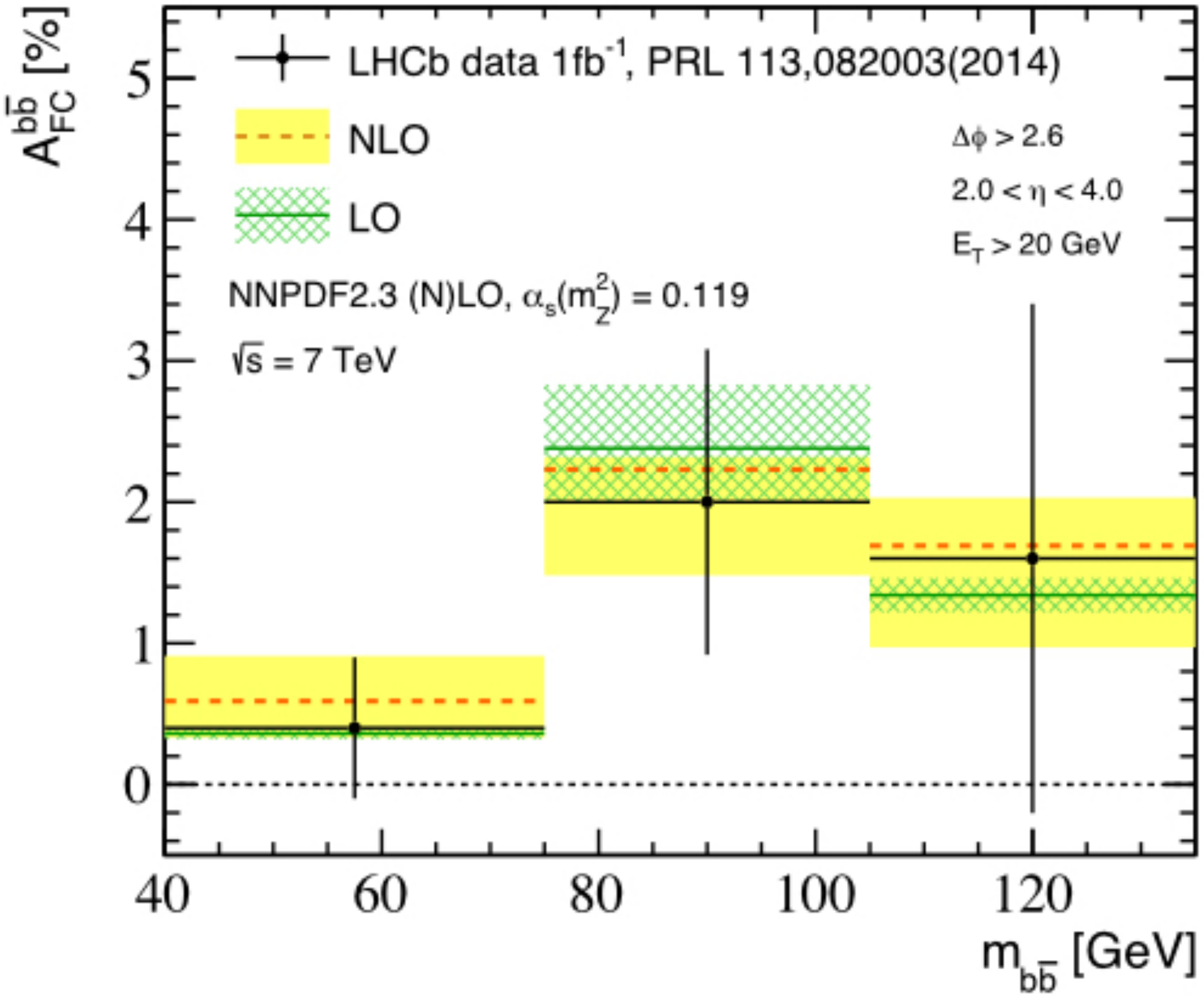
Z-boson couplings to heavy flavours & triple-gauge boson couplings are only known at % level

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

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





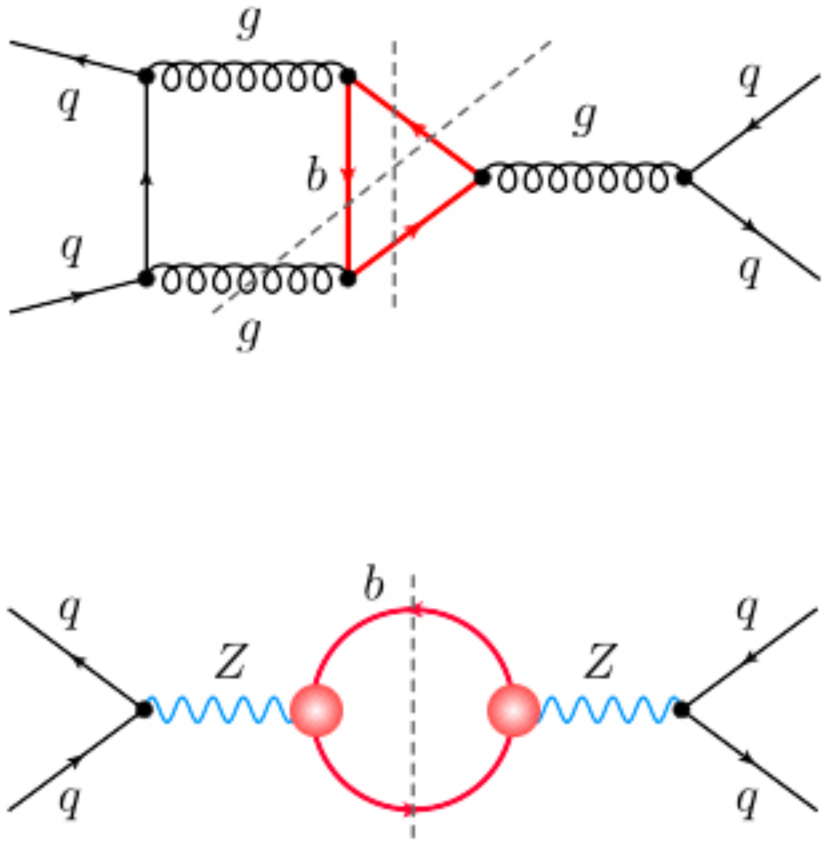


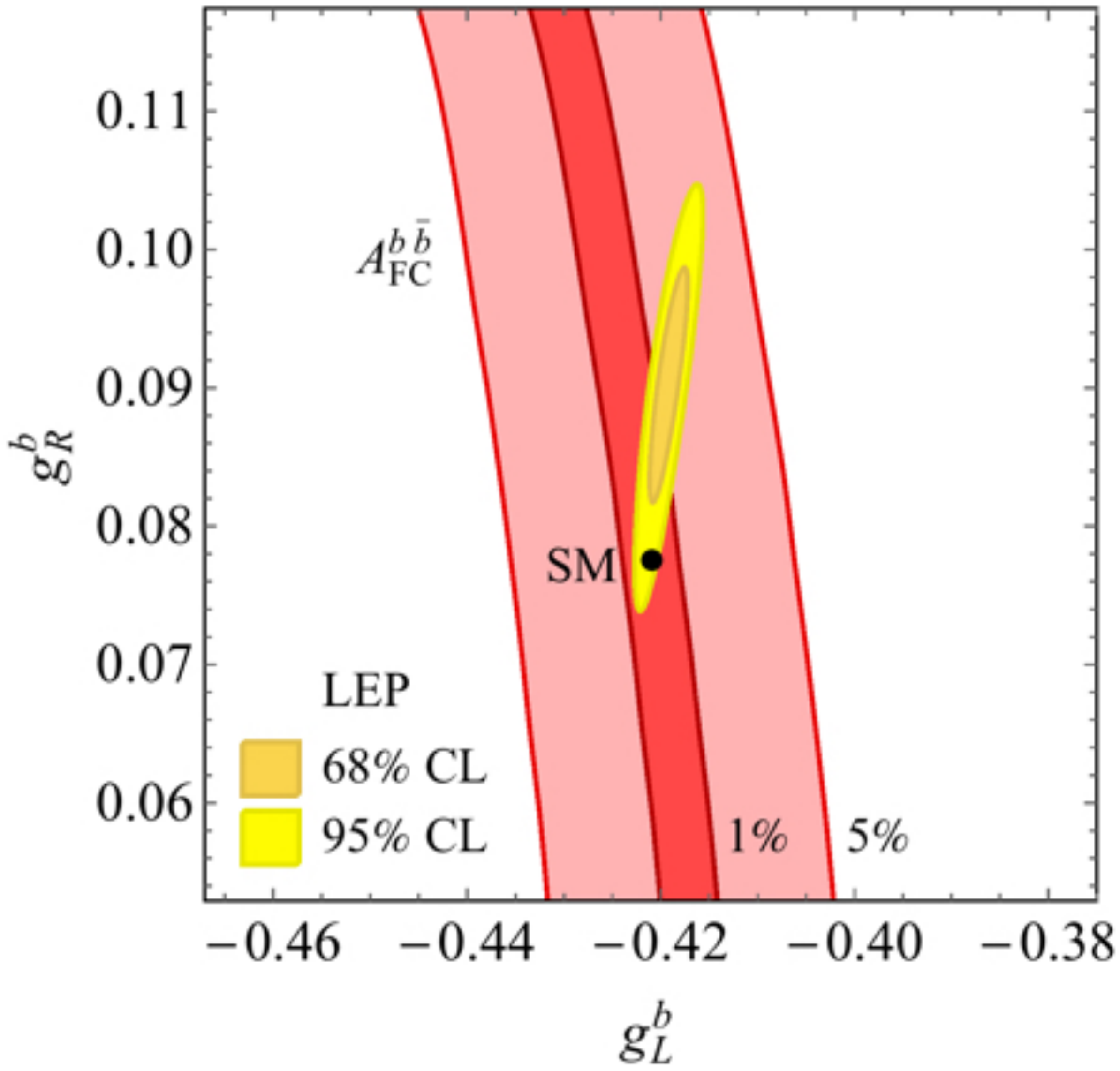
Gauld et al., 1505.02429

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

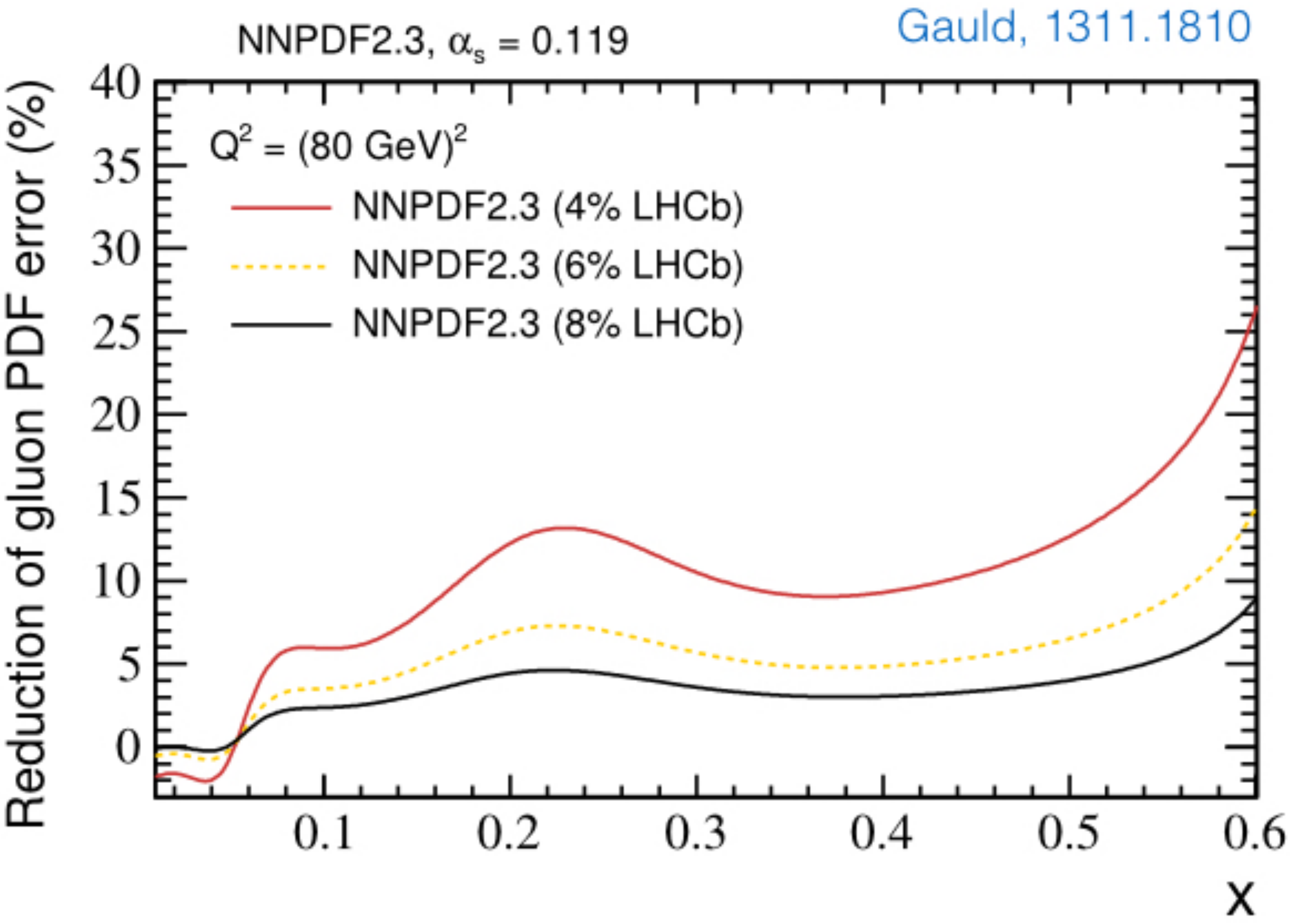




To reach LEP sensitivity need to achieve total relative error on $A_{FC}^{b\bar{b}}$ at % level. Needs dedicated LHCb & theory effort

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

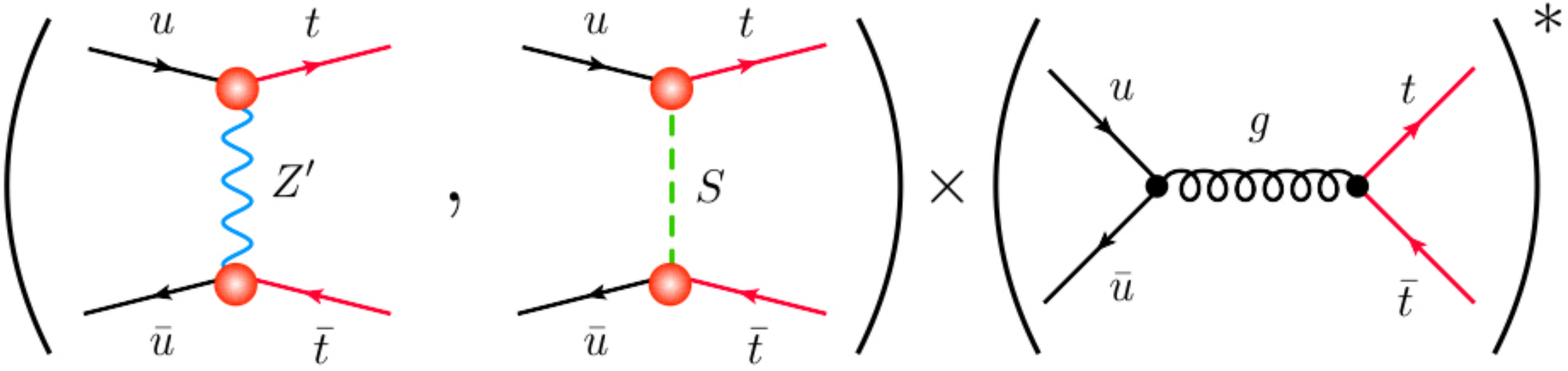
Why $t\bar{t}$ production at LHCb?



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

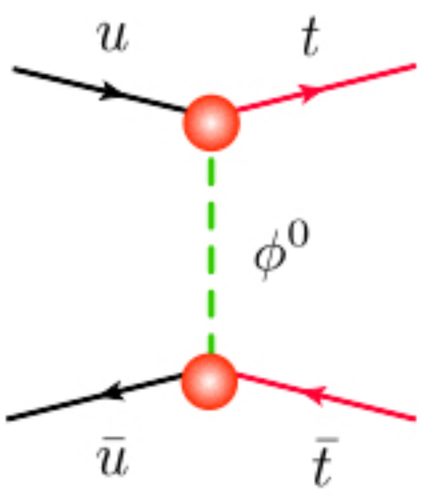
Why tt̄ production at LHCb?

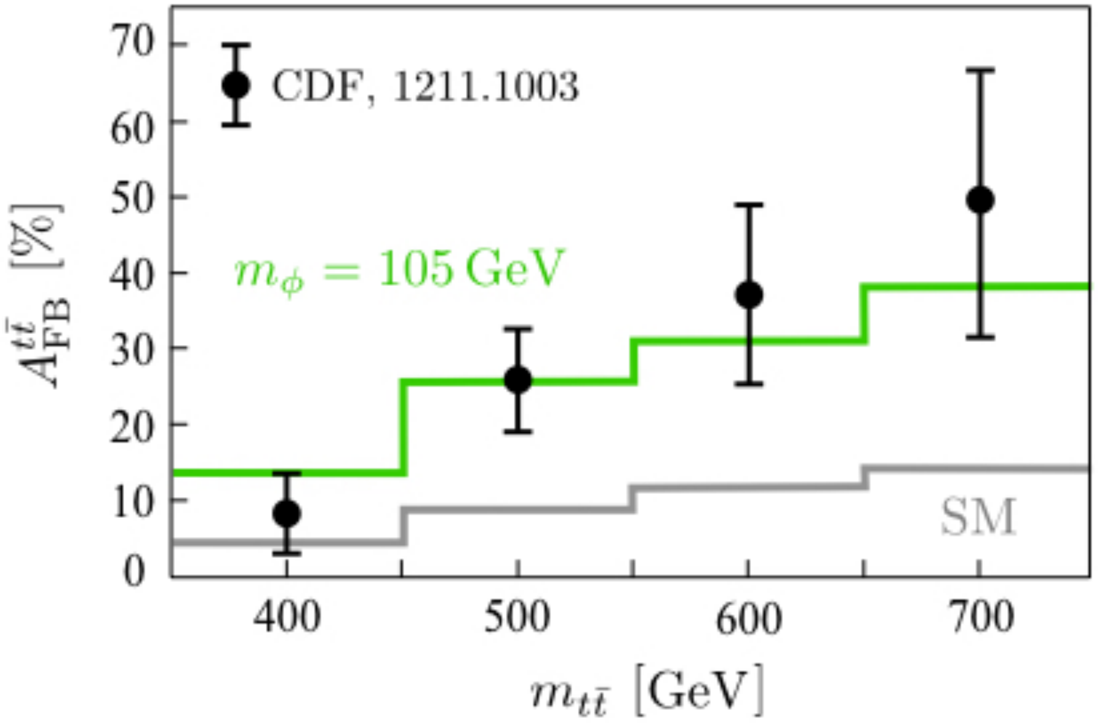


In new-physics models in which top production proceeds via t-channel exchange, cross section & asymmetry enhanced at large pseudo-rapidities not accessible at ATLAS & CMS

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

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



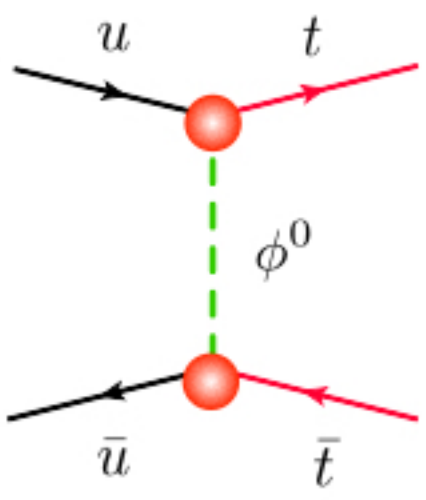


☑

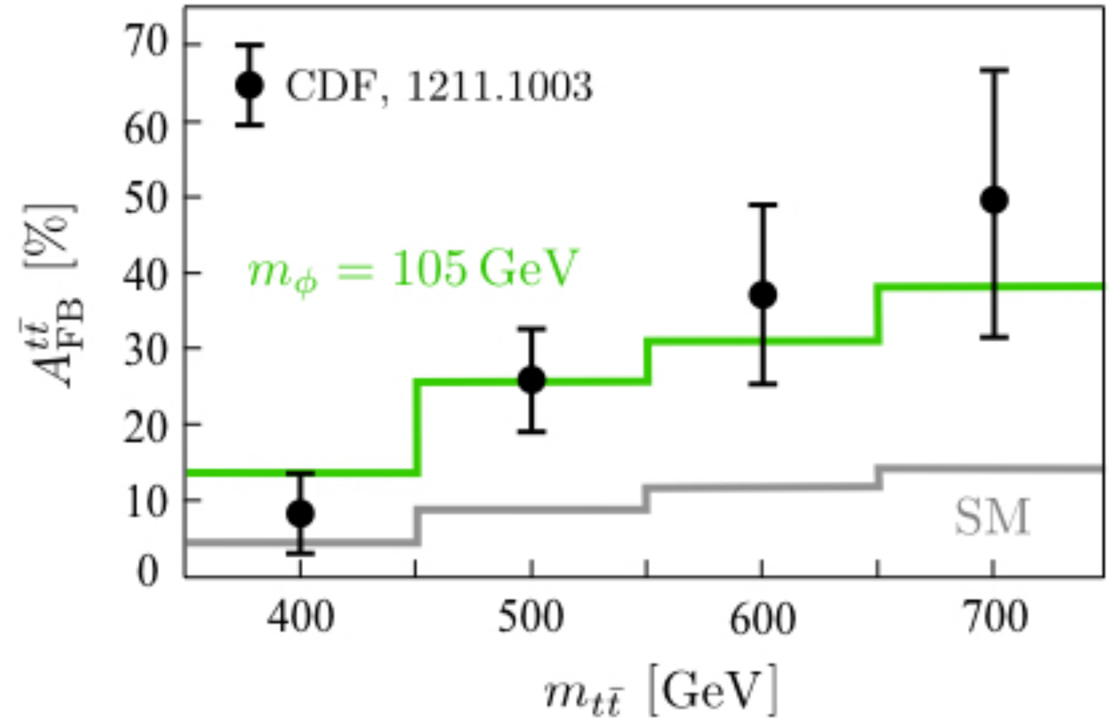
$$\mathcal{L} \supset \lambda \left(\phi^0 \, V_{tb} \bar{t}_L u_R + \phi^- \, \bar{b}_L u_R \right) + \mathrm{h.c.}$$

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

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



→



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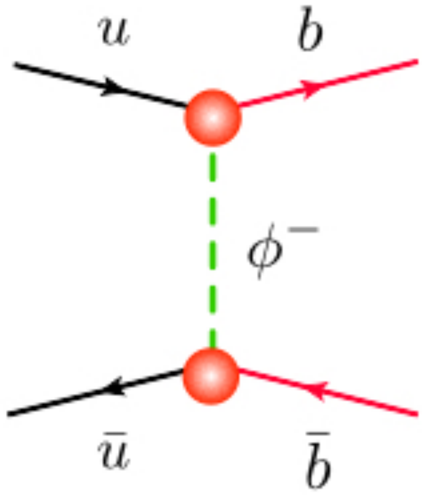

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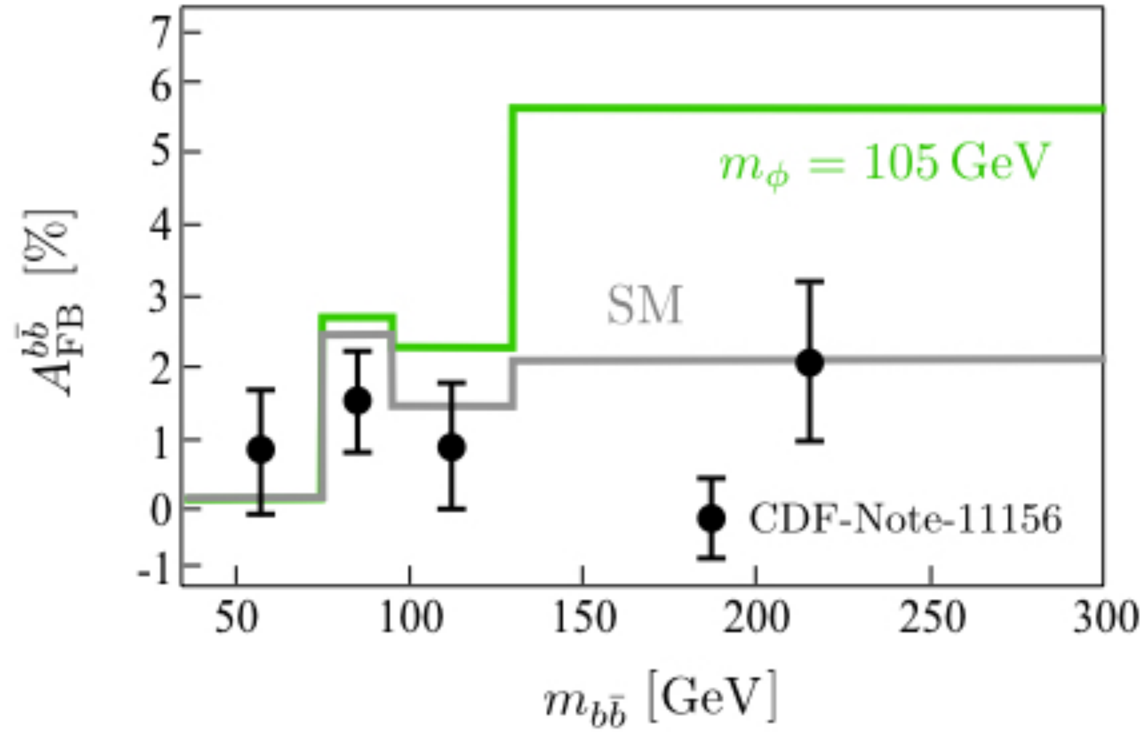

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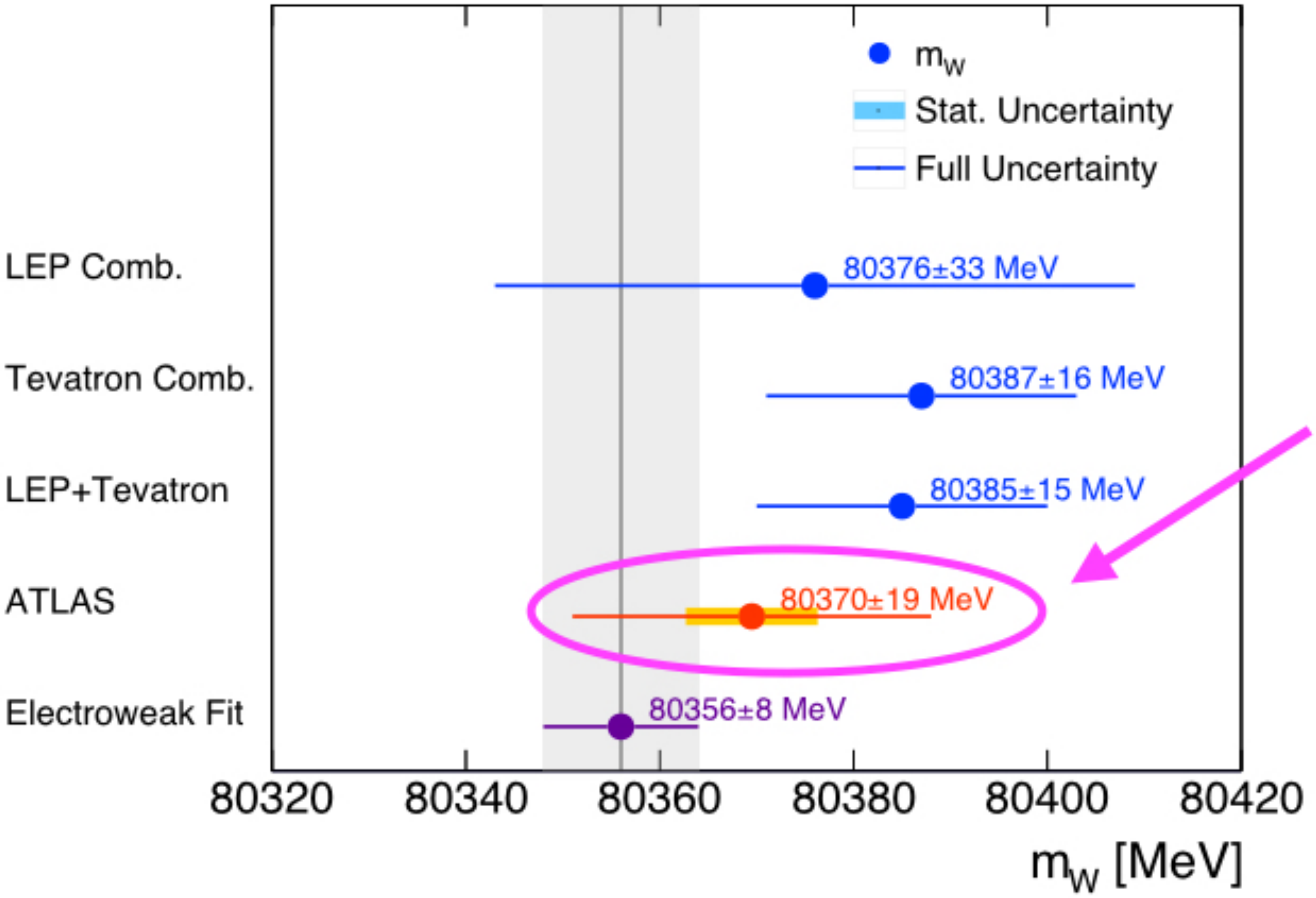
Murphy, 1504.02439

W mass measurement at LHC

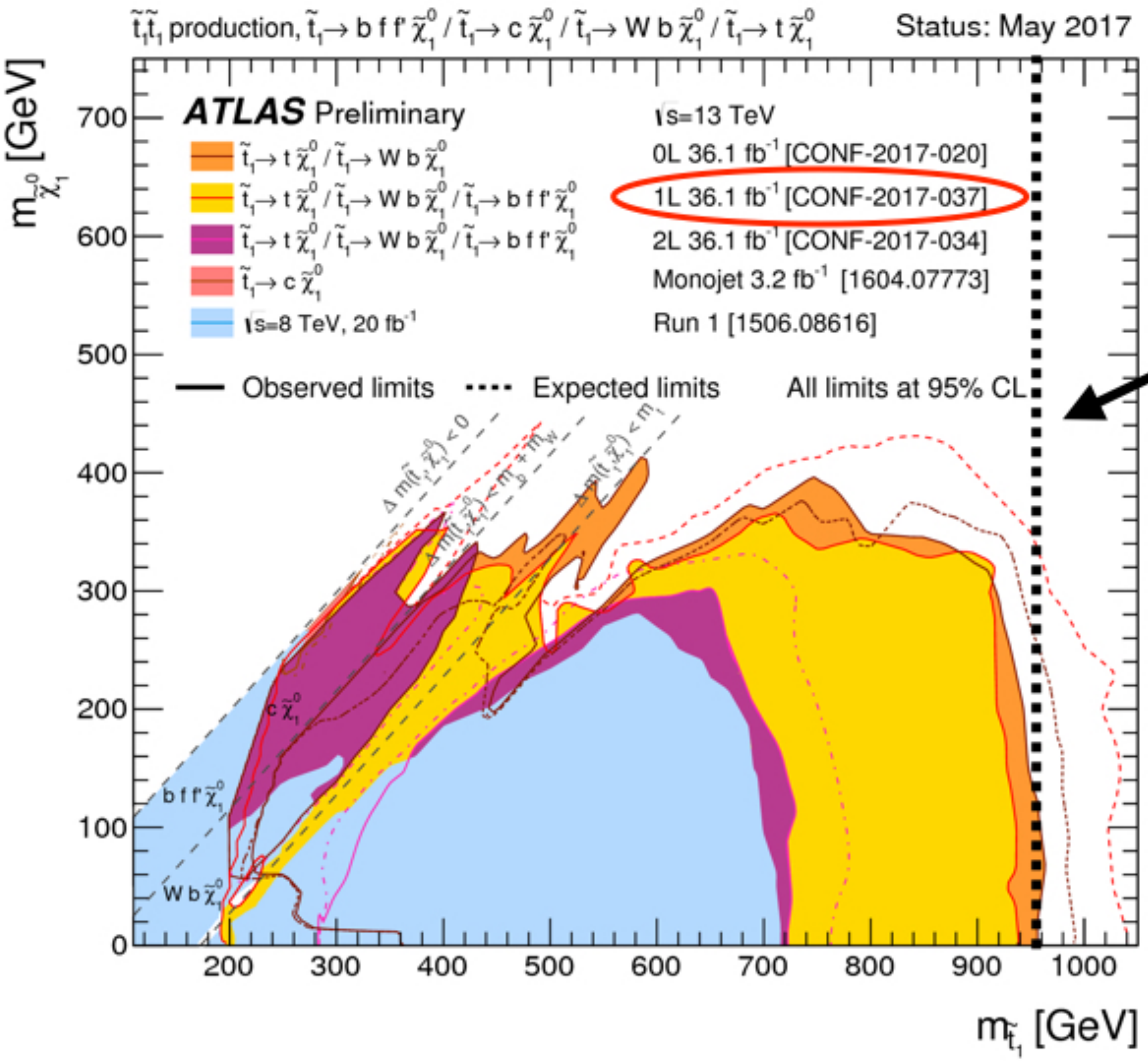
ATLAS, 1701.07240



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

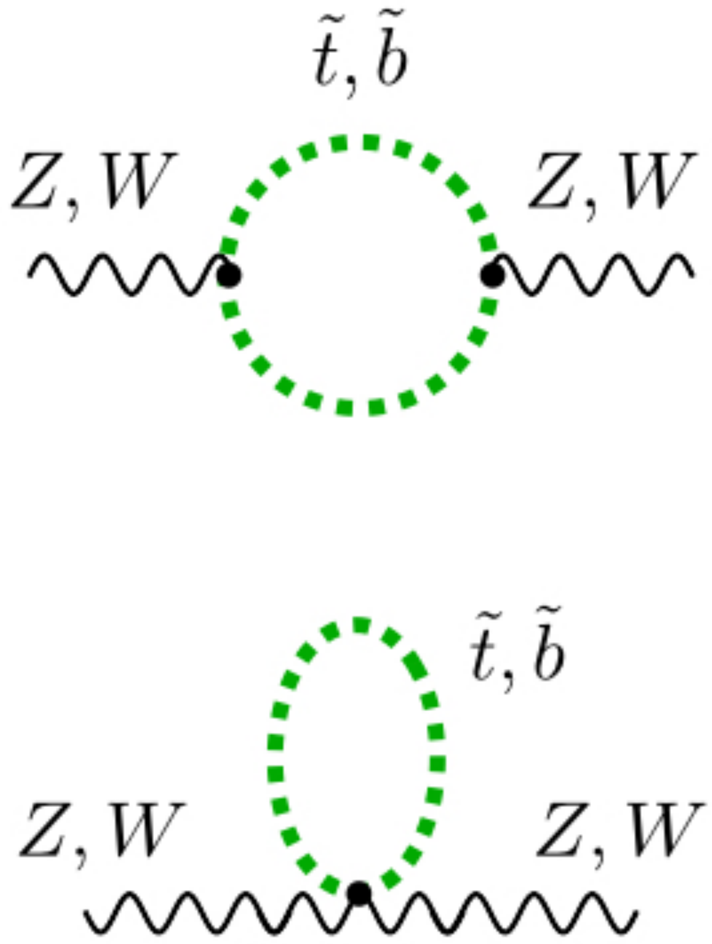
Stop searches at LHC

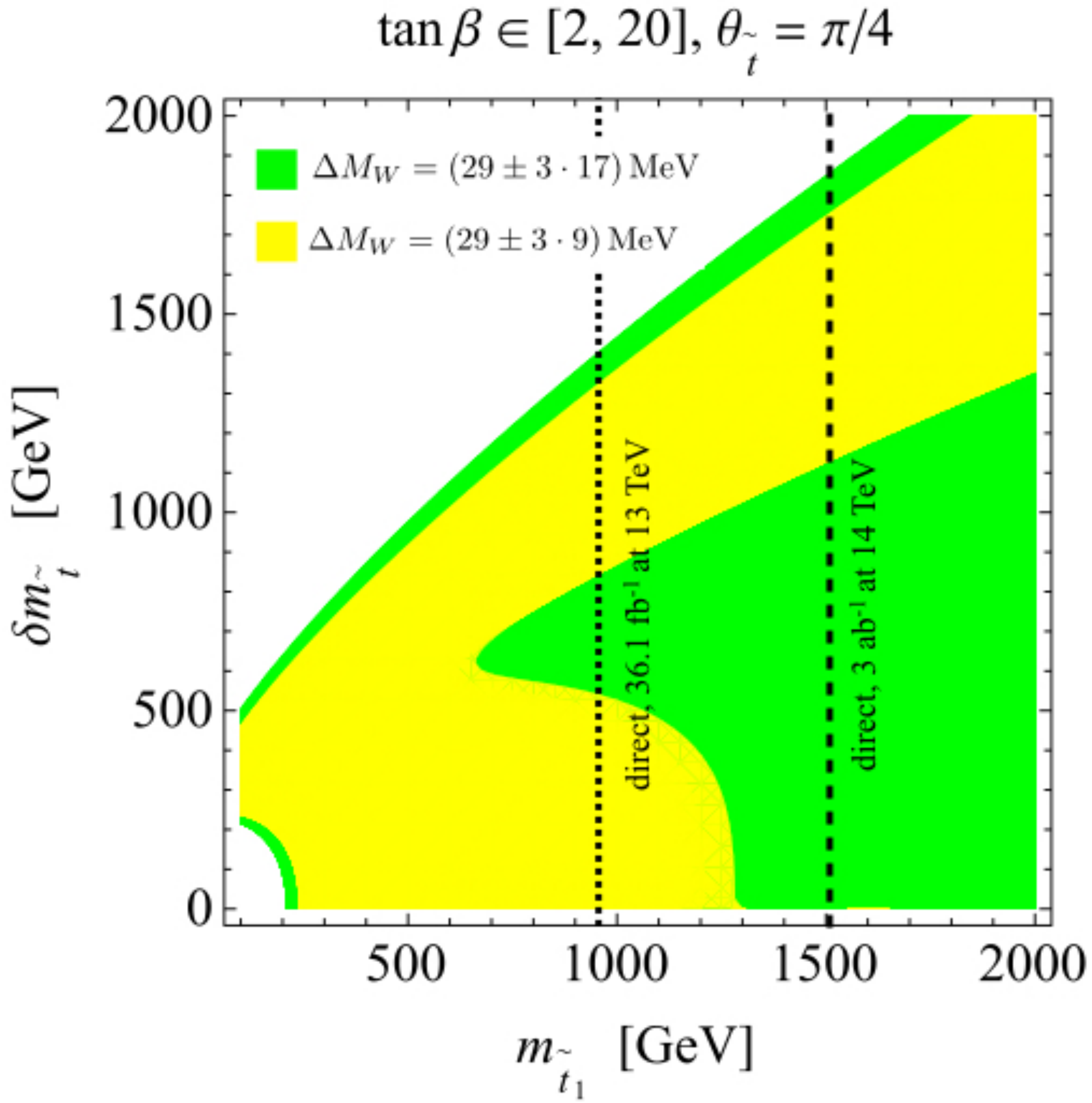


950 GeV

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

δM_W = 5 MeV $\longrightarrow$?

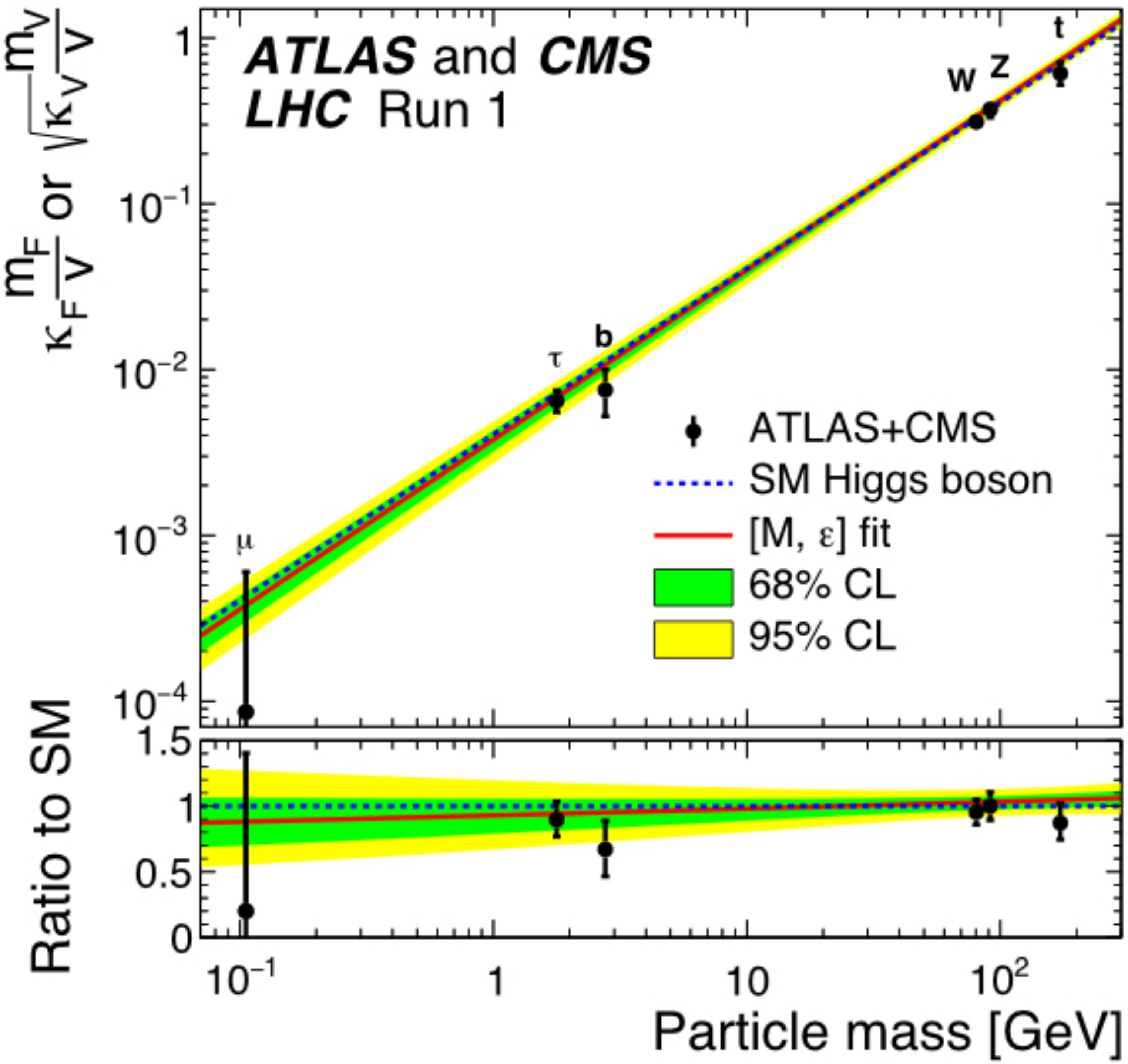




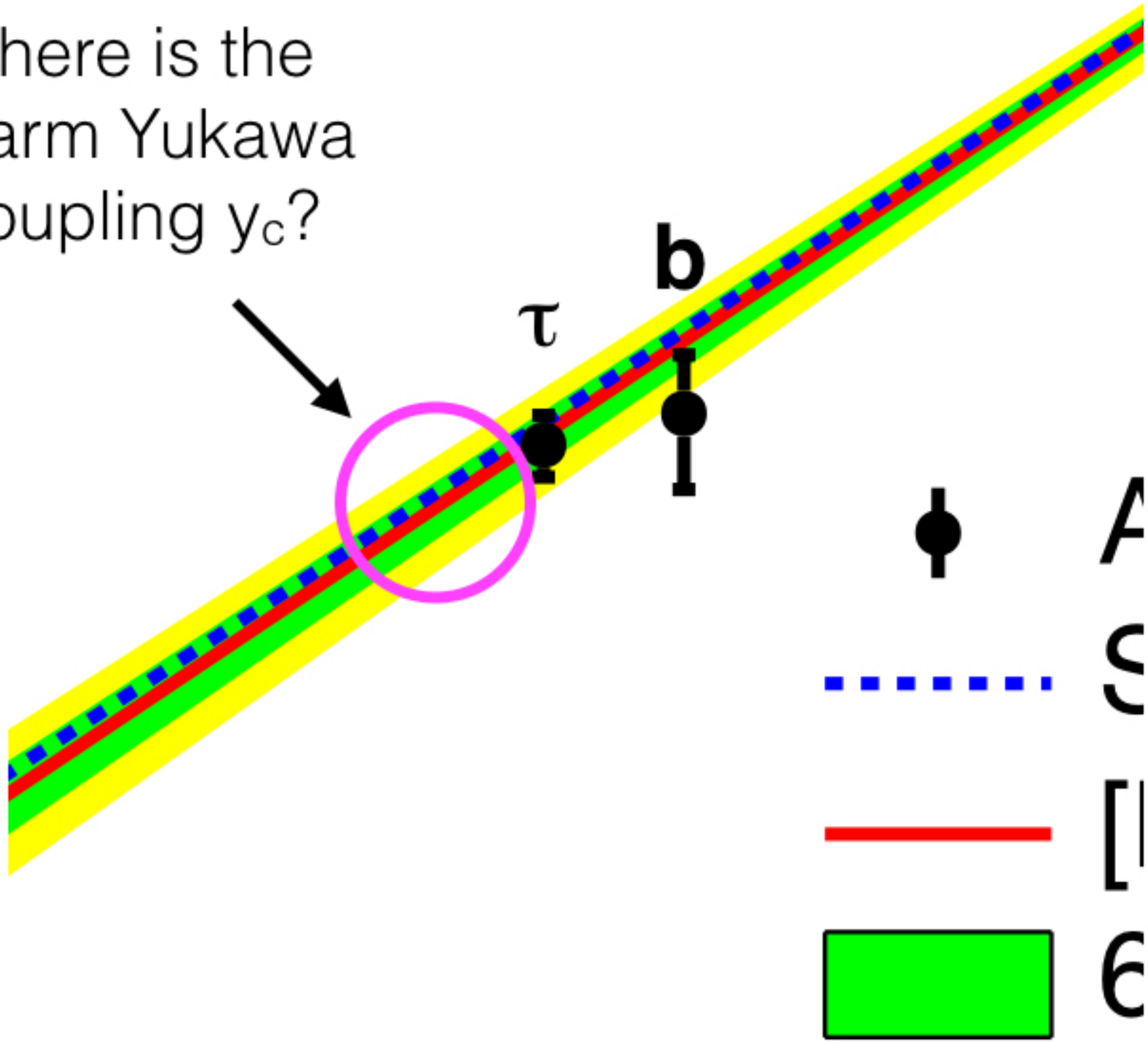
W mass provides complementary constraints on stop sector

Higgs couplings after Run I

ATLAS & CMS, 1606.02266



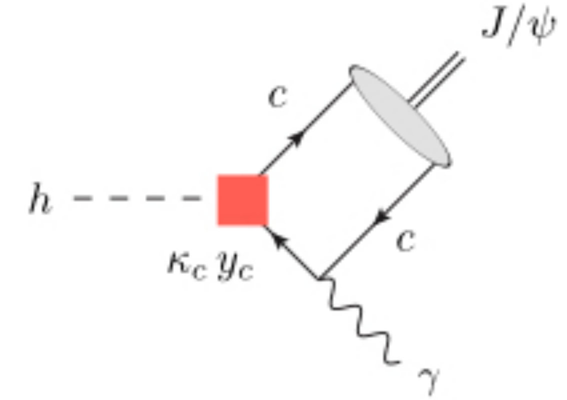
Higgs couplings after Run I



where is the charm Yukawa coupling y_c?

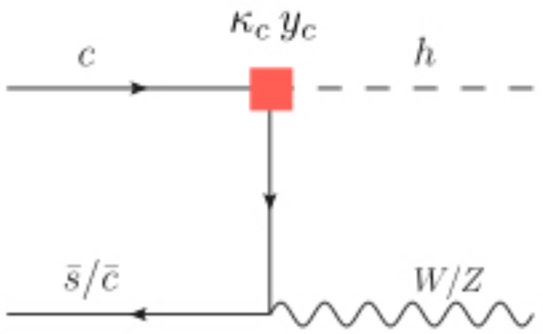
Assortment of Run I bounds on y$_c$

exclusive Higgs decay



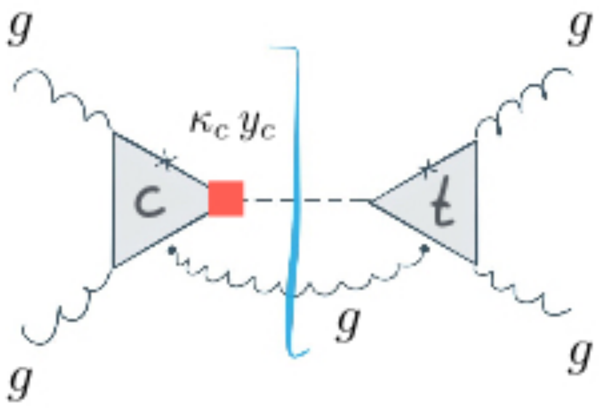
$|\kappa_c| < 429$

Vh production



$|\kappa_c| < 234$

Higgs p$_T$ spectrum

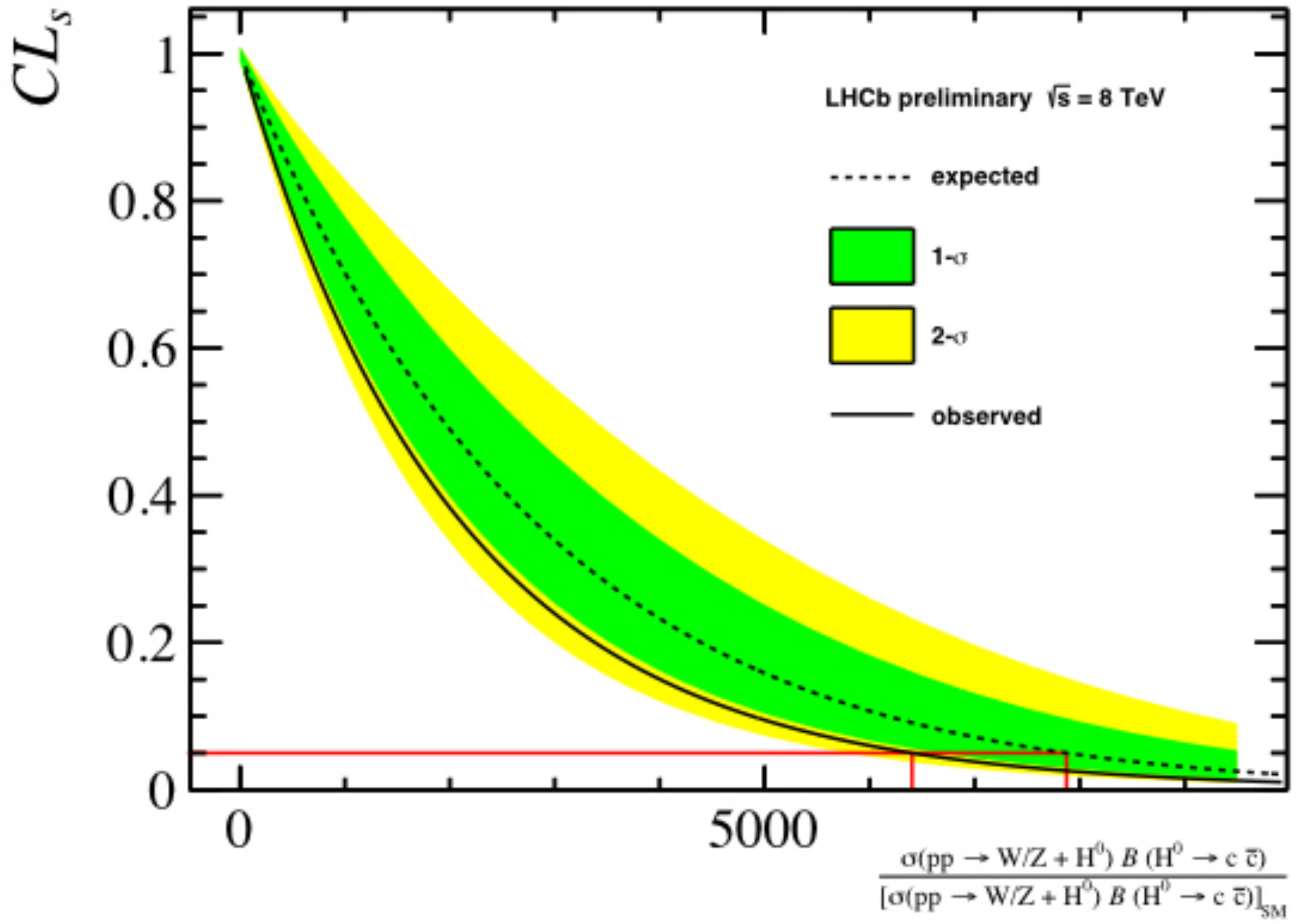


$\kappa_c \in [-16, 18]$

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

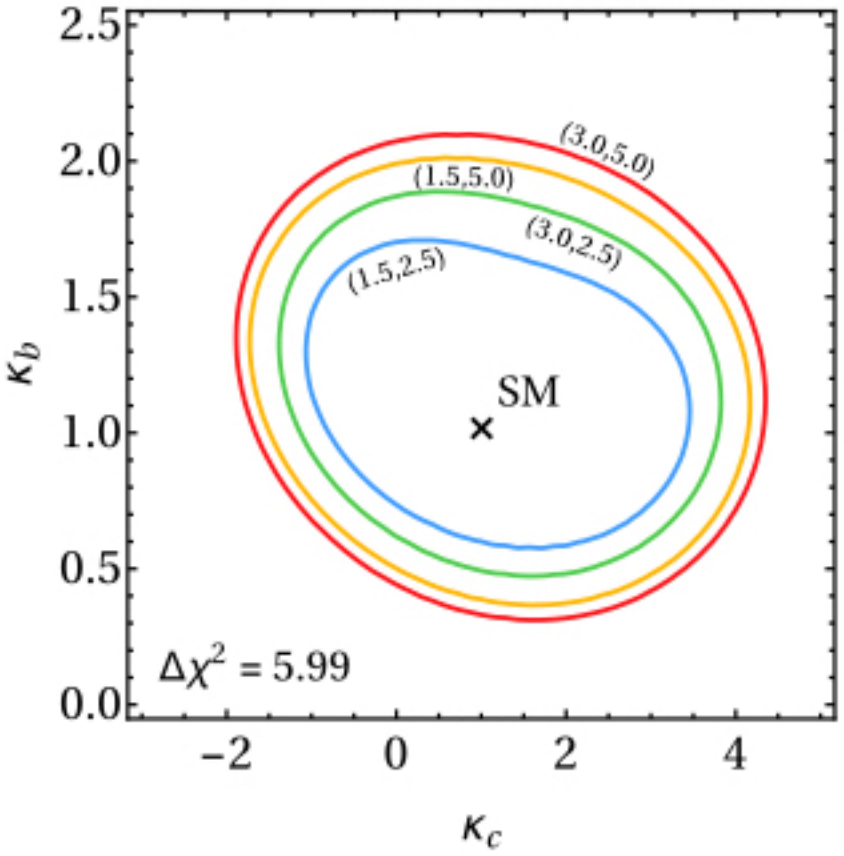


$\longrightarrow \quad |\kappa_c| < 80$

Bound is better as recast of ATLAS & CMS Vh analyses

Perez, Soreq, Stamou & Tobioka, 1503.00290

HL-LHC: constraints on κ_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

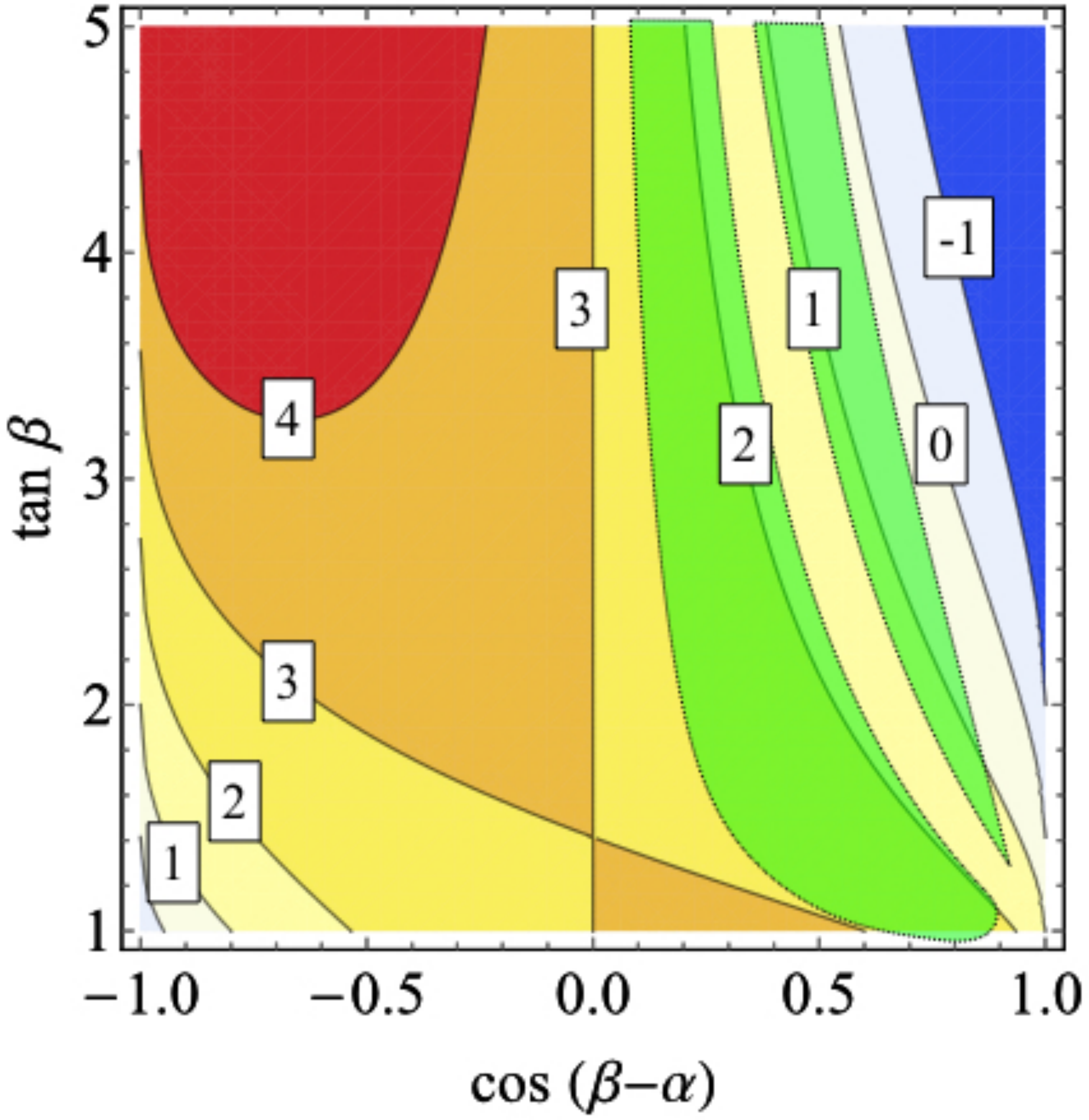
Bishara, UH, Monni & Re, supplemental material to 1606.09253

LHCb Upgrade II: constraints on κ_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

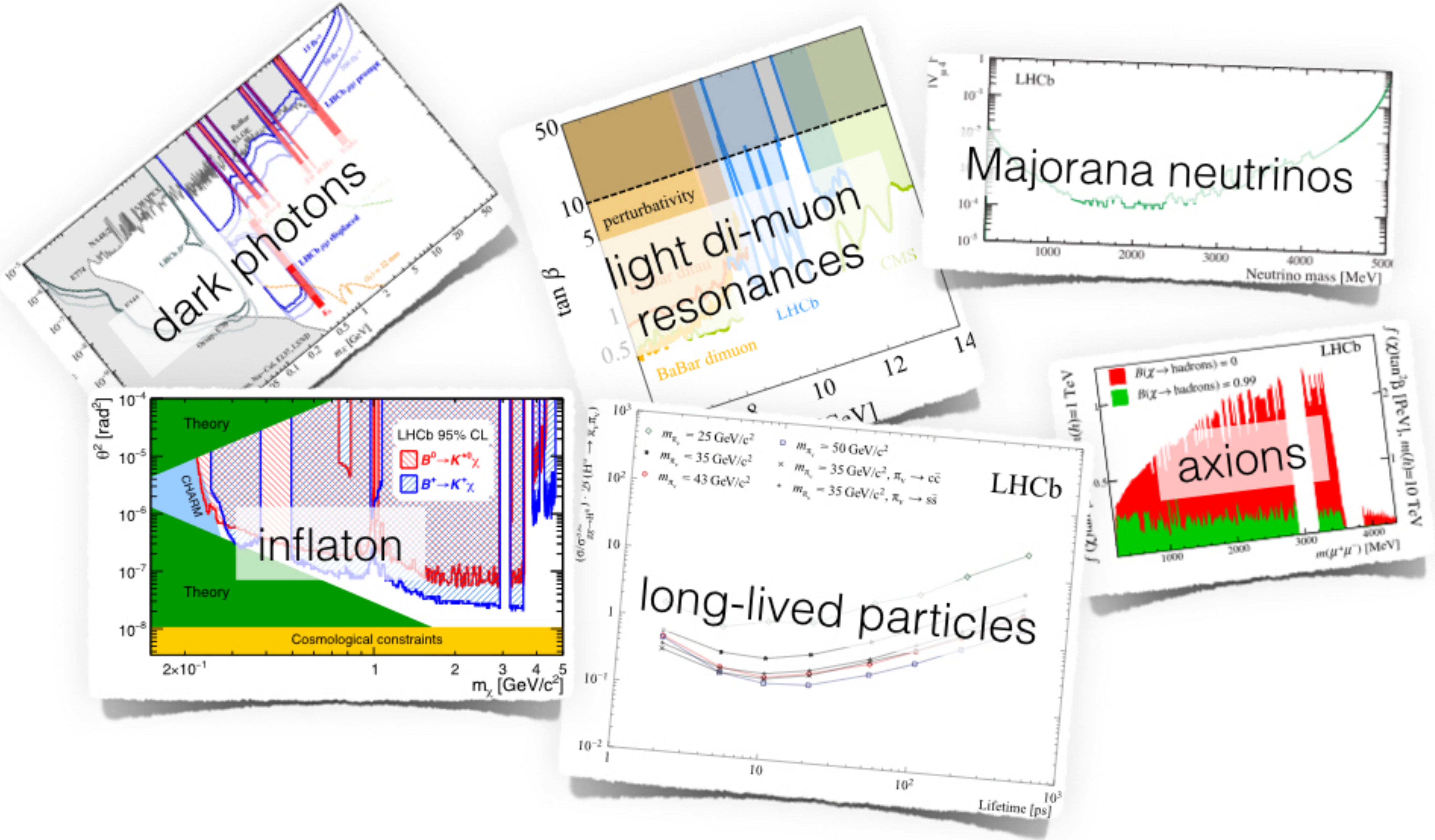
🟩 allowed by global fits to Run I Higgs data

(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

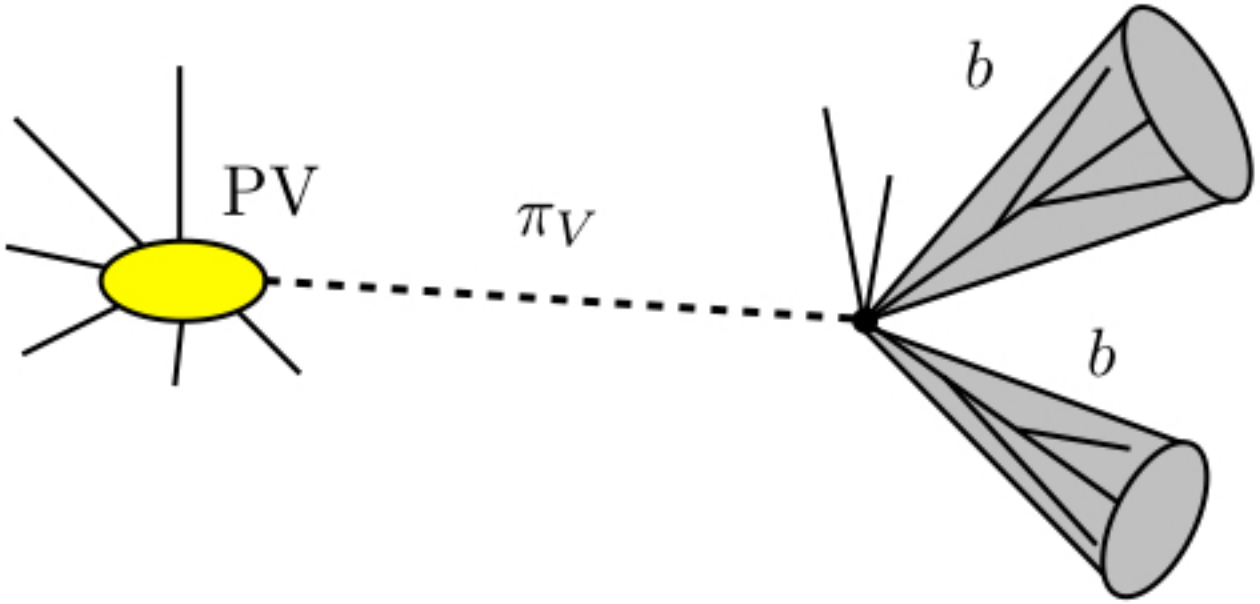


see talk by Mike Williams & backup for light di-muon resonance searches

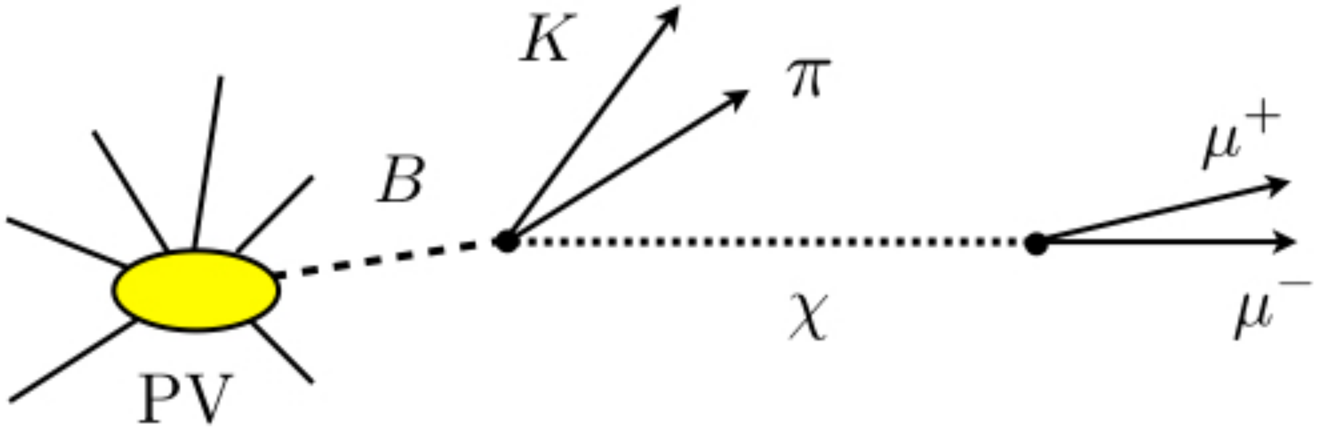
Long-lived particles (LLPs)

LHCb looks for LLPs in:

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



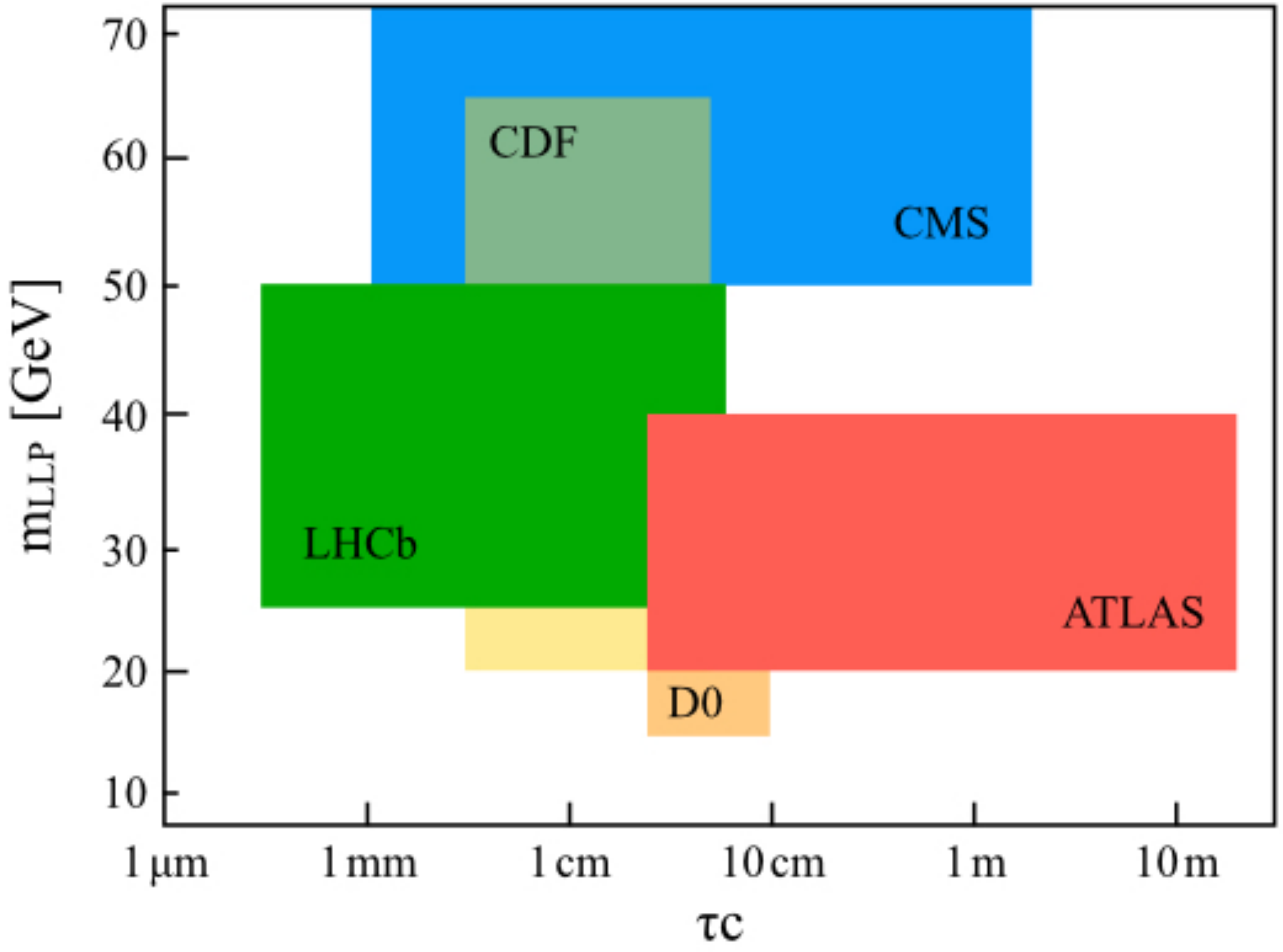
In addition searches for charged massive stable particles using RICH are performed



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

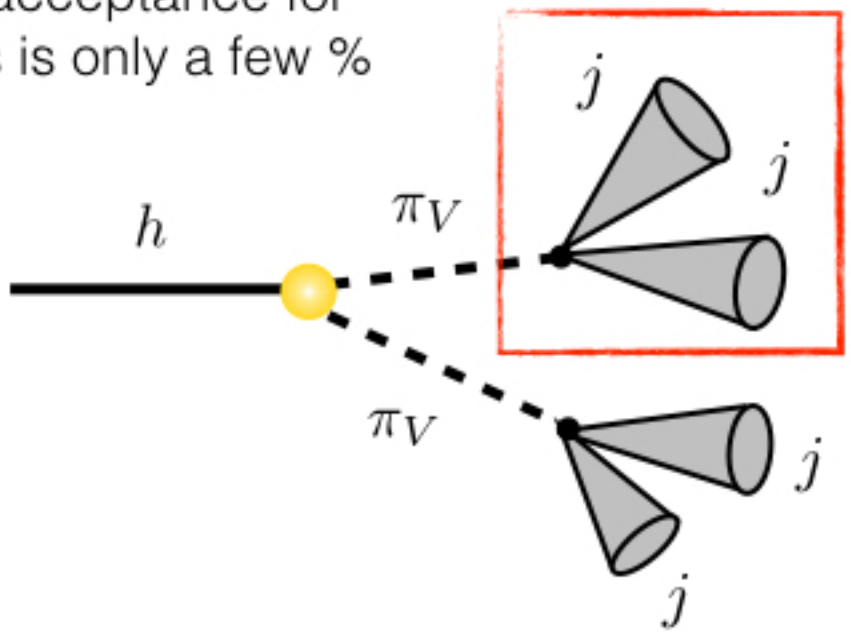
Di-jet searches for LLPs

David, CERN-THESIS-2016-077



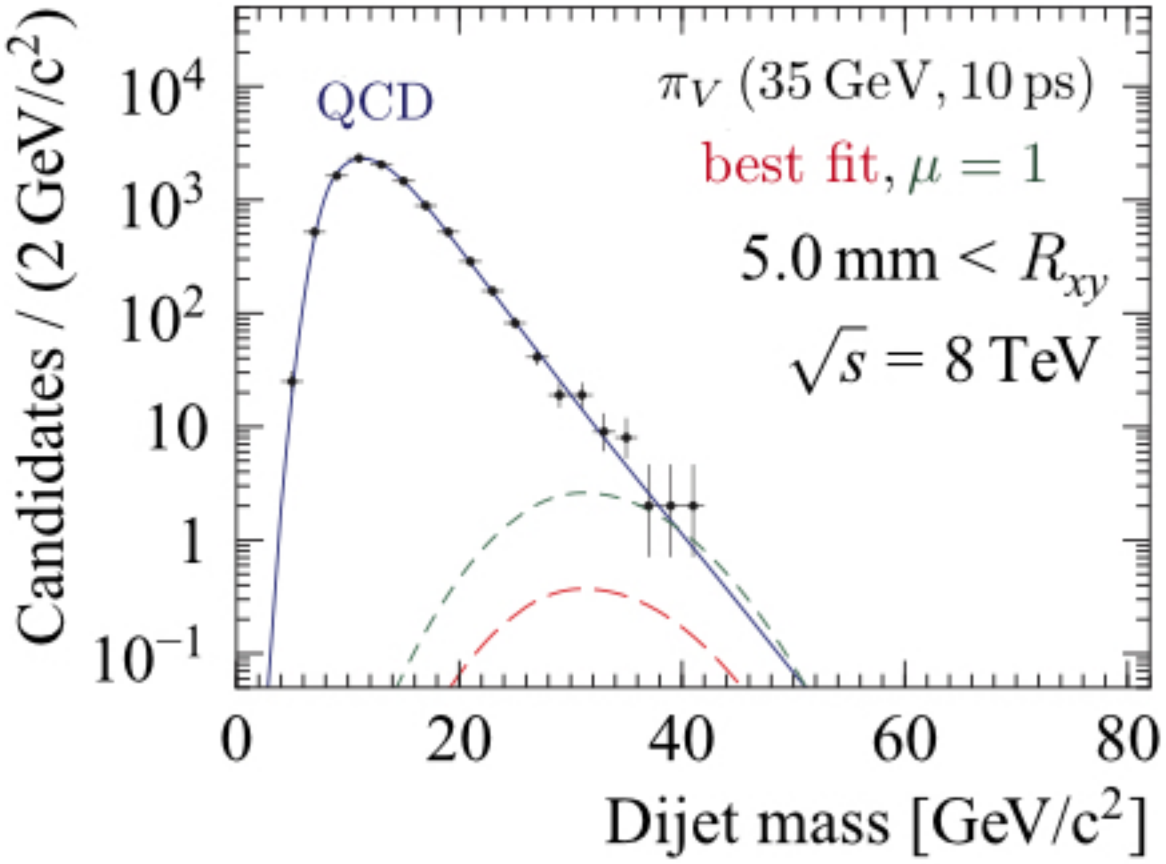
LHCb coverage complementary to ATLAS & CMS: lower lifetimes down to 1ps (excellent vertexing & boost) as well as lower masses down to 25 GeV (soft trigger & forward acceptance)

Displaced Higgs decay



LHCb acceptance for all 4 jets is only a few %

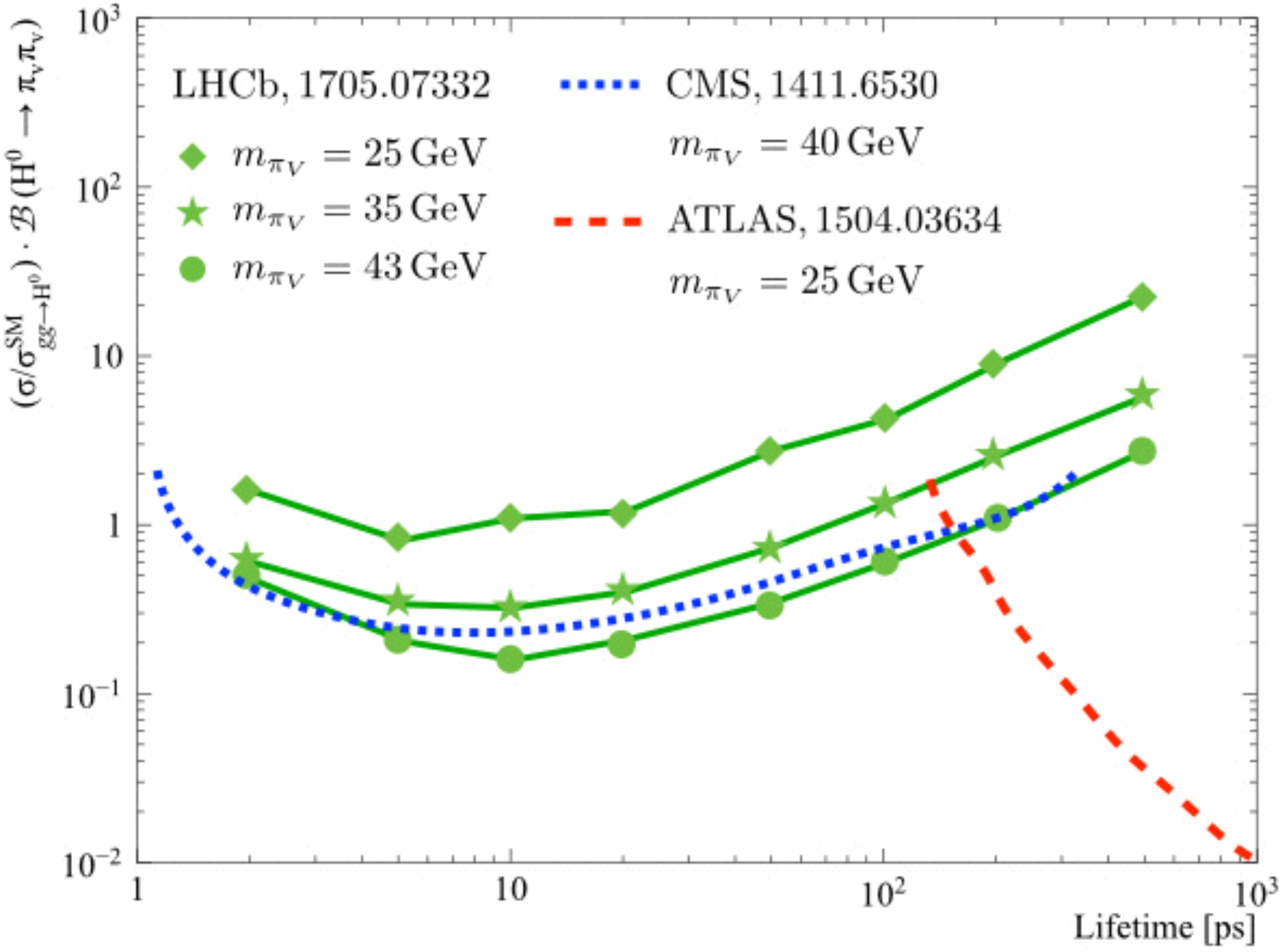
single displaced vertex with 2 jets



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

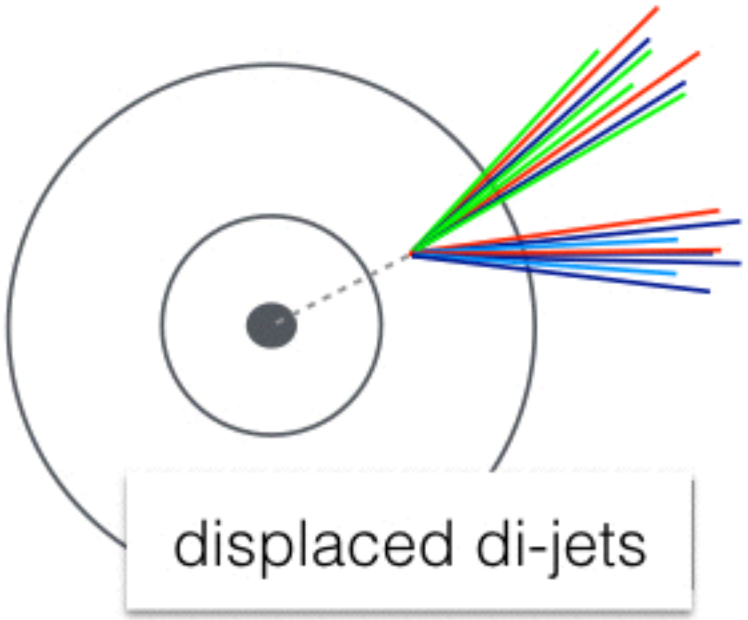


At low lifetimes & masses, LHCb constraints as good as CMS bounds despite lower luminosity & acceptance

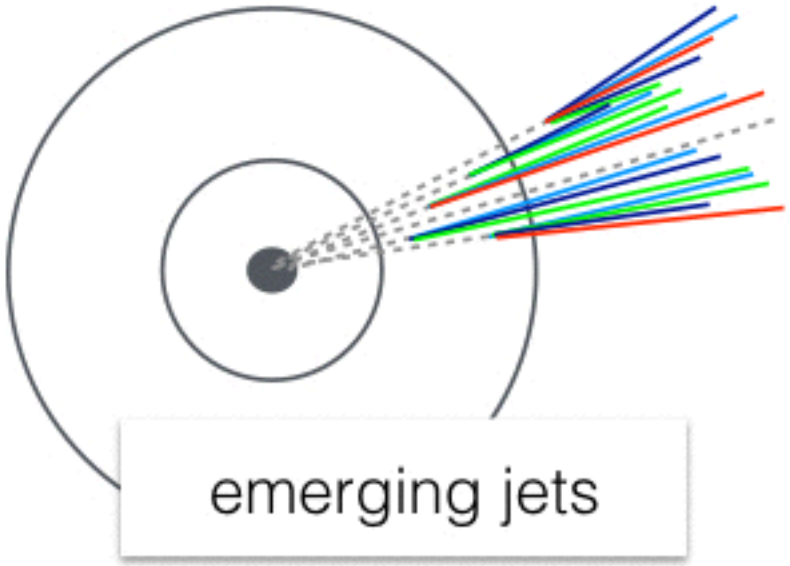
Future: emerging jets

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



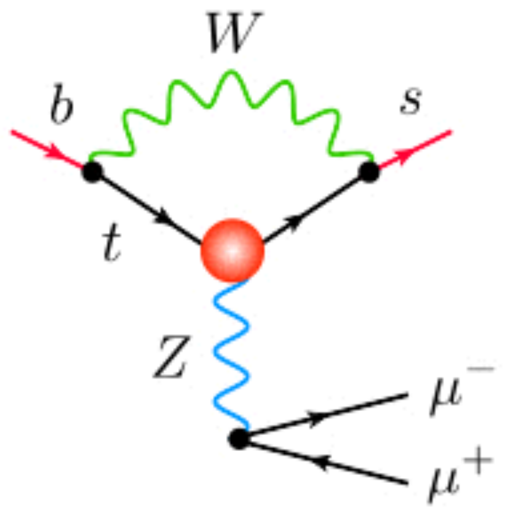
Conclusions

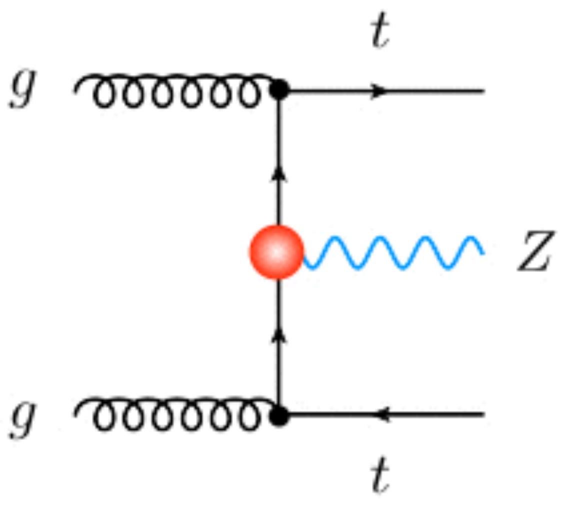
In Run I, LHCb has developed & pursued a wide programme of general physics measurements. Obtained results are often complementary to that of ATLAS & CMS

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 …

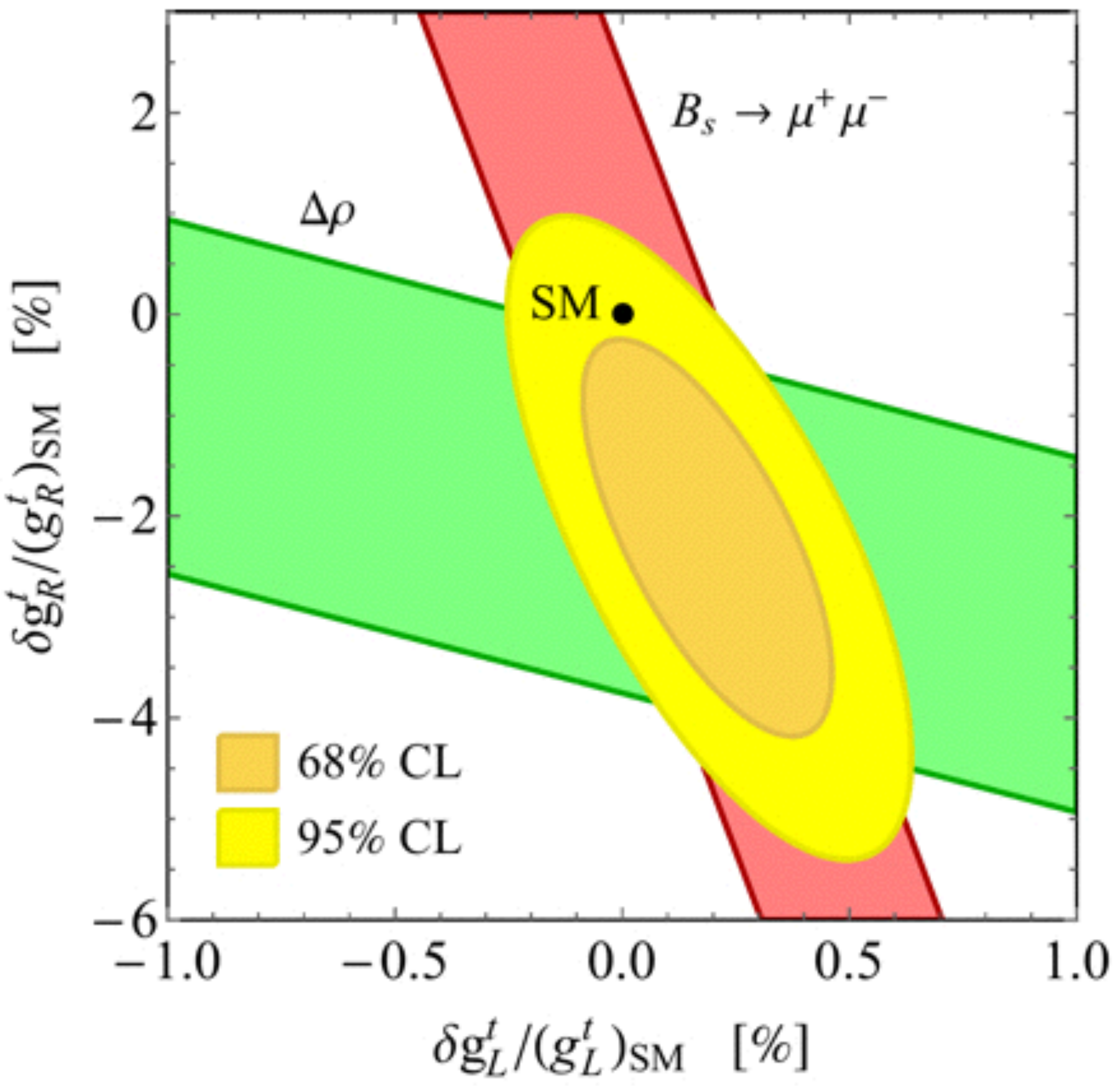
Backup

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





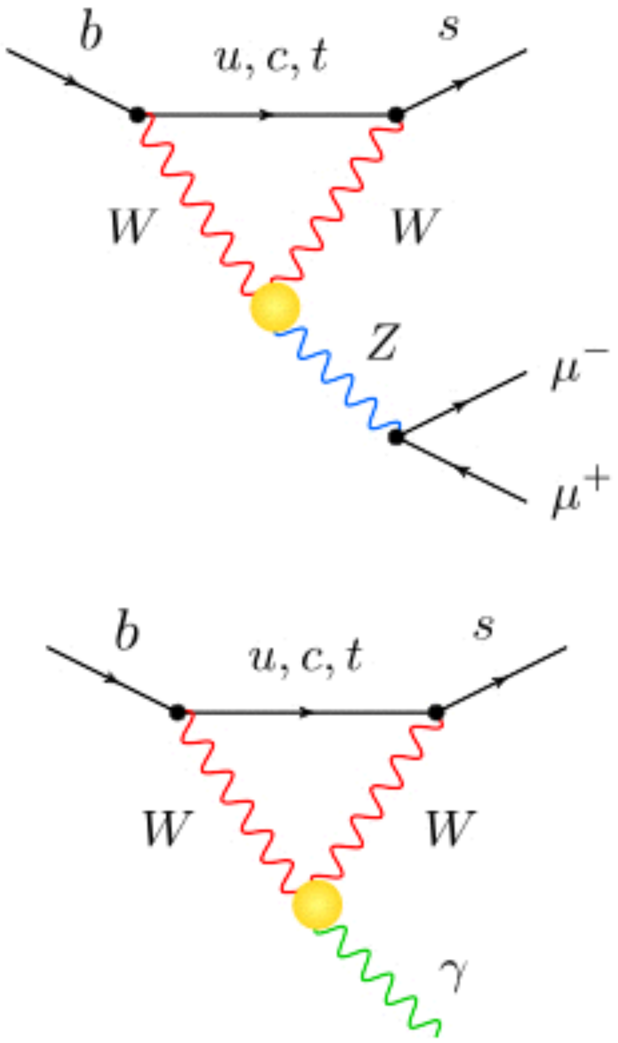
UH based on Brod et al., 1408.0792



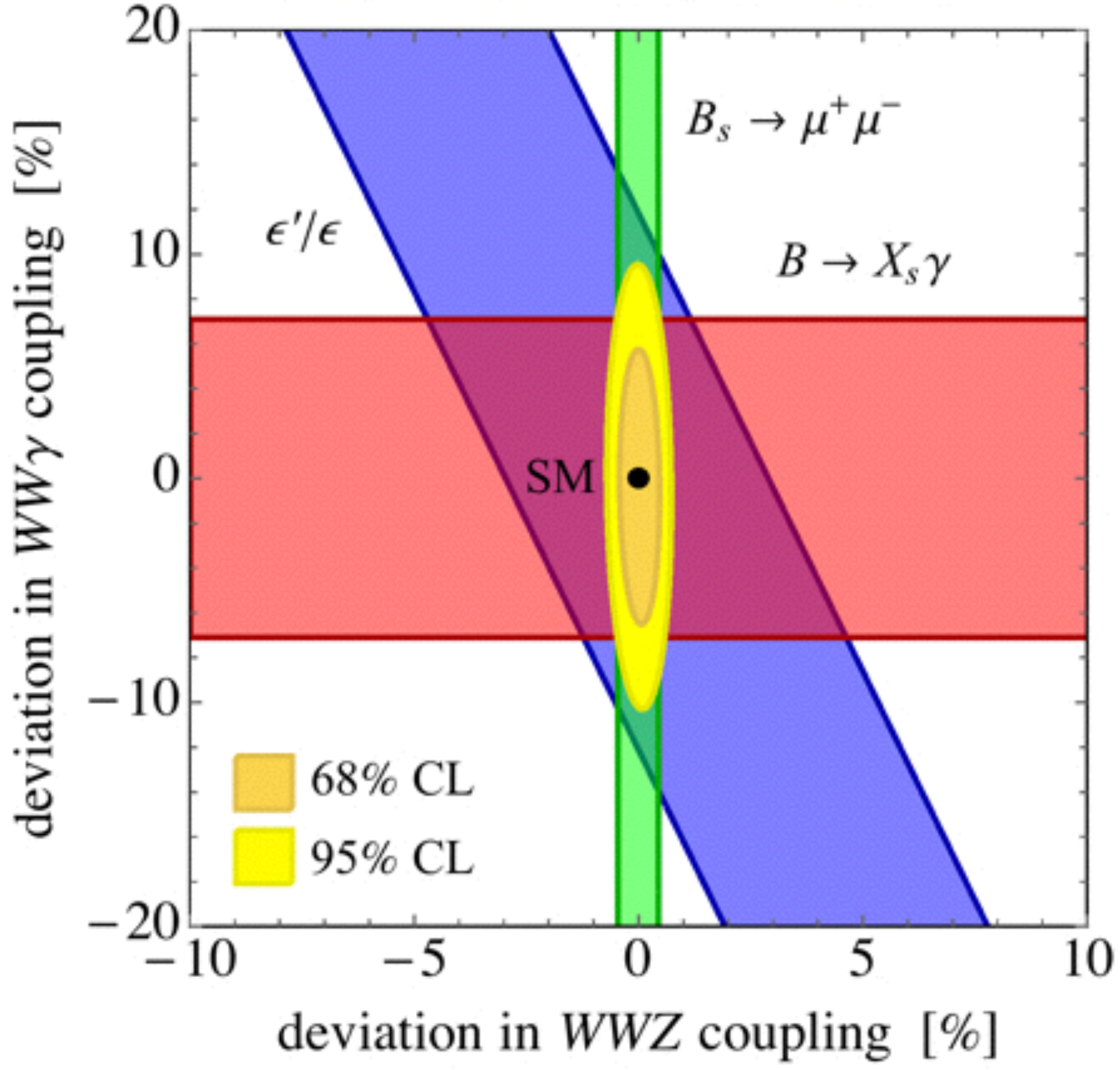
Future $B_s \rightarrow \mu^+\mu^-$ measurements may constrain $Zt\bar{t}$ couplings at few % level. Direct measurements only able to reach O(30%) precision

Röntsch & Schulze, 1404.1005

WWZ/γ couplings from flavour

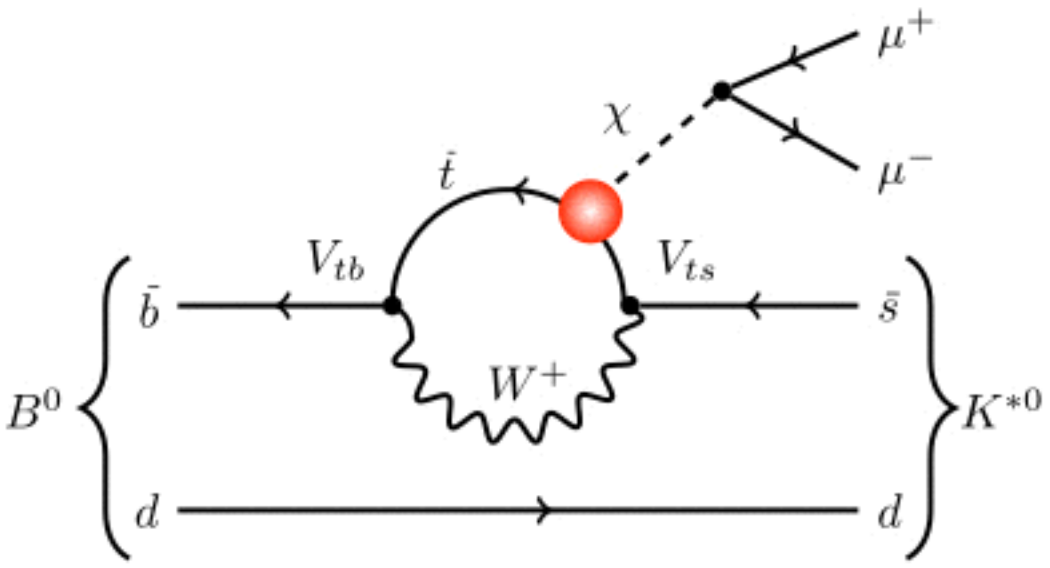


based on Bobeth & UH, 1503.04829

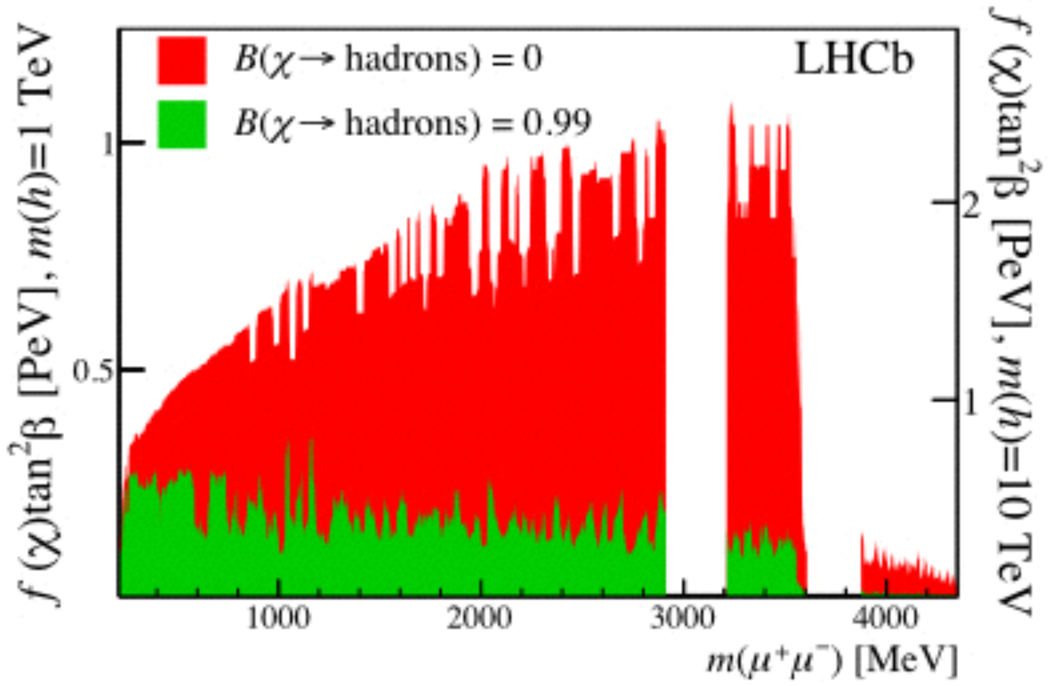


Future $B_s \to \mu^+\mu^-$ measurements can test WWZ coupling with O(1%) precision. Only O(10%) sensitivity in case of WWγ from $B \to X_s\gamma$

Axions in di-muon spectrum



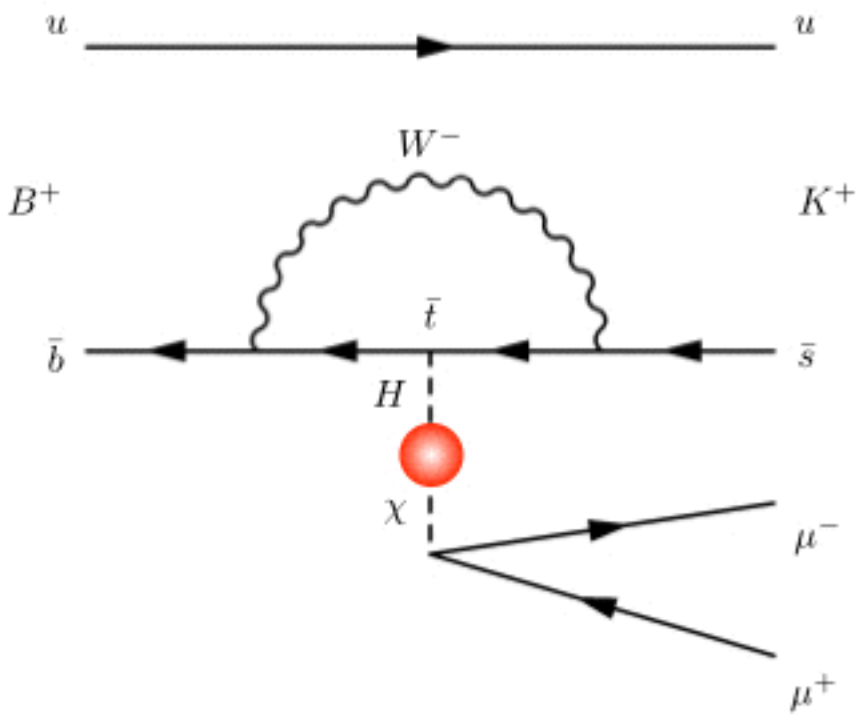
LHCb, 1508.04094



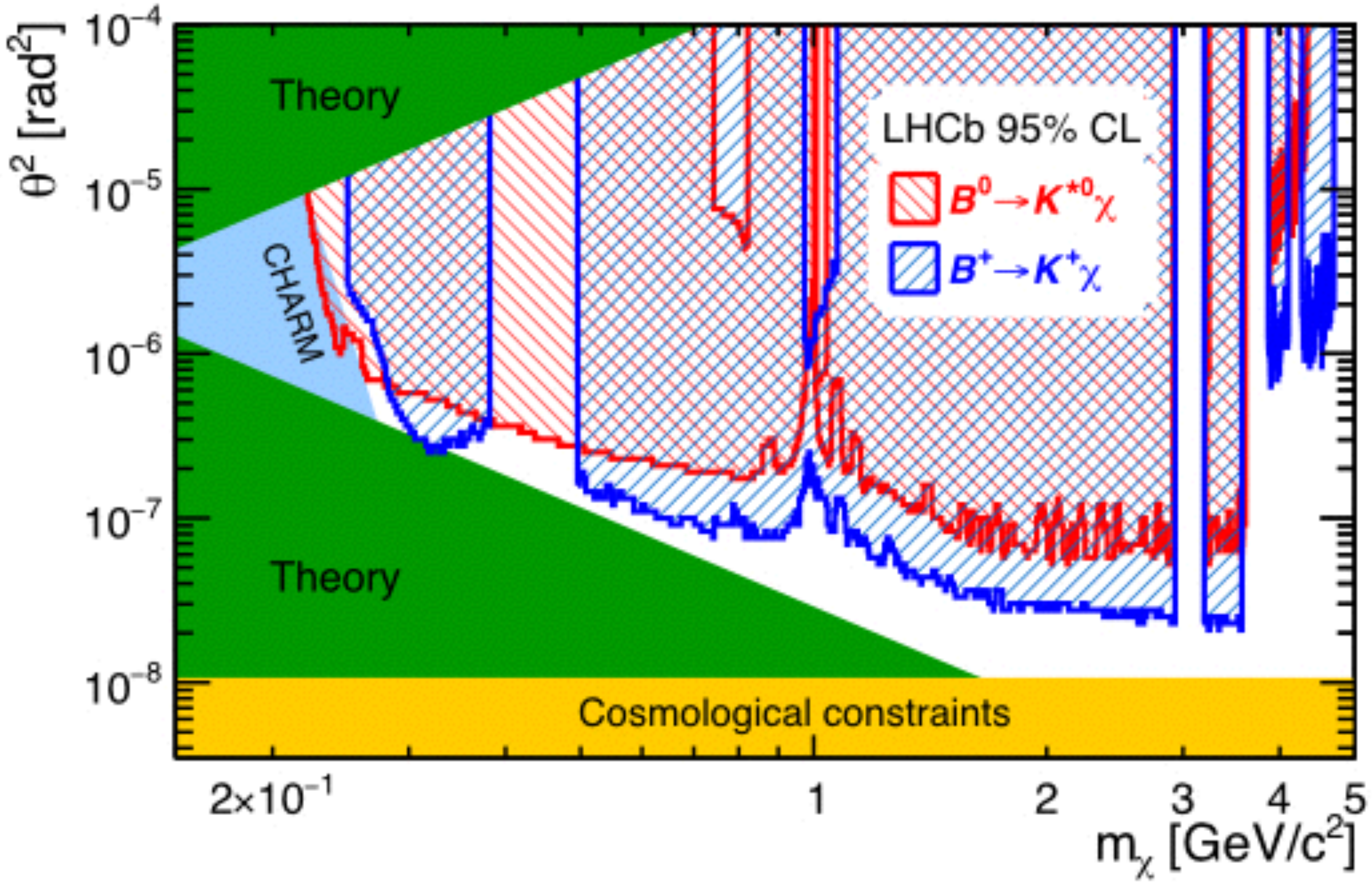
LHCb measurement of di-muon spectrum in B→K*$\mu^+\mu^-$ decay sets strong constraints on axion-top couplings in axion-portal models

Freytsis, Ligeti & Thaler, 0911.5355

Inflatons in di-muon spectrum



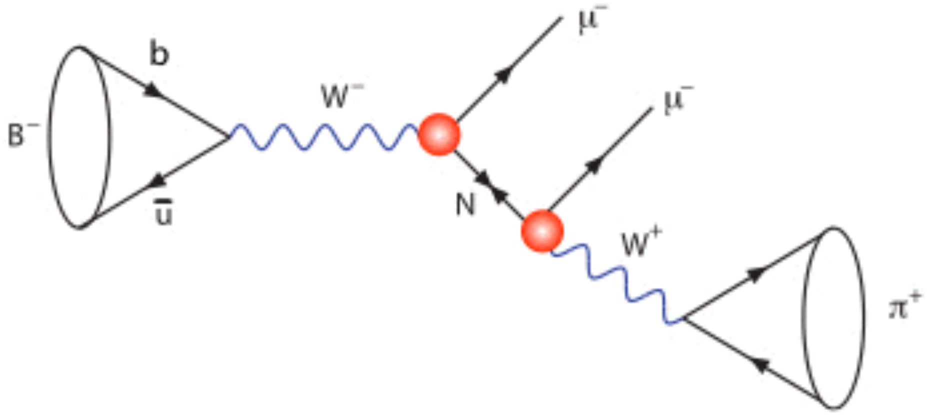
LHCb, 1612.07818



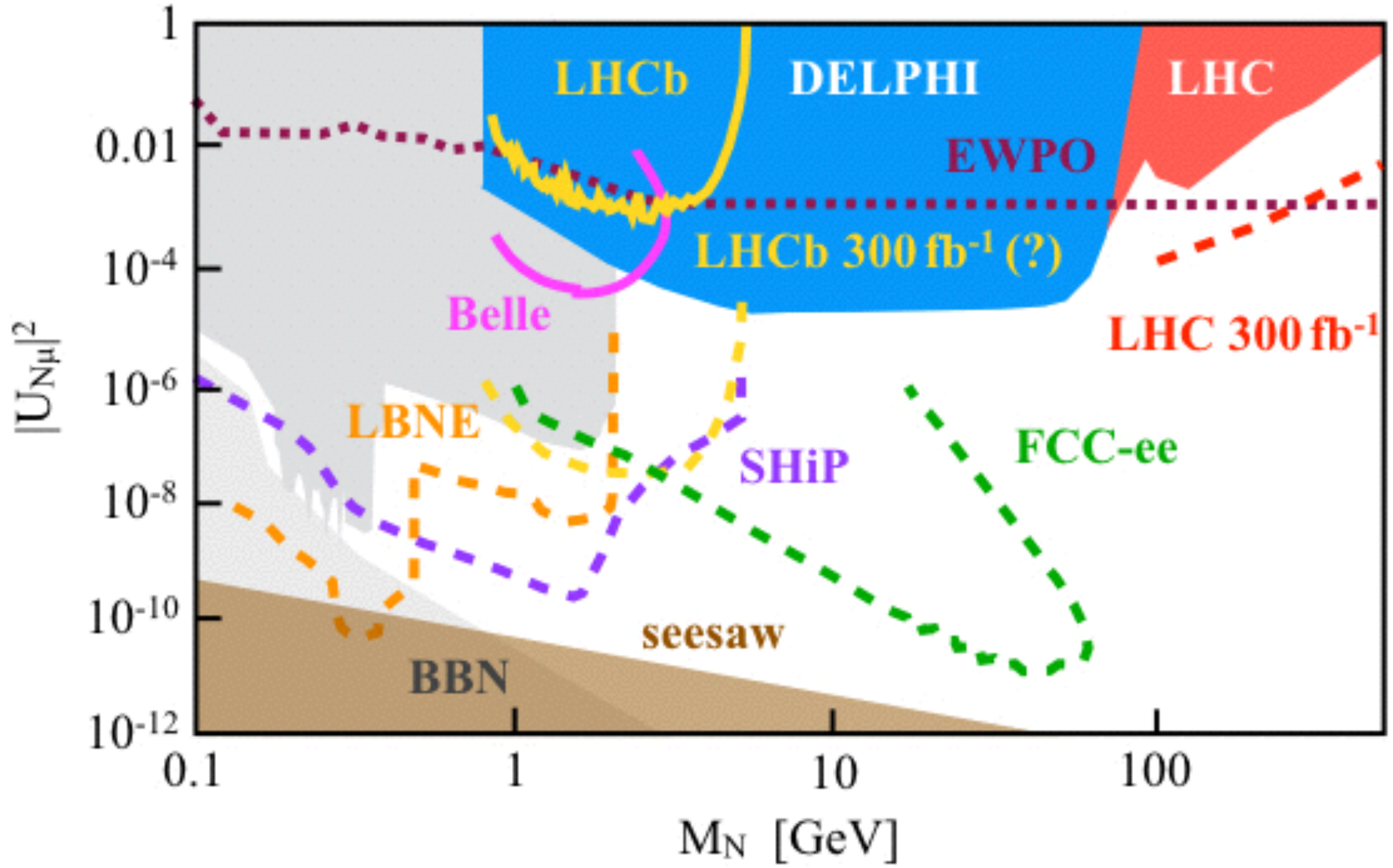
Di-muon spectrum can also be used to severely constrain GeV-mass scalar particles such as an inflaton if it mixes with SM Higgs boson

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

Majorana neutrinos



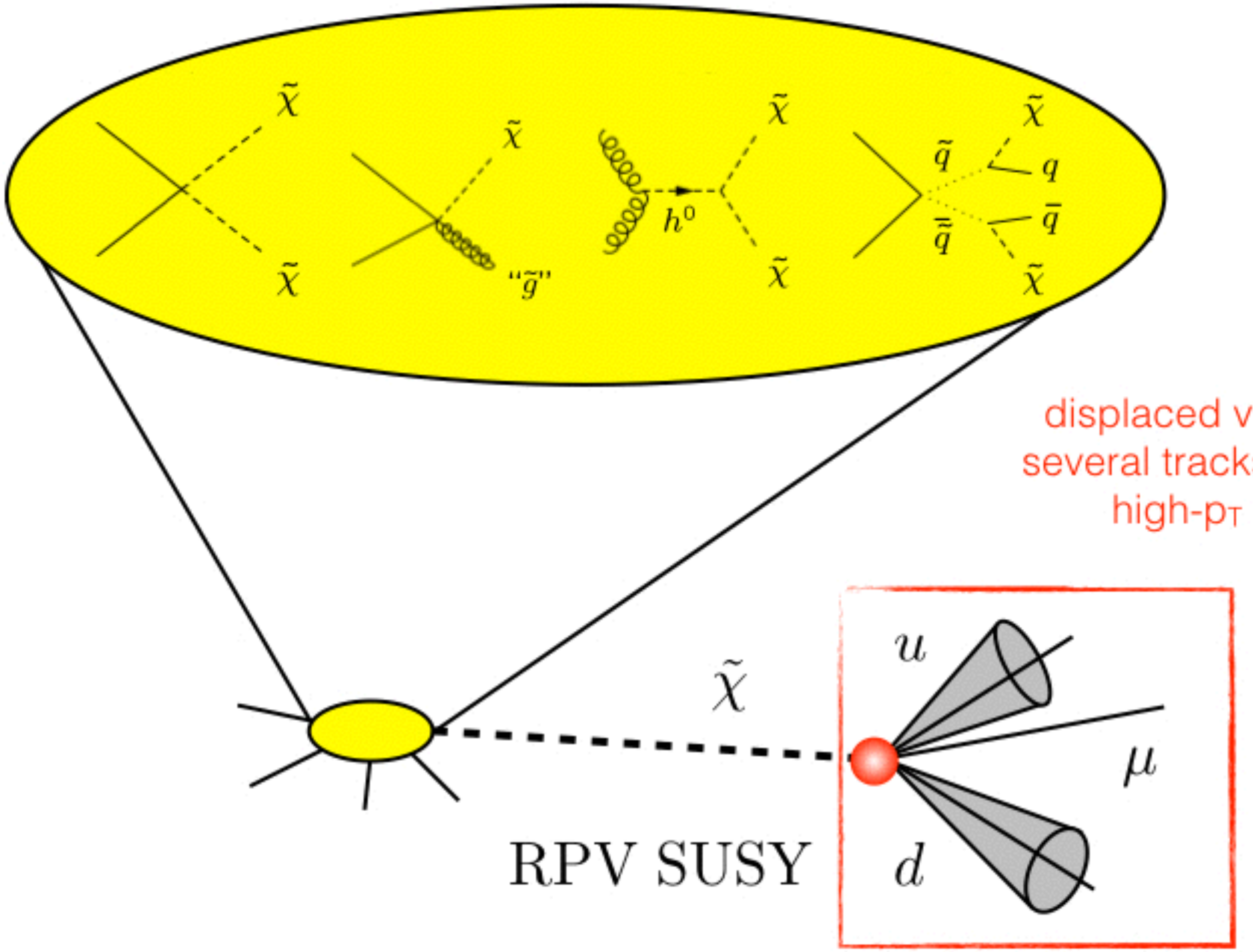
UH update of SHiP physics case, 1504.04855



LHCb Run I search for B$^{\pm}\rightarrow\pi^{\pm}\mu^{+}\mu^{-}$ 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

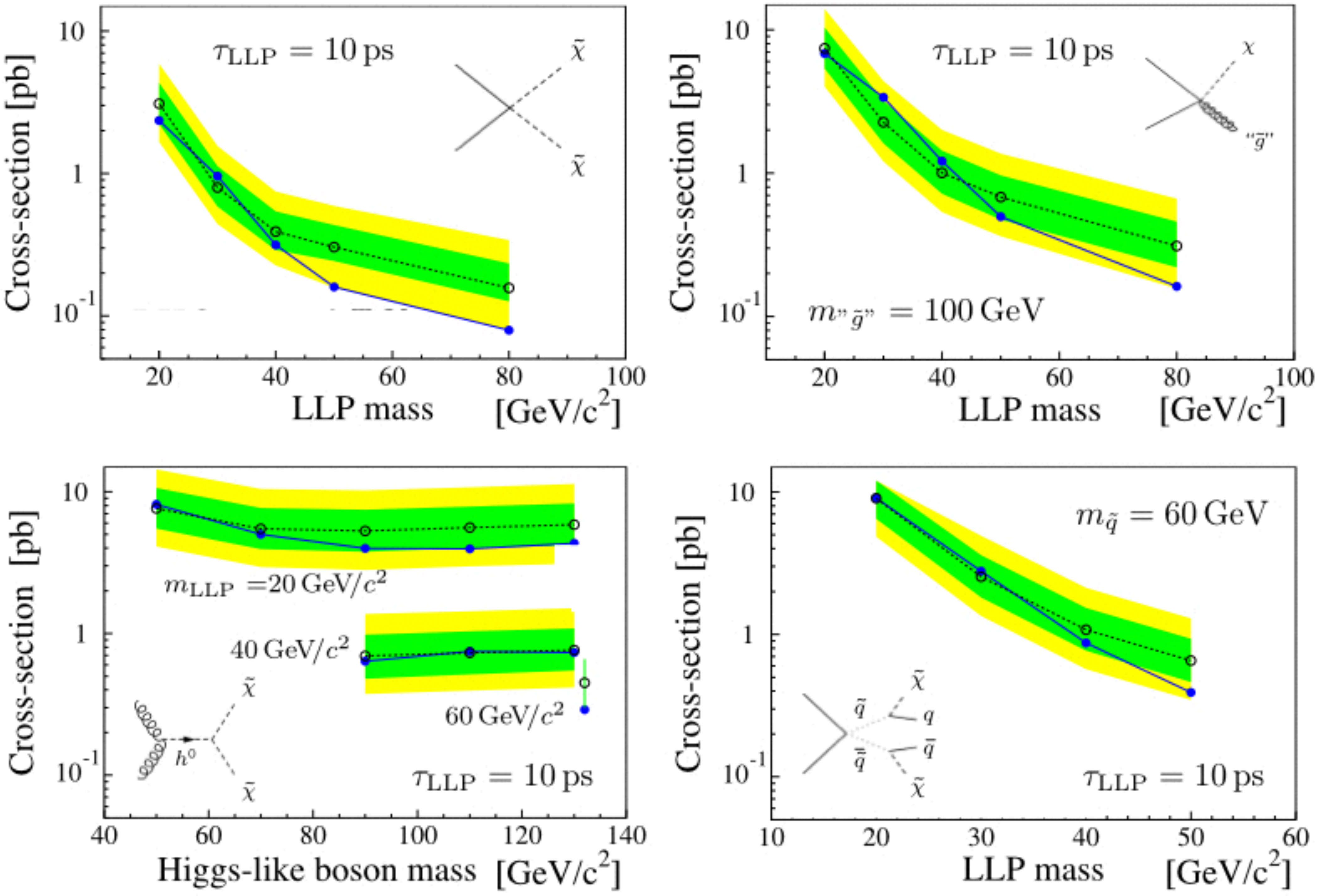
LLPs in muon plus jets channel



displaced vertex with several tracks including high-p_T muon

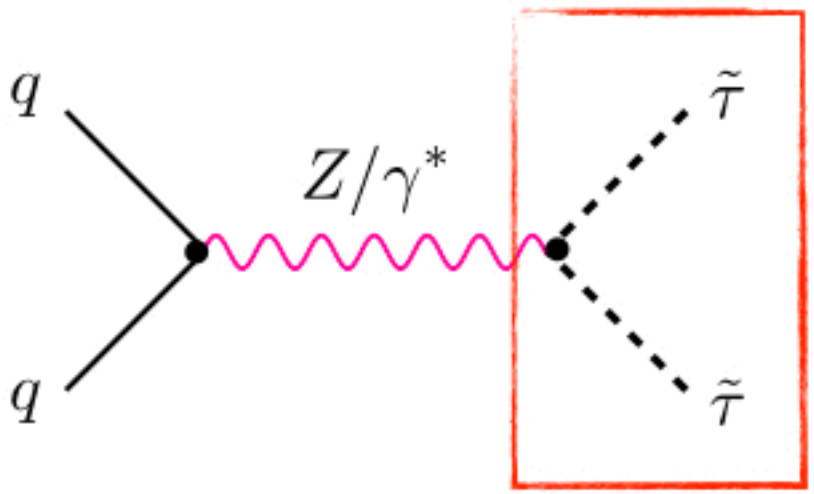
LHCb, 1612.00945

LLPs in muon plus jets channel

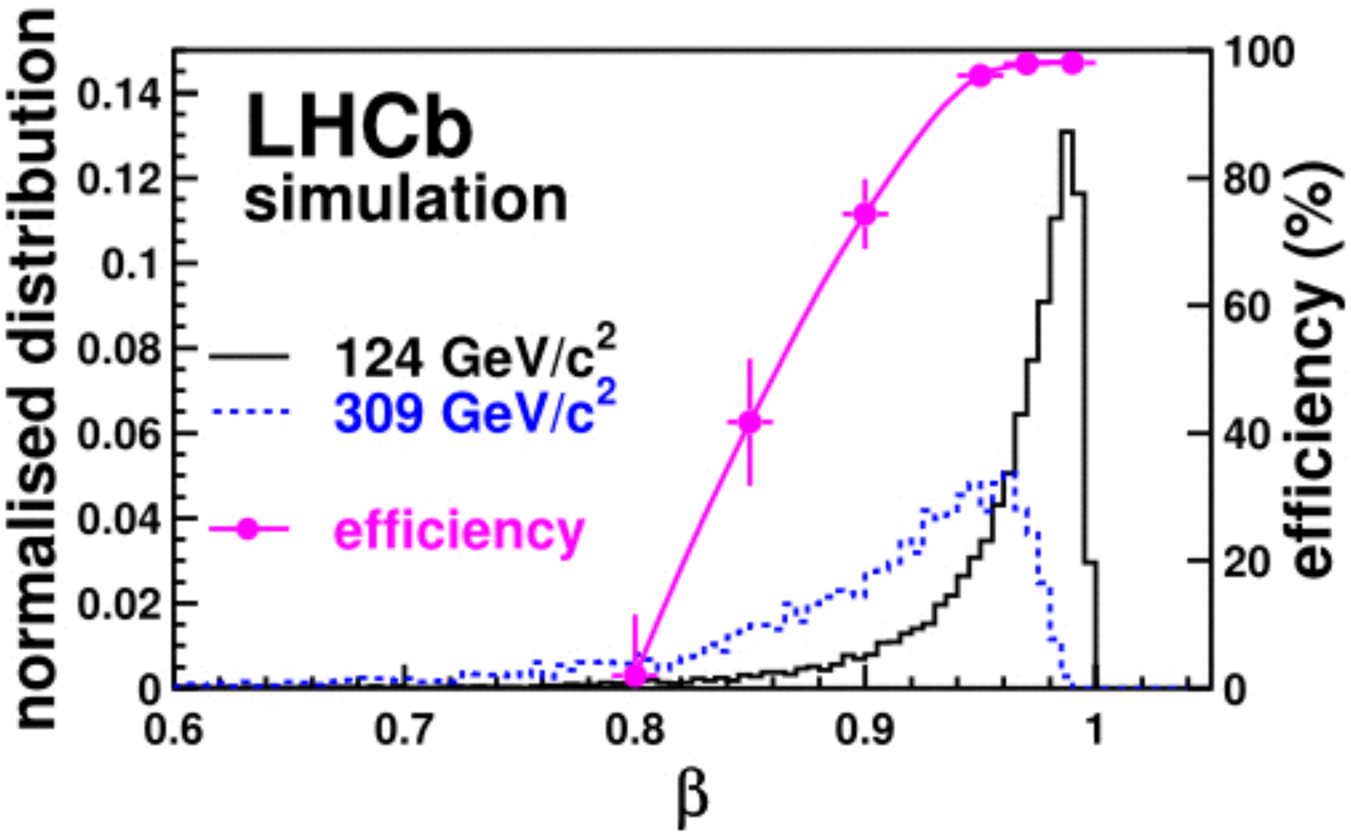


LHCb, 1612.00945

Charged massive stable particles



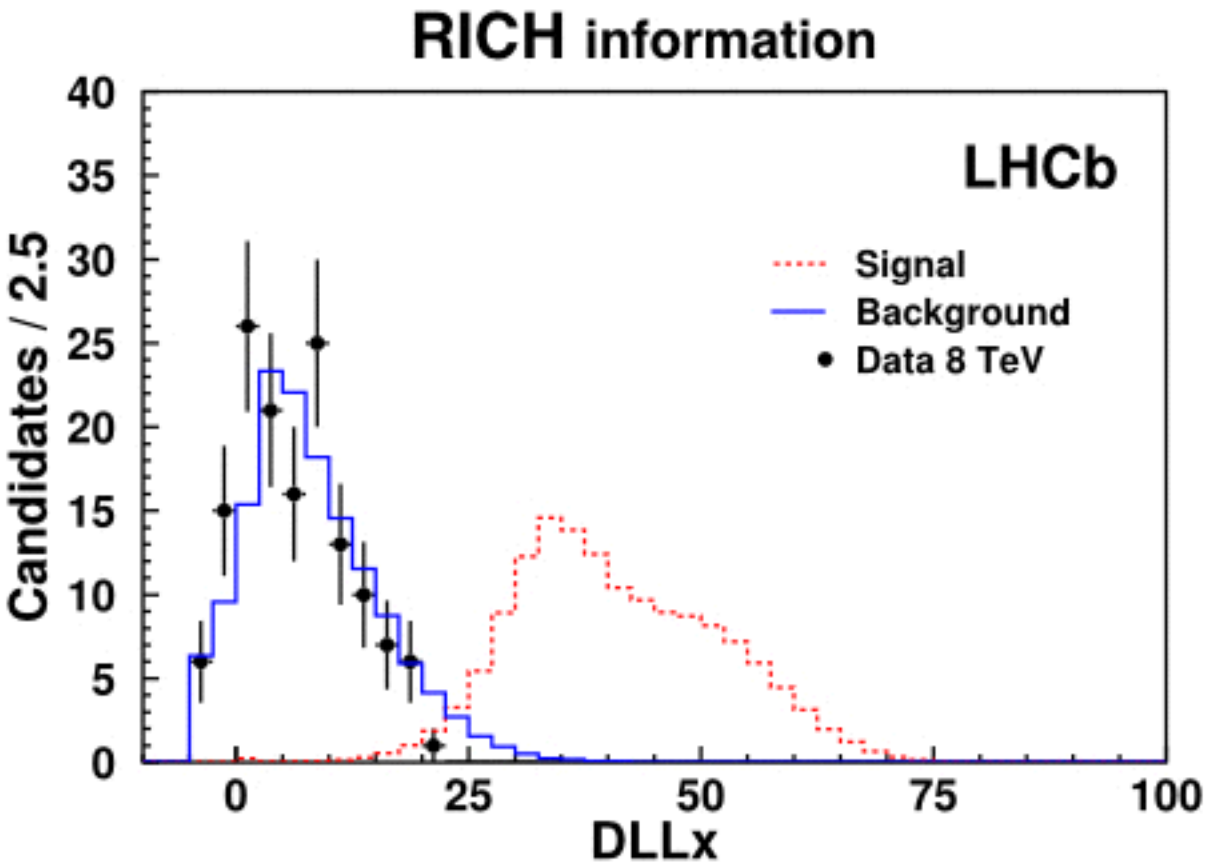
long-lived stau, possibly NLSP in mGMSB

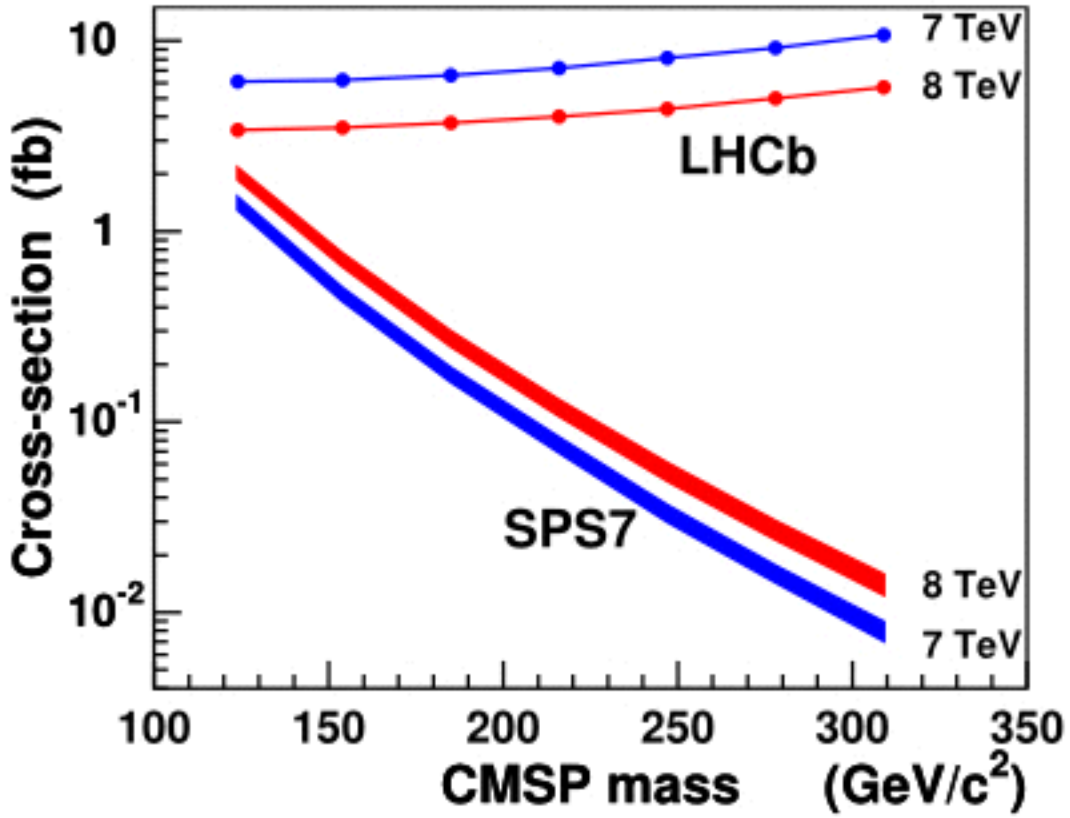


Charged massive stable particles produced with relatively low velocity & can be identified by their longer time-of-flight, their energy loss (ionisation) & absence of Cherenkov radiation

LHCb, 1506.09173

Charged massive stable particles





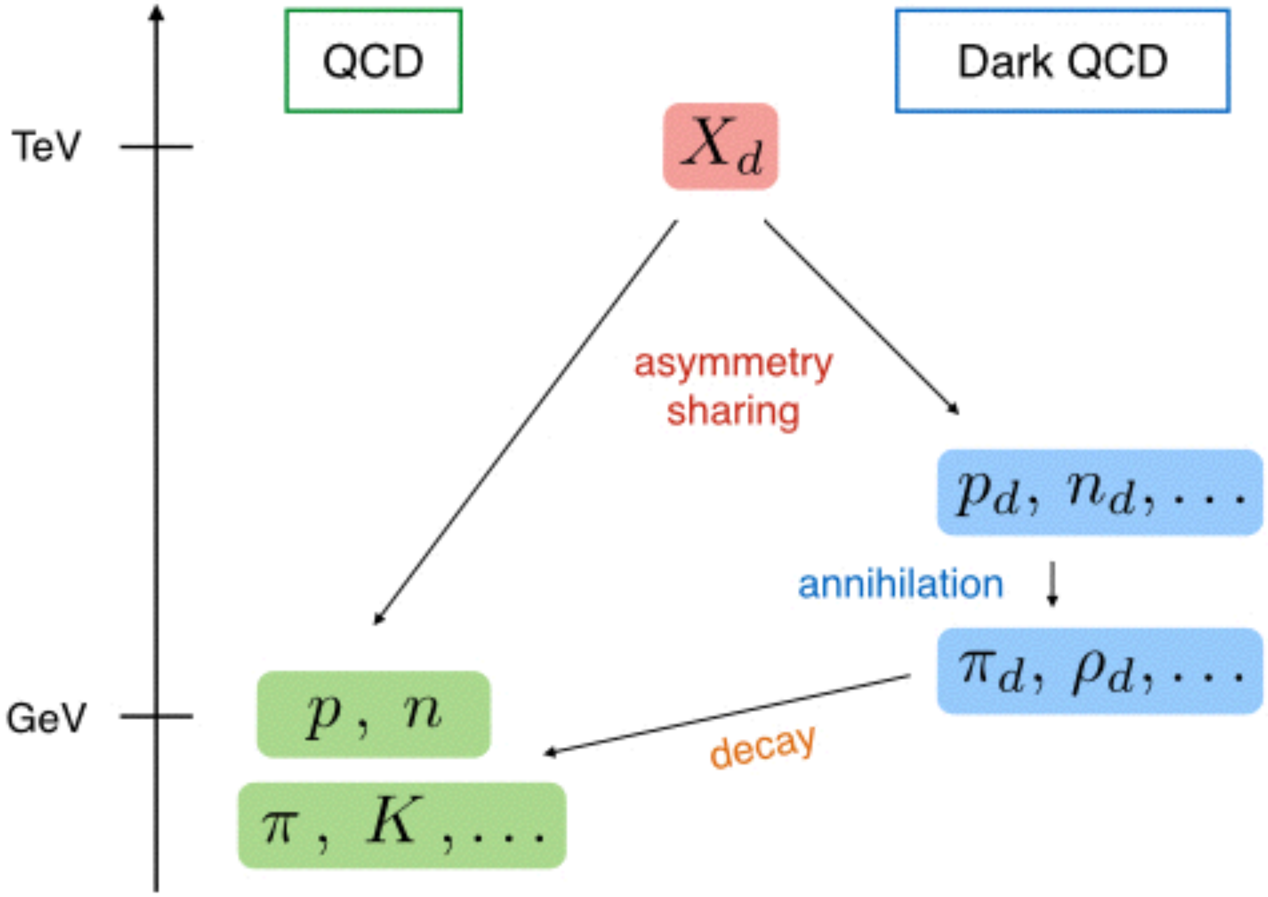
Select pair of muon-like tracks in mass range [120, 300] GeV. Neural network used to combine RICH information with energy loss from VELO & calorimeters. Existing LHCb limits not competitive with D0 (low mass) & ATLAS (high mass)

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

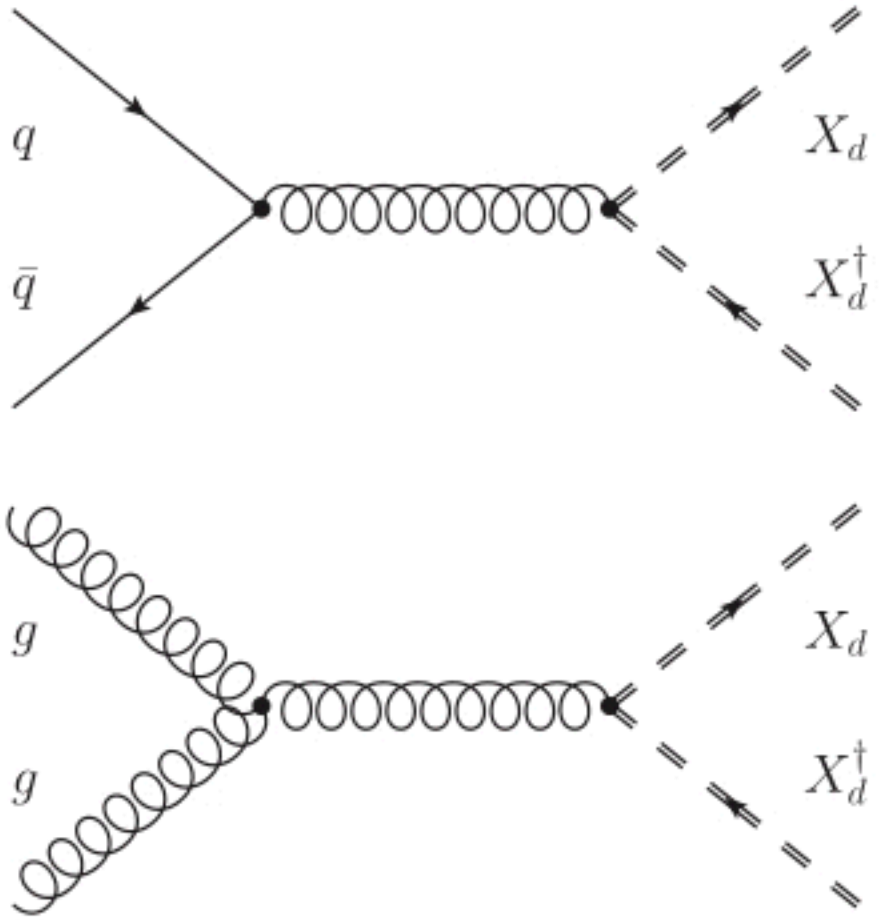
Dark pions are Goldstone bosons of $n_f \times n_f$ dark flavour symmetry. They decay to down-type quarks with centimeter to meter decay lengths:

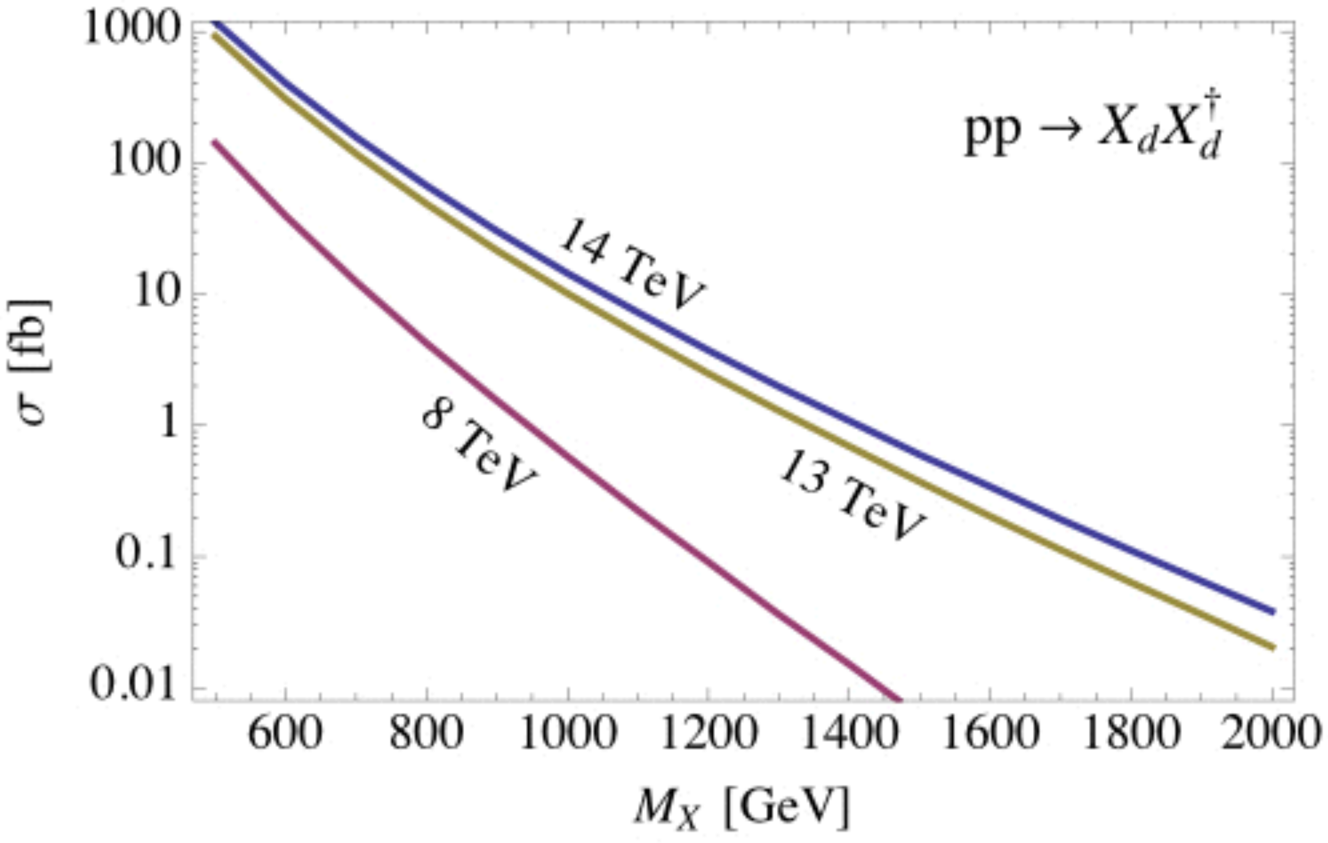
$$\Gamma(\pi_d \to \bar{d}d) = \frac{\kappa^4 N_c f_{\pi_d}^2 m_{\text{down}}^2}{32\pi M_{X_d}^4} m_{\pi_d}$$

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

Schwaller, Stolarski & Weiler, 1502.05409

Emerging jets: mediator production

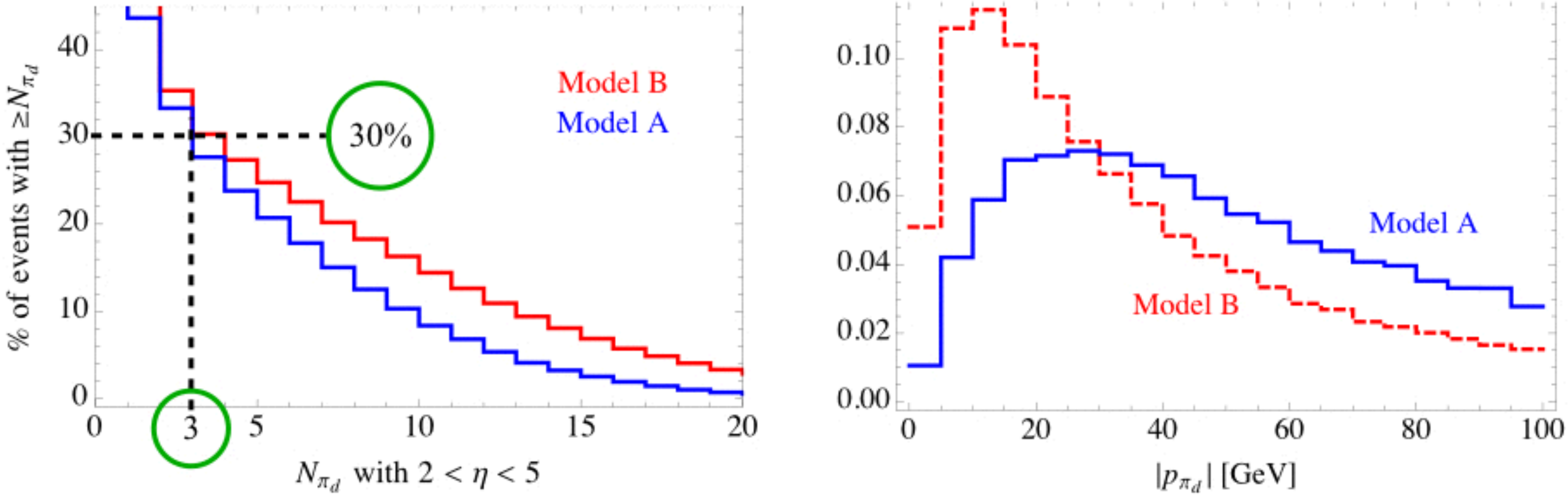




Schwaller, Stolarski & Weiler, 1502.05409

Dark pion searches at LHCb

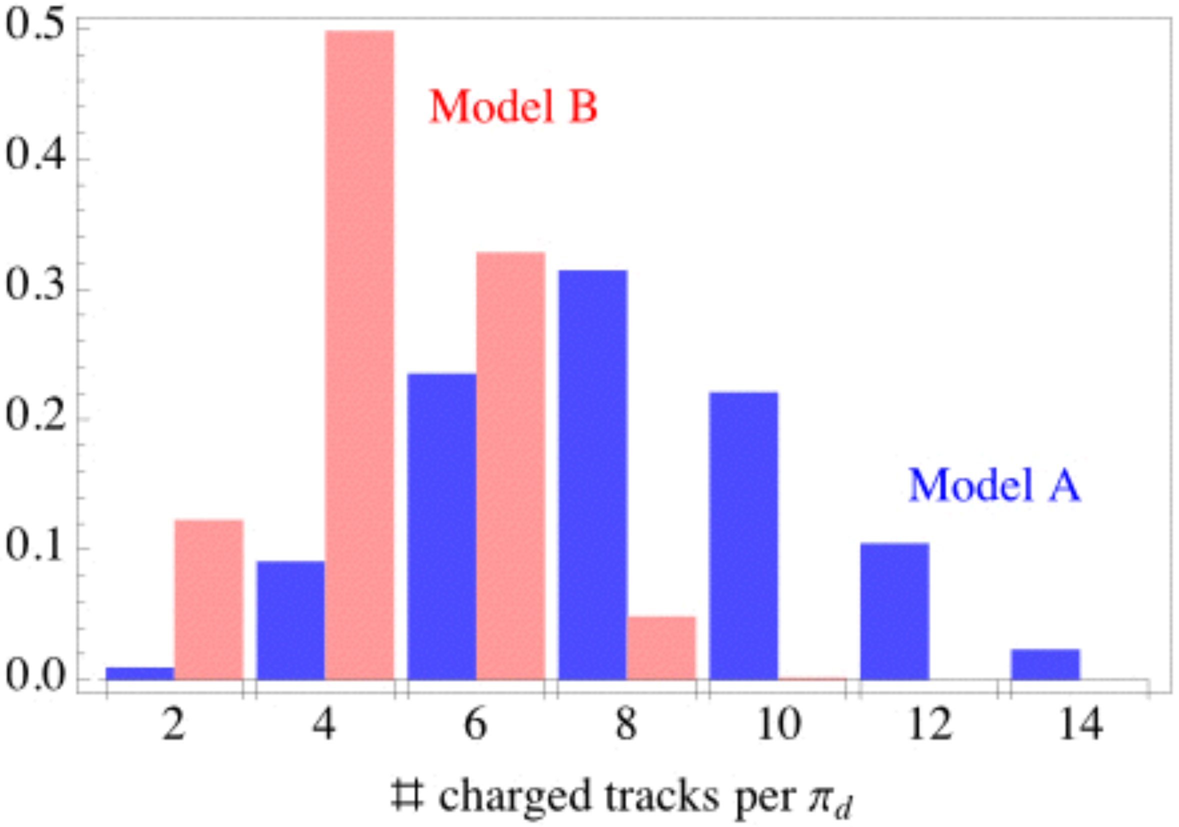
$$\sigma(pp \to \bar{Q}_d Q_d) \approx (8.2\ \text{pb}) \times N_d \times n_f \times \left(\frac{\text{TeV}}{\Lambda}\right)^4$$



Schwaller, Stolarski & Weiler, 1502.05409

Dark pion searches at LHCb

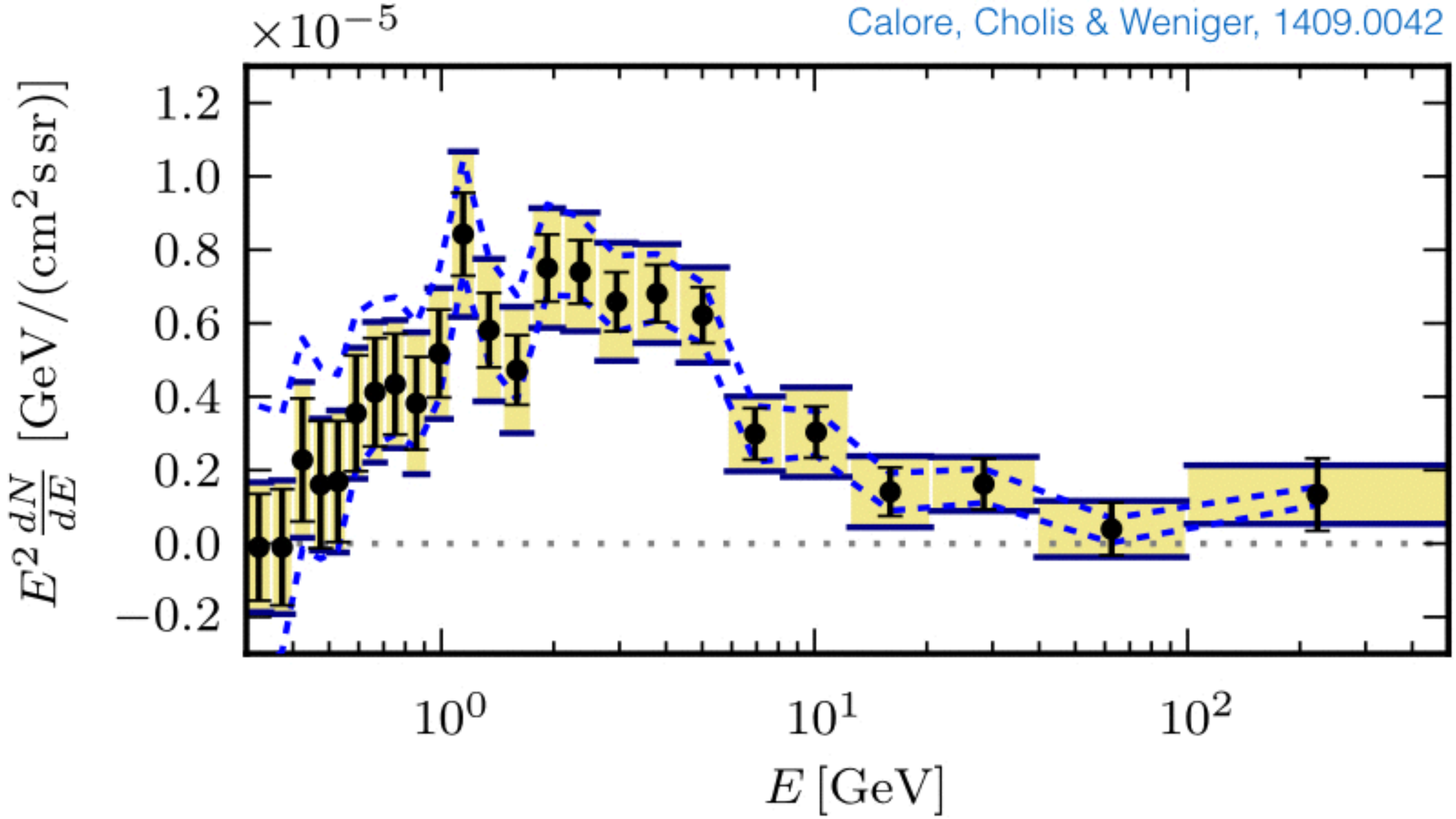
	Model **A**	Model **B**
Λ_d	10 GeV	4 GeV
m_V	20 GeV	8 GeV
m_{π_d}	5 GeV	2 GeV
$c\,\tau_{\pi_d}$	150 mm	5 mm



Number of tracks of O(10) for m_{π_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

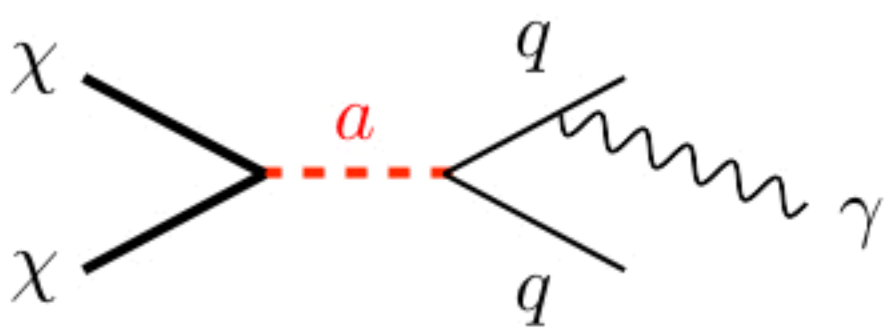
Fermi-LAT excess

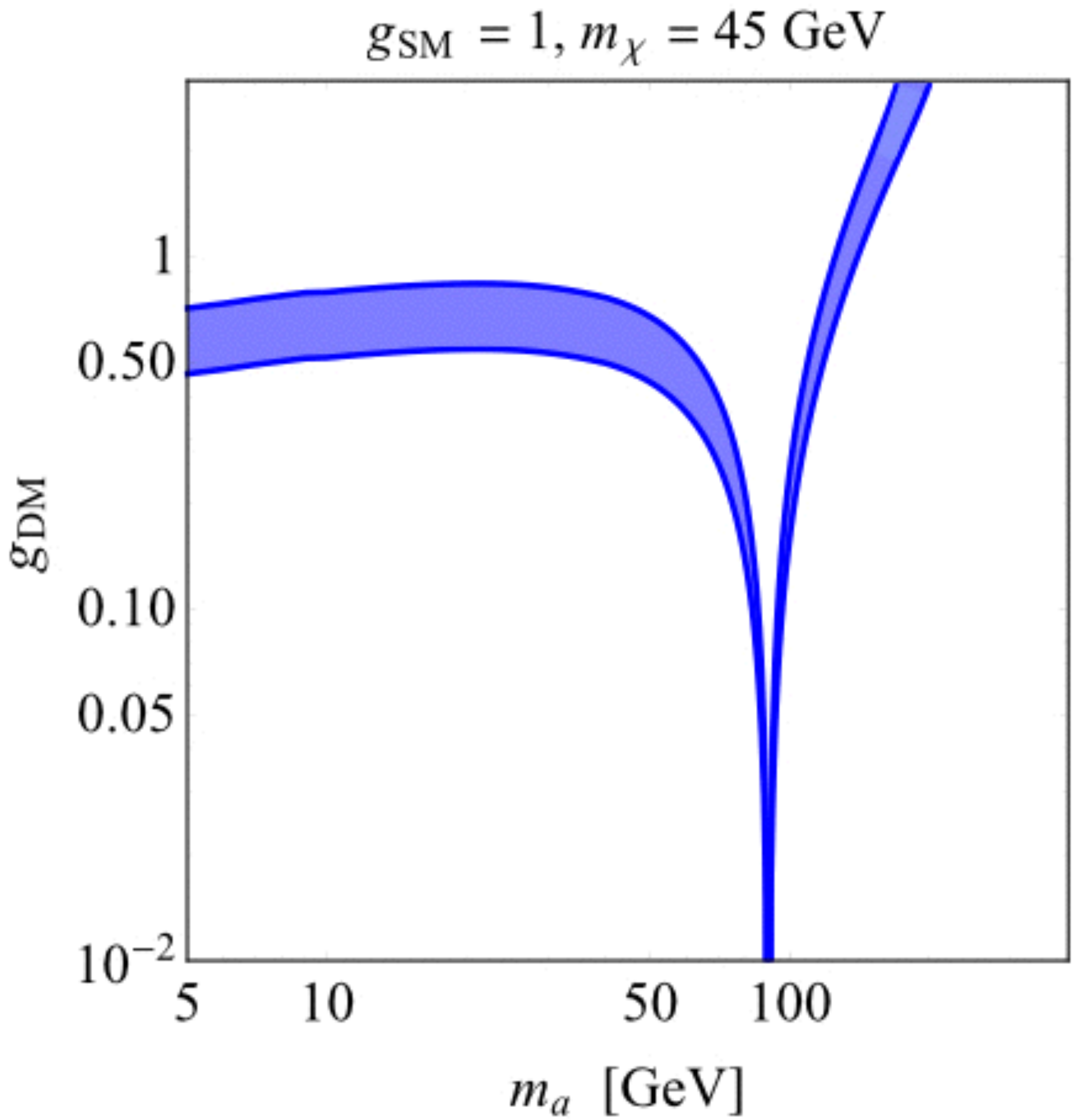


Fermi-LAT observes an excess at a few GeV in γ-ray emission data from galactic center & inner galaxy

Fermi-LAT excess

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

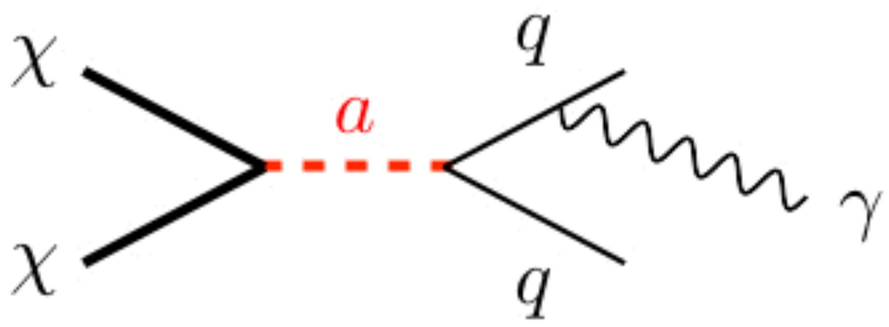


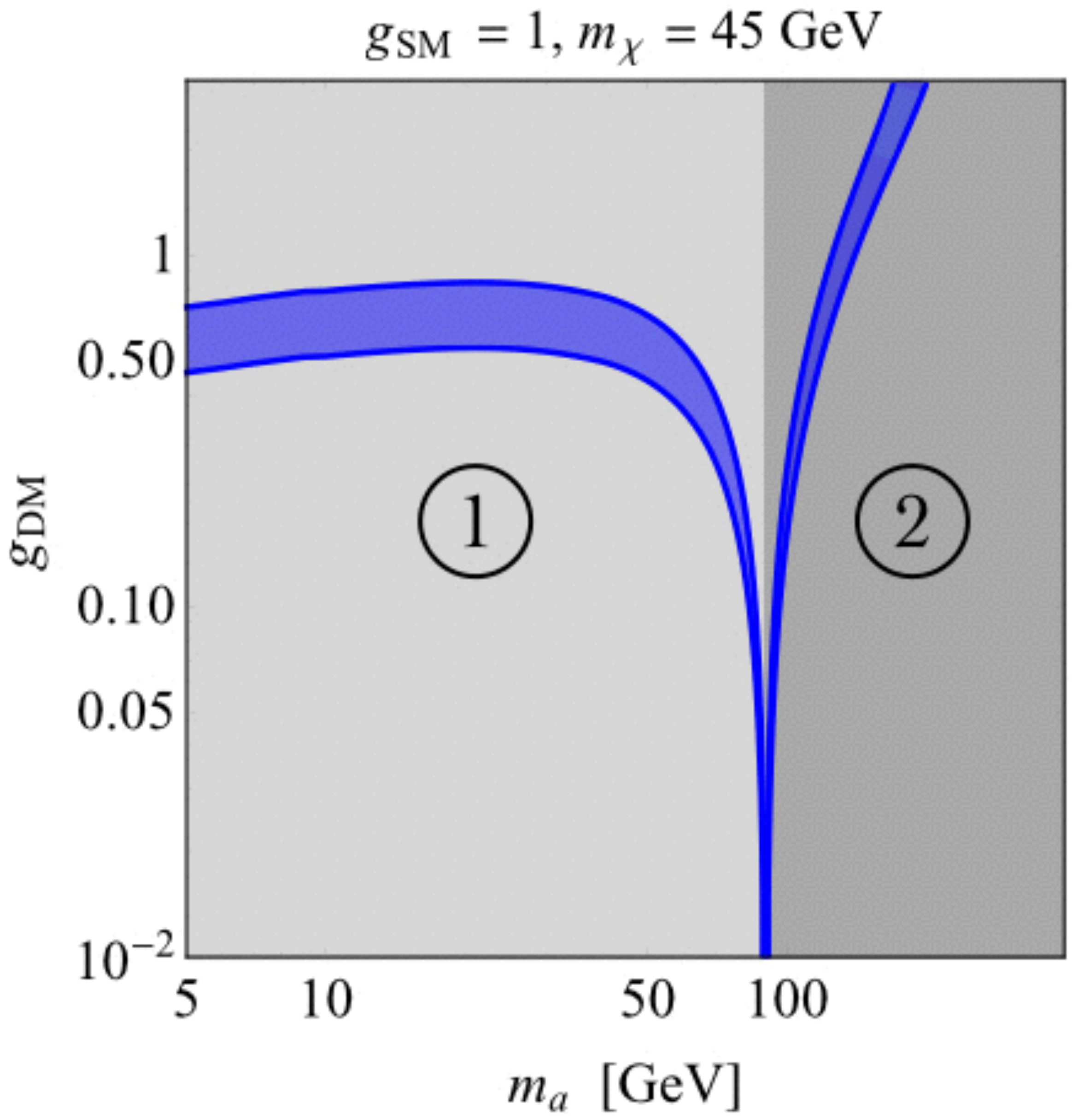


Simplified model with Dirac dark matter, pseudoscalar mediator & Higgs-like couplings fits excess with reasonable parameters

Fermi-LAT excess

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

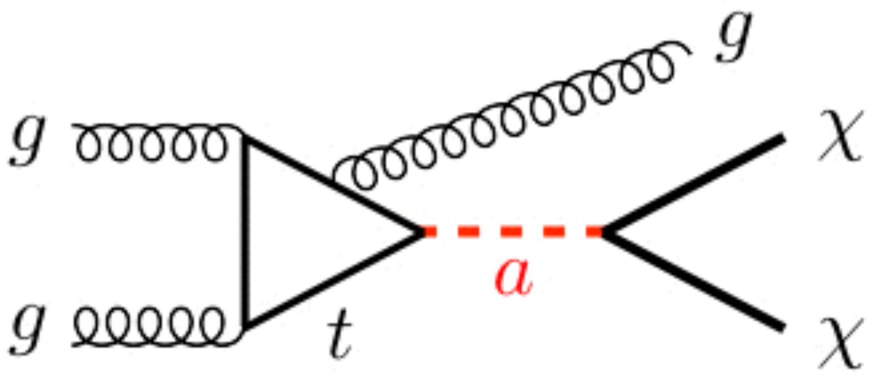




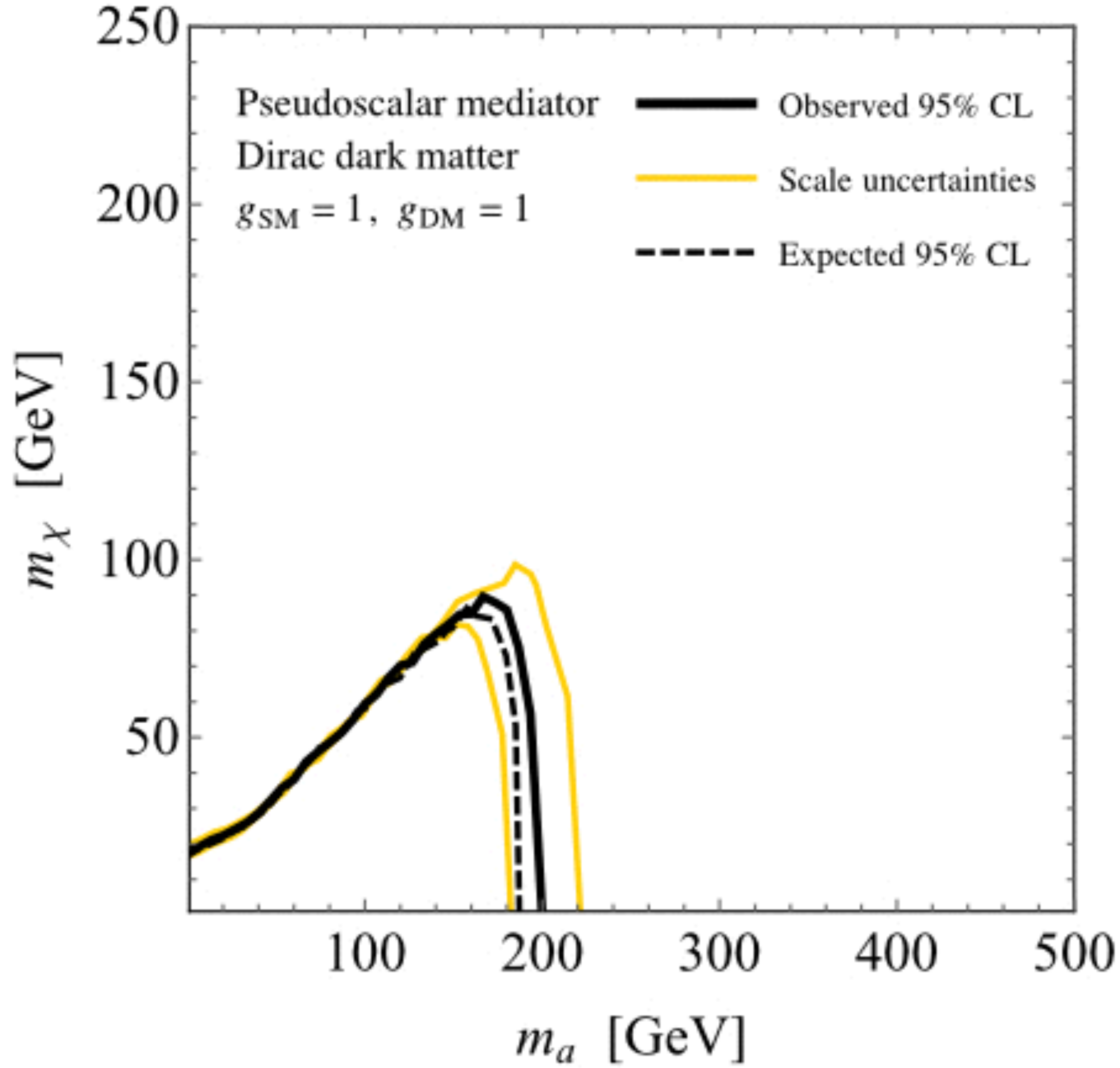
In fact, allowed parameter space can be divided into two parts. One where $m_a < 2m_\chi$ & another one where $m_a > 2m_\chi$

LHC dark matter searches

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



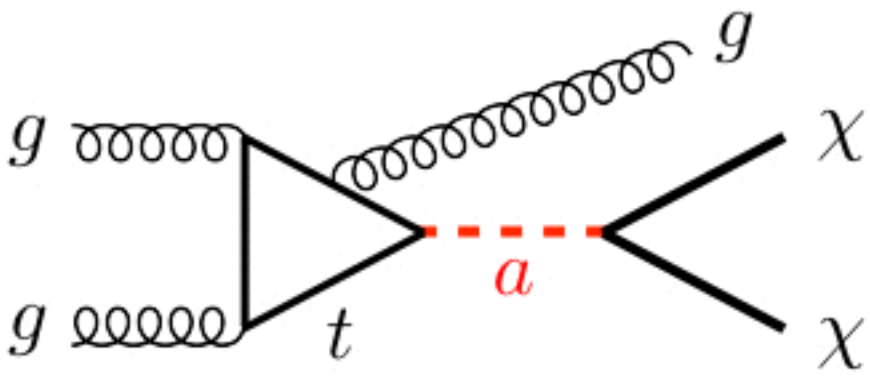
Boveia et al., 1603.04156



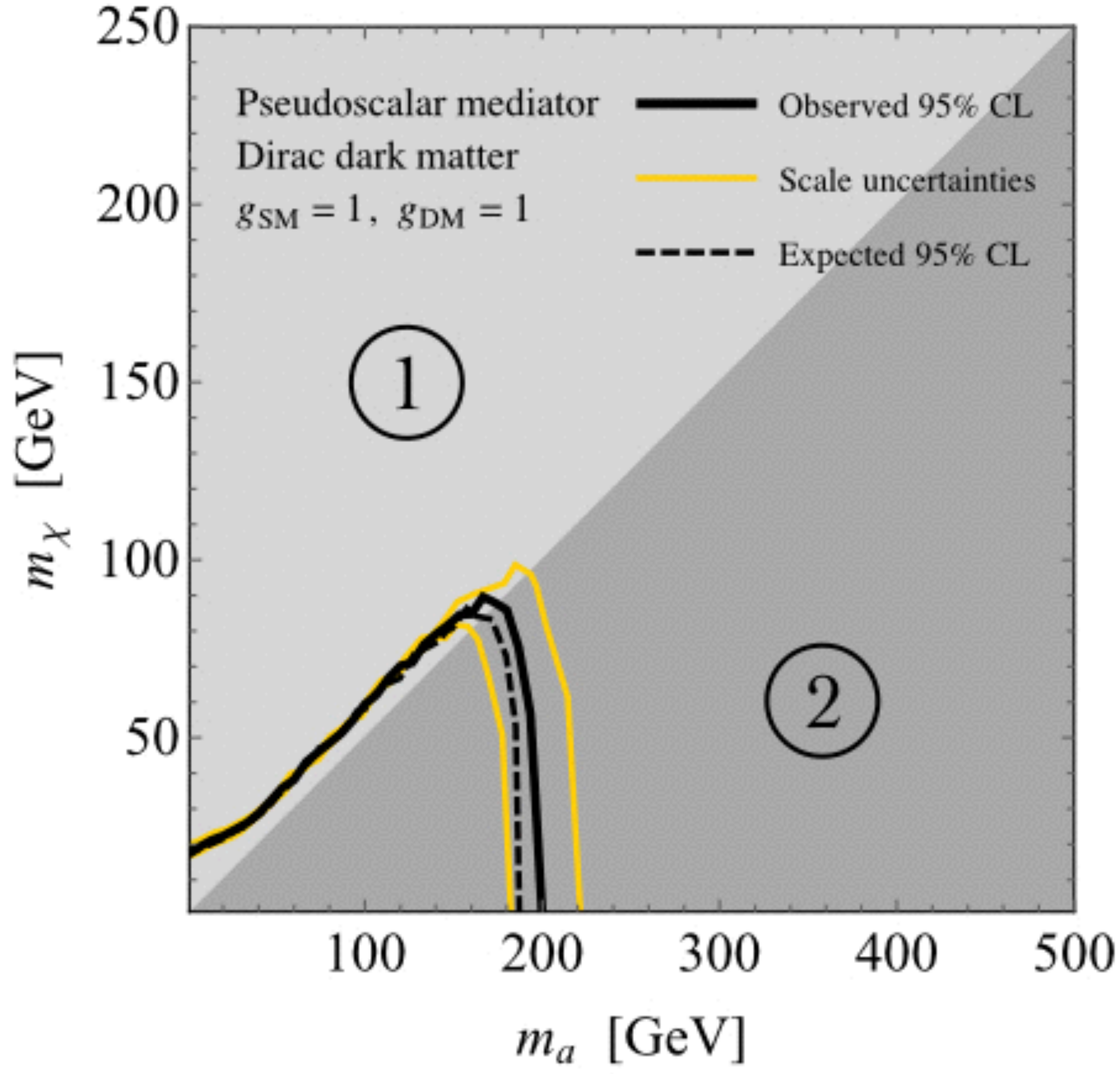
Simplified model that allows to explain Fermi-LAT excess can be tested by ATLAS & CMS for instance via mono-jet searches

LHC dark matter searches

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



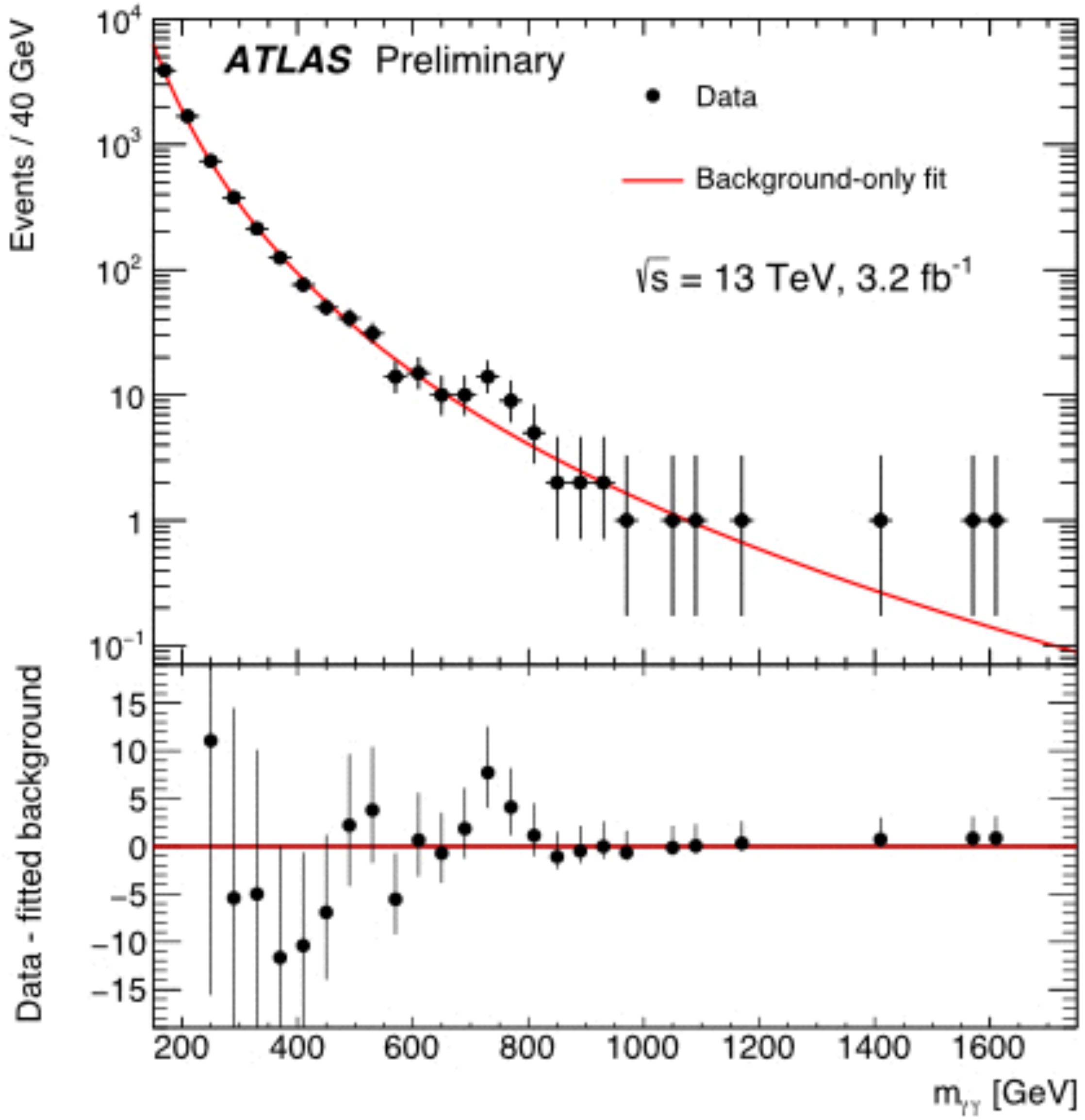
Boveia et al., 1603.04156



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. $m_a < 2m_\chi$)

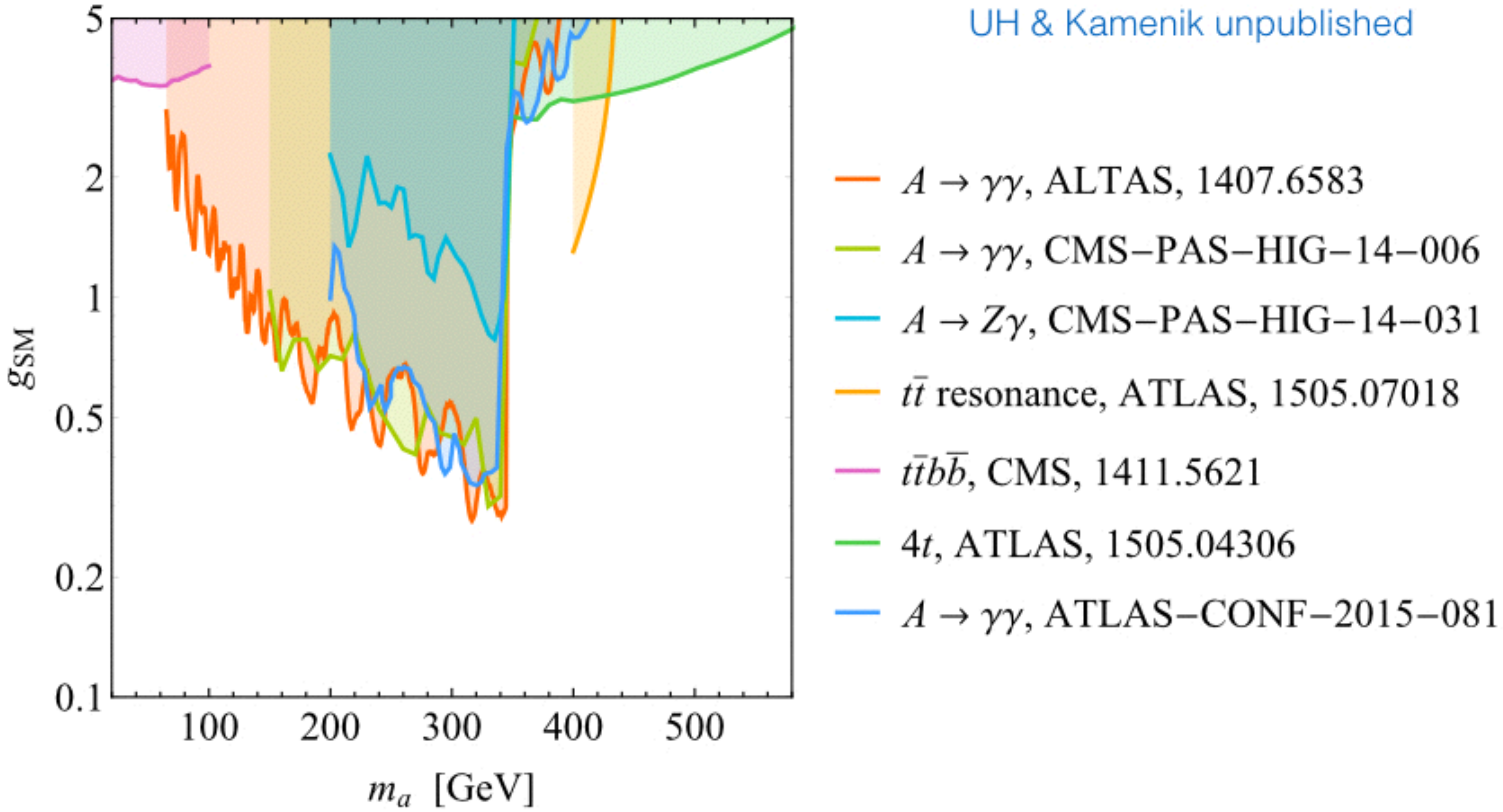
LHC standard model searches

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

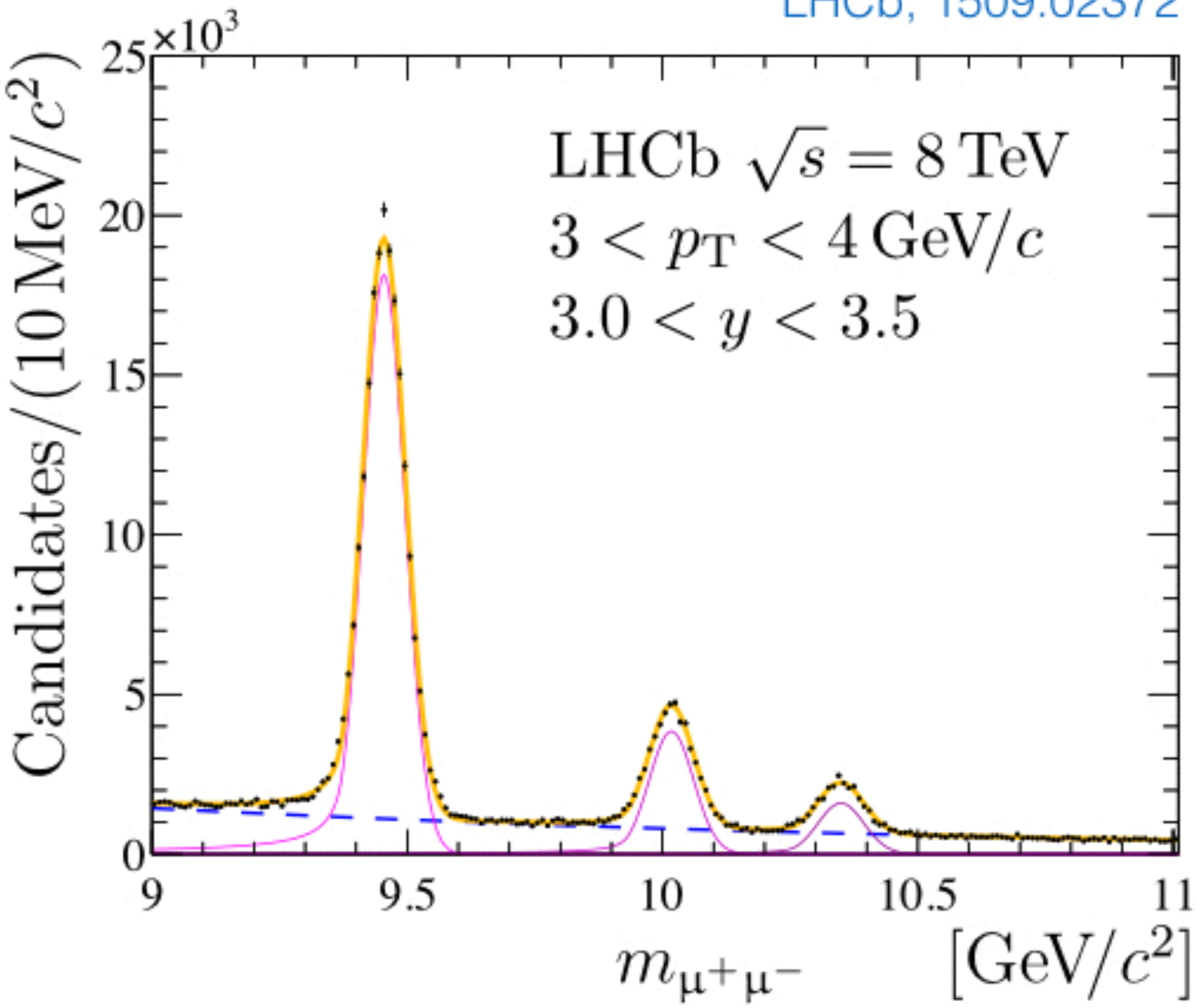


UH & Kamenik unpublished

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

ϒ production at LHCb

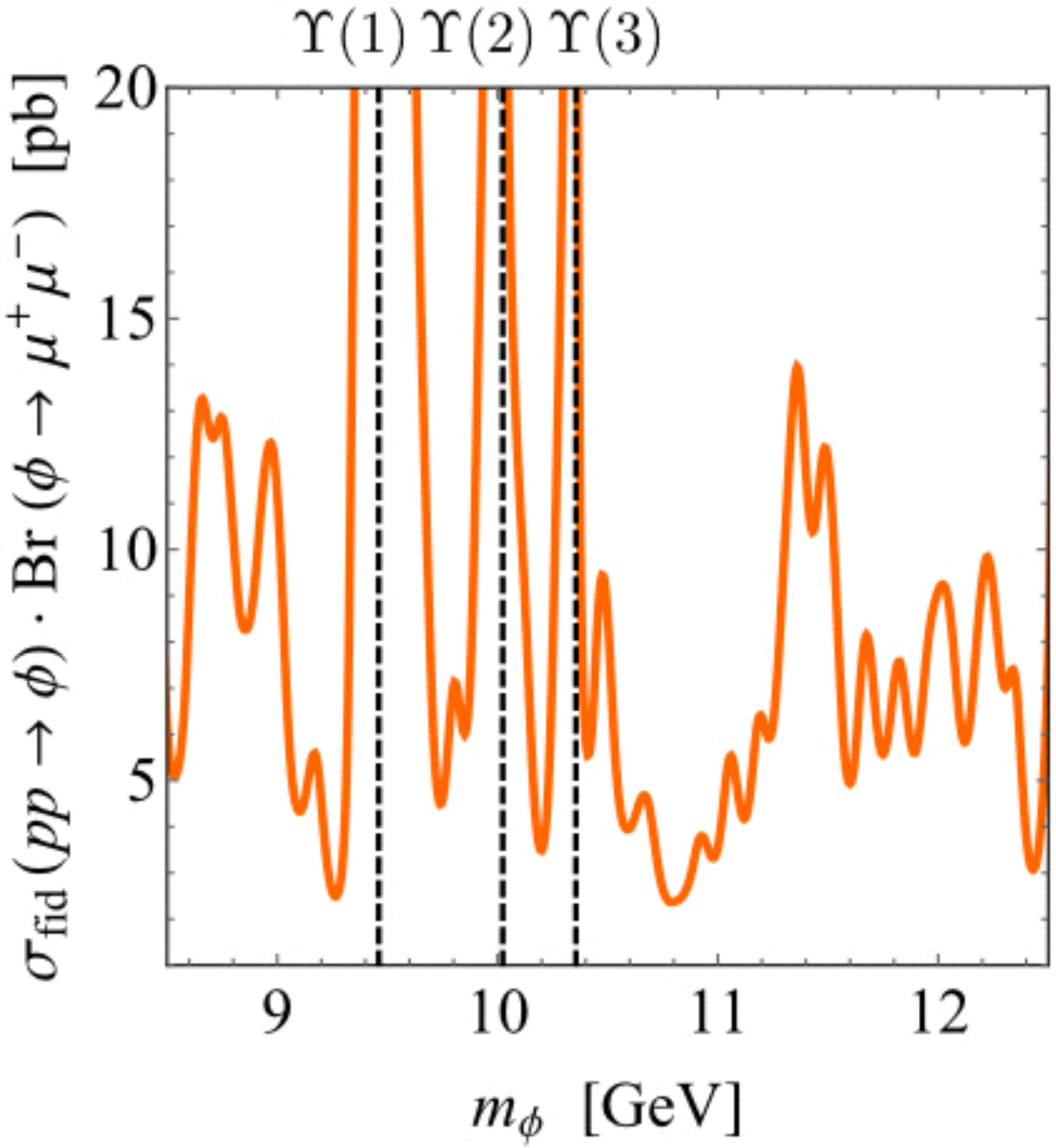
LHCb, 1509.02372



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

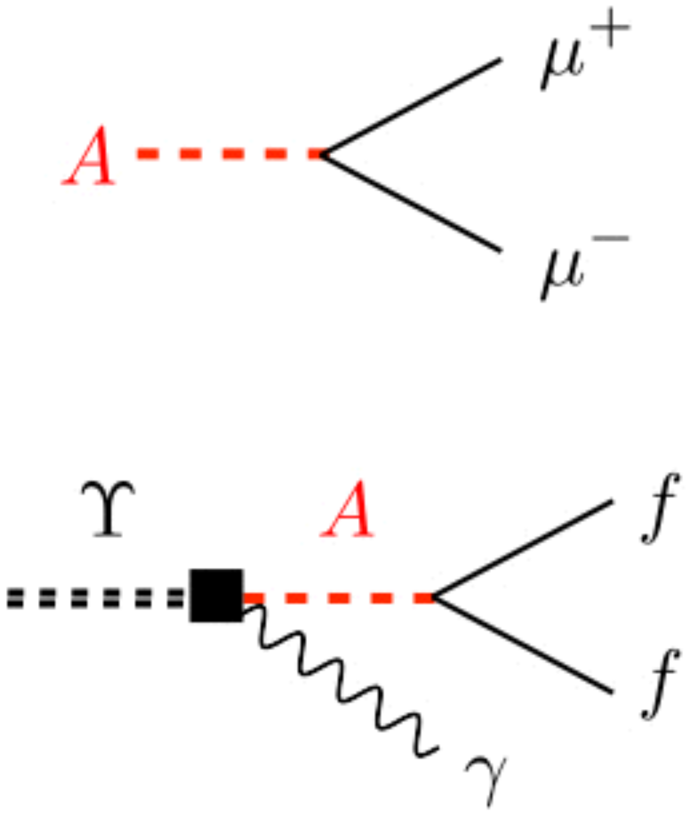
Bound on $\sigma_{\text{fid}}(pp \to \phi) \cdot \text{Br}(\phi \to \mu^+\mu^-)$

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

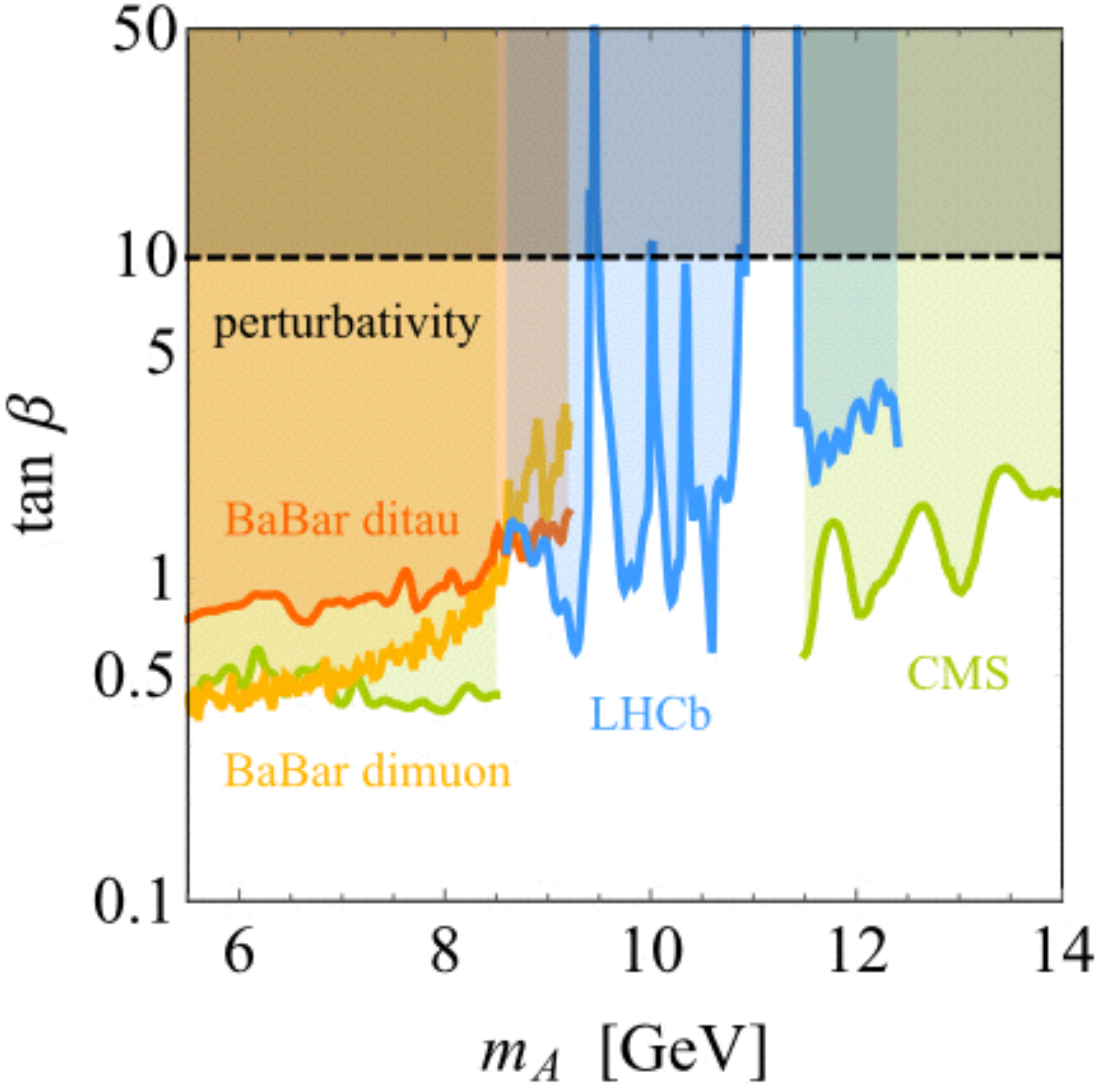


UH & Kamenik, 1601.05110

Type II two-Higgs doublet model



UH & Kamenik, 1601.05110



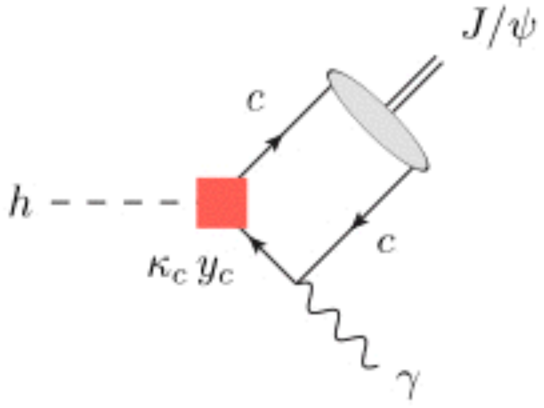
LHCb provides best bound for $m_A \in [8.6, 11]$ GeV. Mass region [11,11.5] GeV remains unexplored, due to strong mixing effects

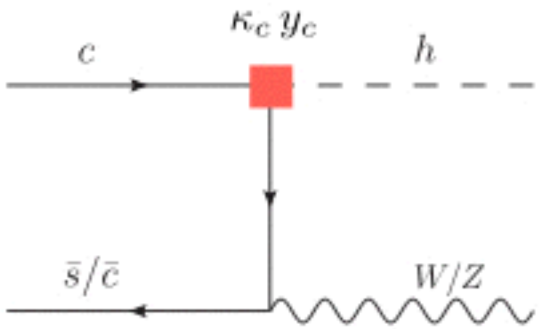
Charm Yukawa coupling

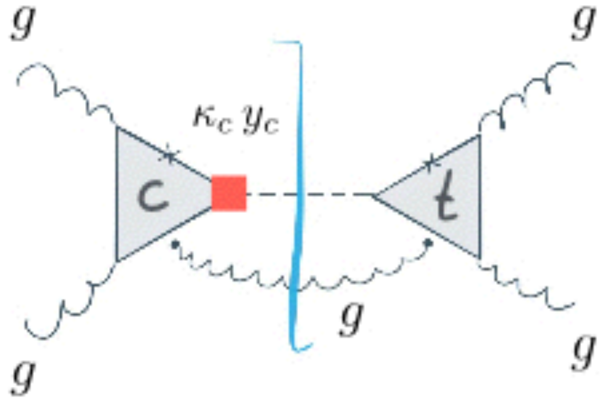
Literature:

- 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 κ_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 κ_c

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

Exclusive Higgs decays: h→J/ψγ

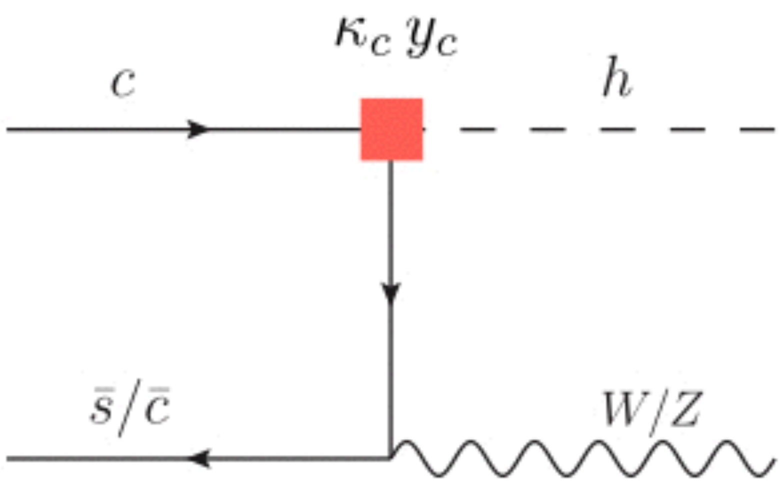
$$\mathrm{Br}\,(h \to J/\psi\gamma) < 1.5 \cdot 10^{-3}$$ ATLAS, 1501.03276; CMS, 1507.03031

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

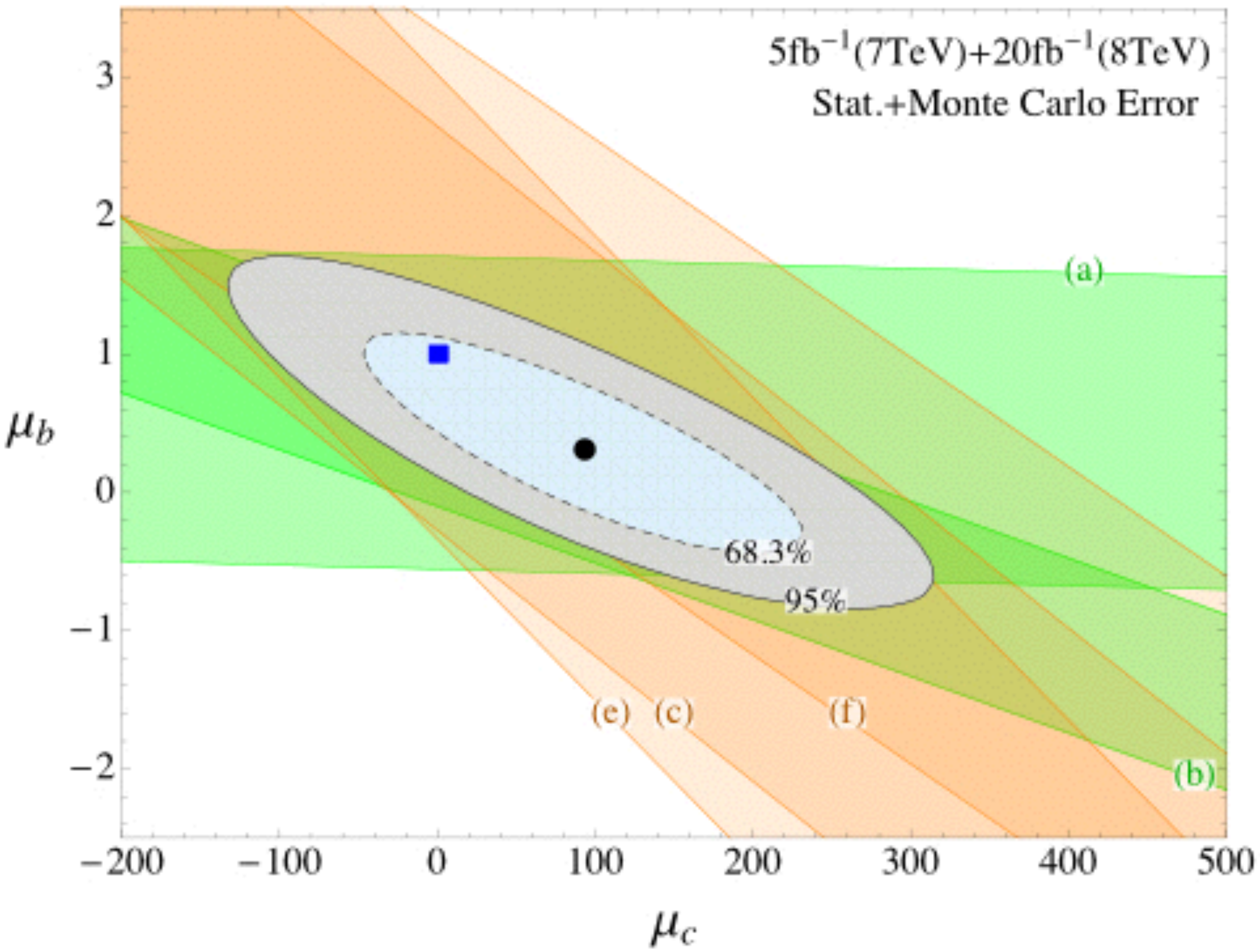
$$\mathrm{Br}\,(h \to J/\psi\gamma) = 2.95\,(1 \pm 0.2) \cdot 10^{-6}$$

$$\longrightarrow \quad \kappa_c \in [-0.51, 3.07]$$ König & Neubert, 1505.03870

Vh production & flavour tagging

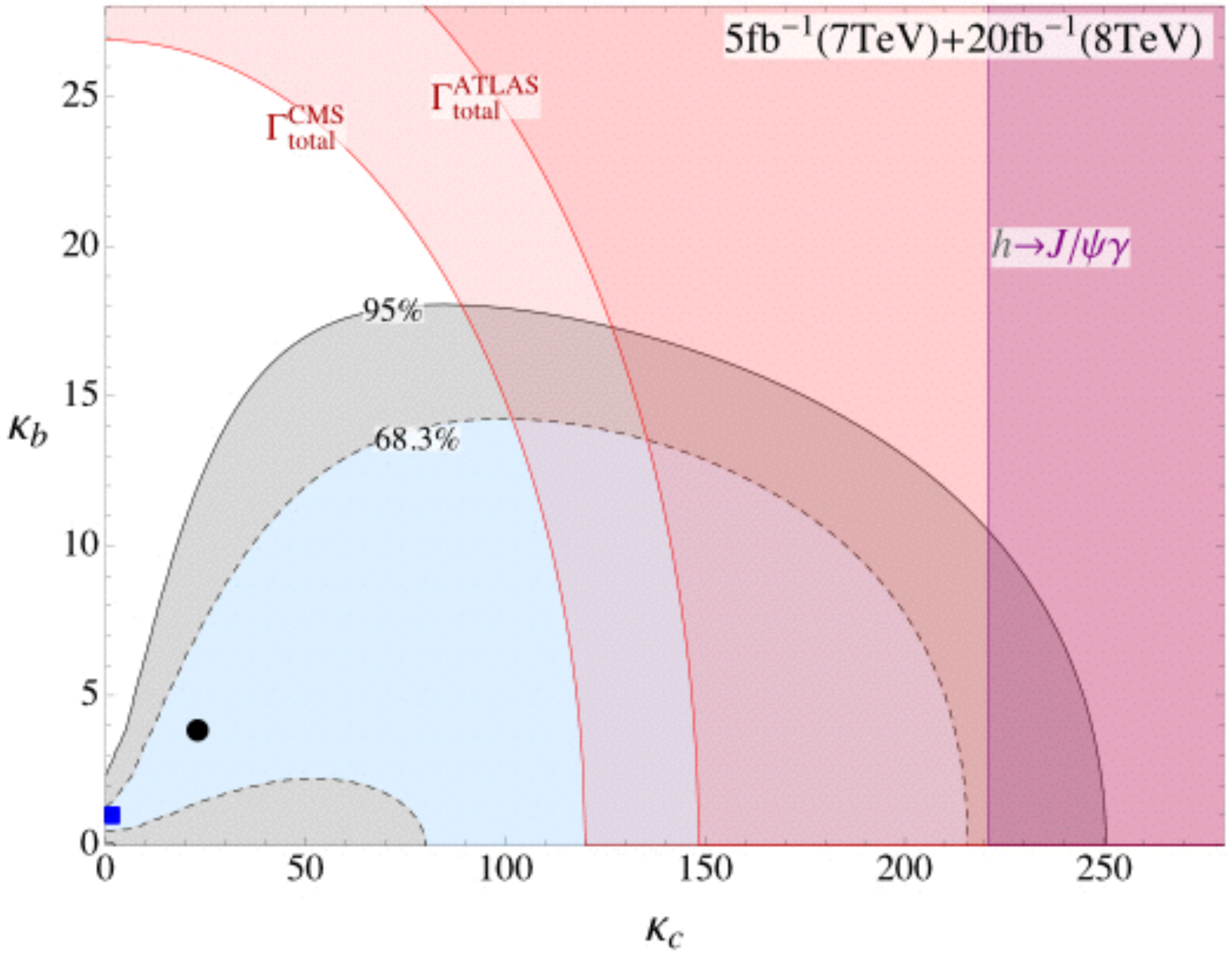


Perez, Soreq, Stamou & Tobioka, 1503.00290



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

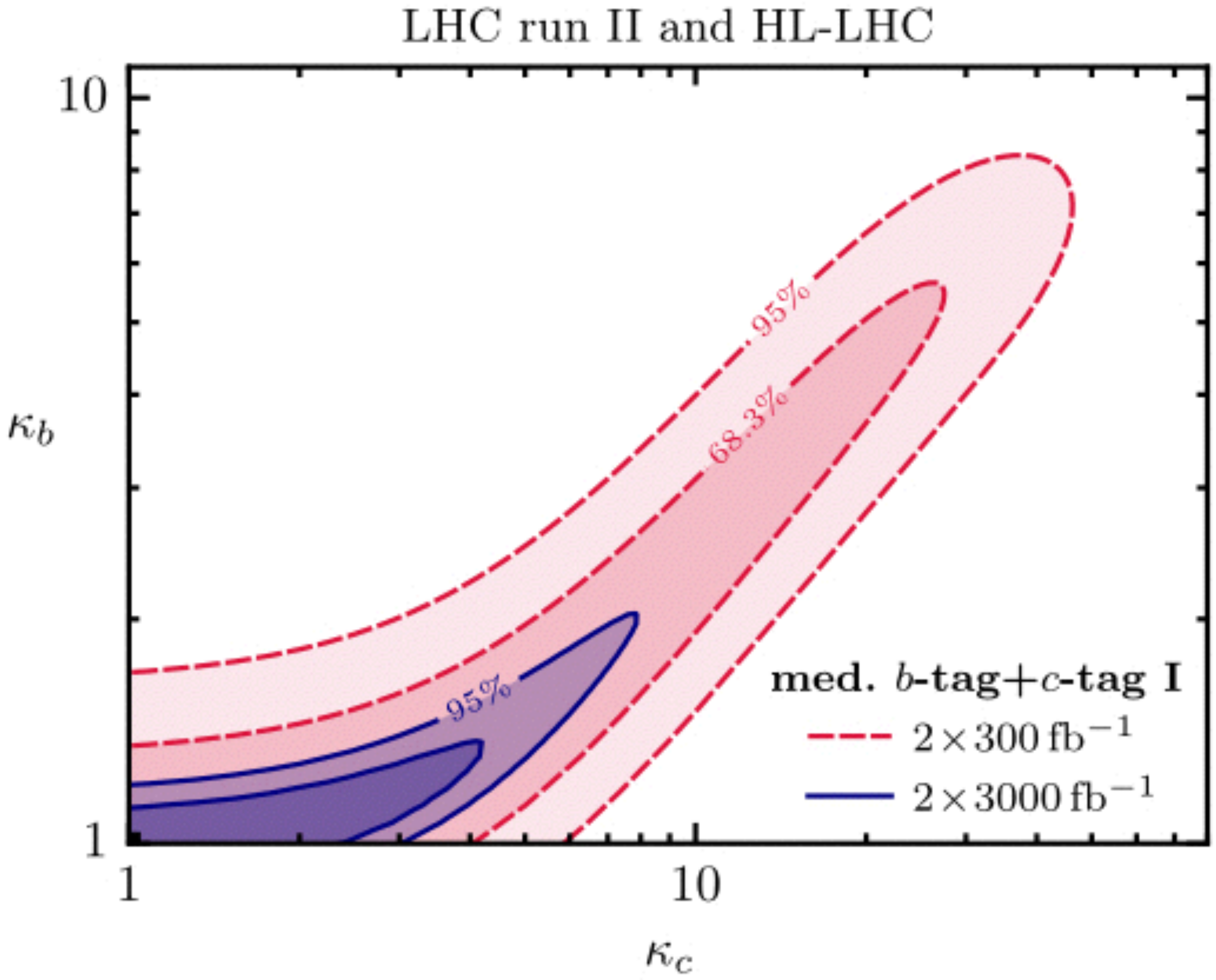
Vh production & flavour tagging



$\longrightarrow$ $\kappa_c \lesssim 234$

Perez, Soreq, Stamou & Tobioka, 1503.00290

Vh production & flavour tagging



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

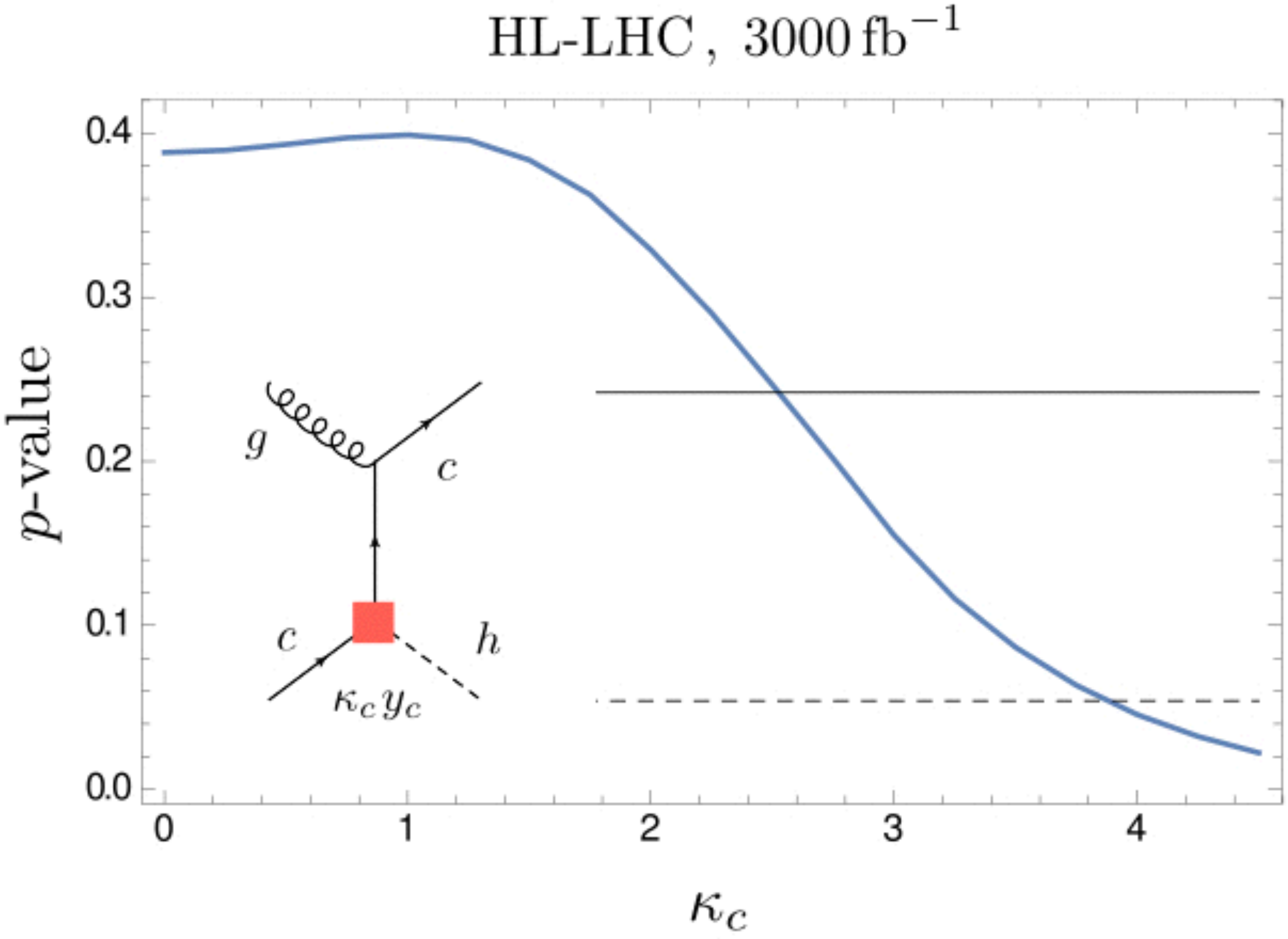
Perez, Soreq, Stamou & Tobioka, 1505.06689

Vh production & flavour tagging

$\mathcal{L}$	$\sqrt{s} = 14\,\mathrm{TeV}$	κ_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

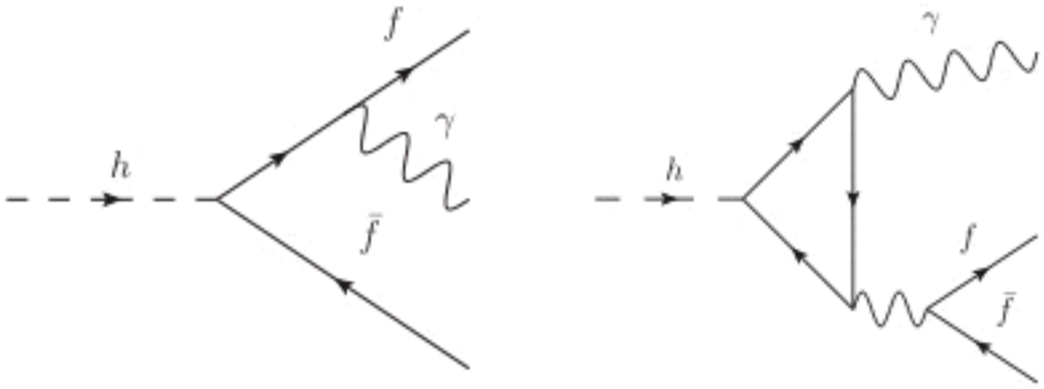
Higgs & charm production

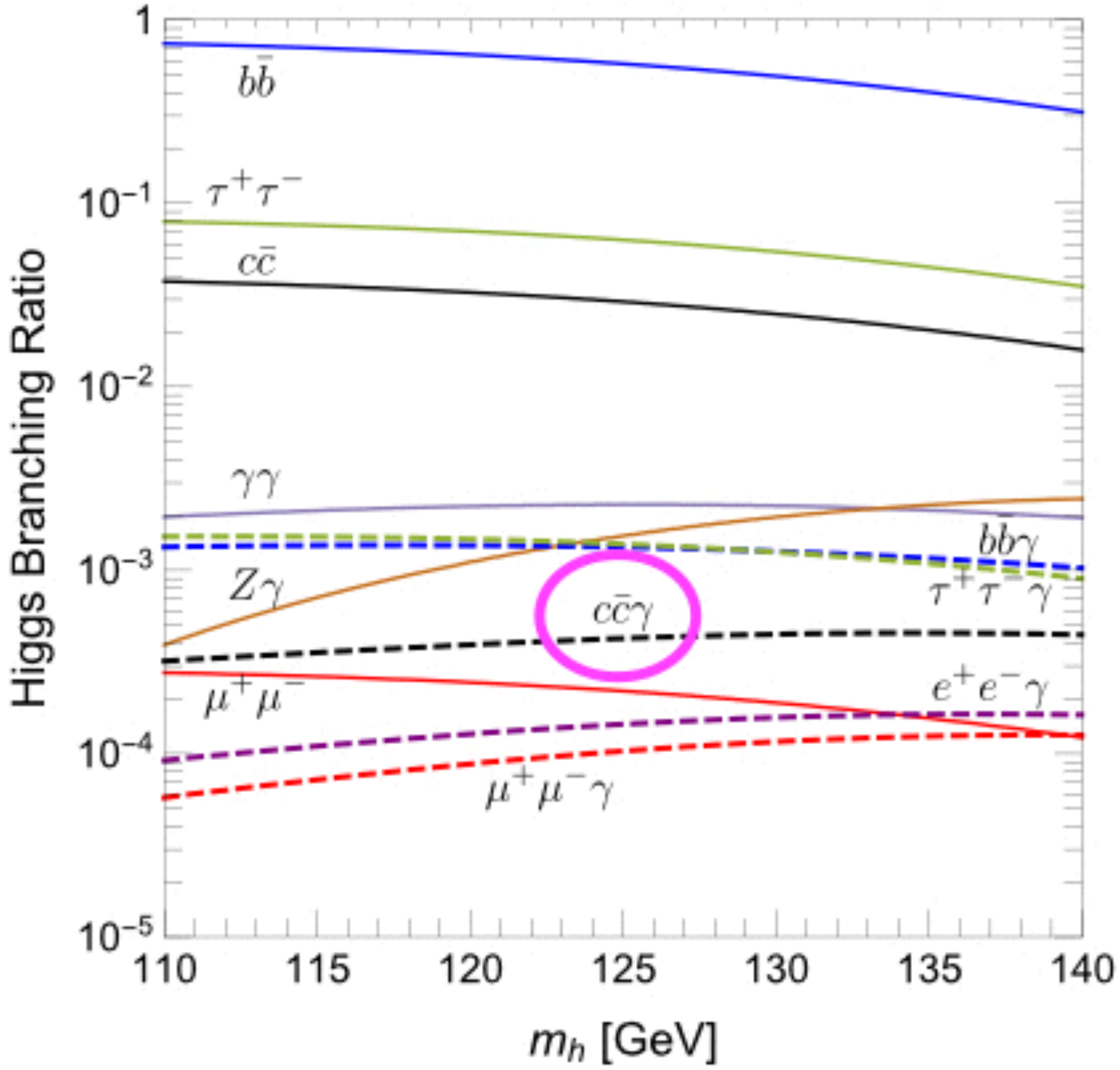


$\longrightarrow \quad \kappa_c < 3.9$

Brivio, Goertz & Isidori, 1507.02916

Charm Yukawa from h→cc̄γ



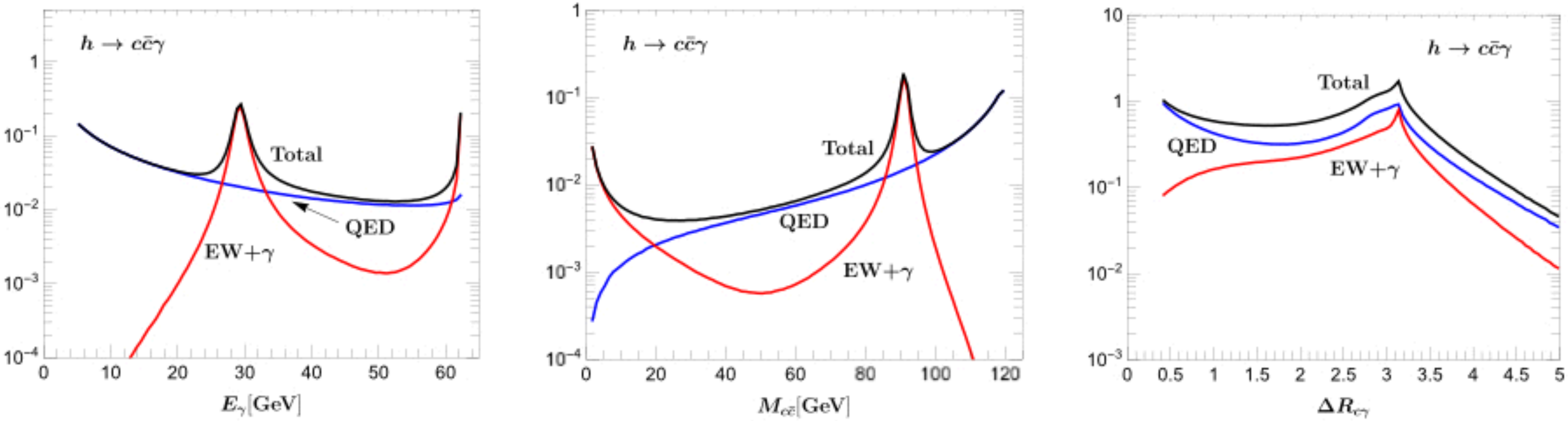


$$\mathrm{Br}(h \to J/\psi\gamma) \simeq 3 \cdot 10^{-6}$$

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

Han & Wang, 1704.00790

Charm Yukawa from $h \to c\bar{c}\gamma$

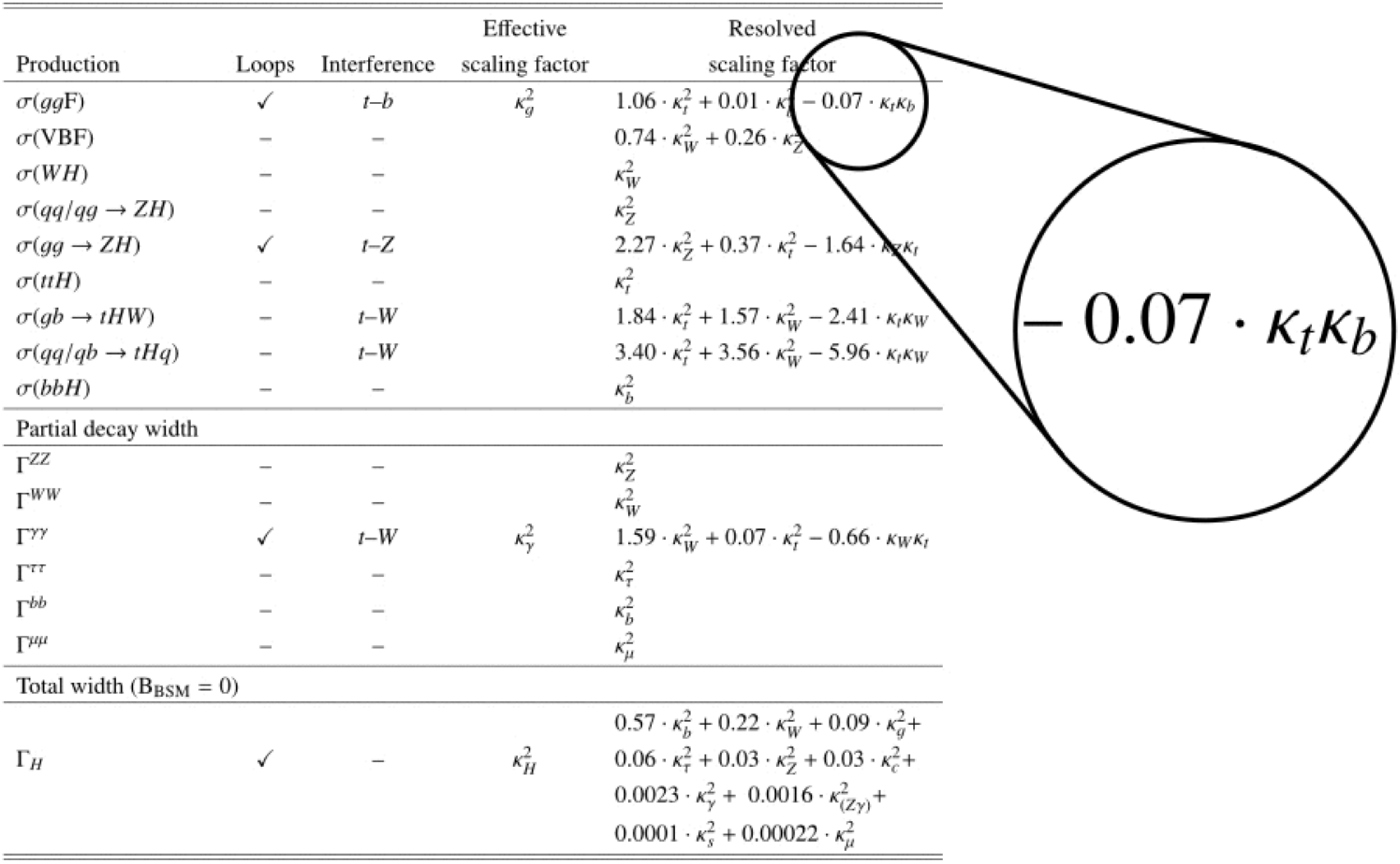


$$|\kappa_c| < 6.3 \quad \text{(HL-LHC)}$$

Han & Wang, 1704.00790

A simple observation

ATLAS & CMS, 1606.02266



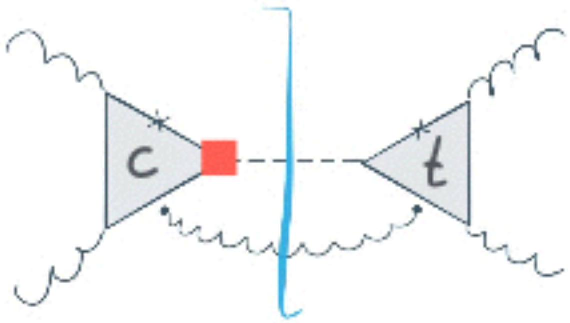
Production	Loops	Interference	Effective scaling factor	Resolved scaling factor
$\sigma(gg\mathrm{F})$	✓	t–b	κ_g^2	$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t\kappa_b$
$\sigma(\mathrm{VBF})$	–	–		$0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	–	–		κ_W^2
$\sigma(qq/qg \to ZH)$	–	–		κ_Z^2
$\sigma(gg \to ZH)$	✓	t–Z		$2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z\kappa_t$
$\sigma(ttH)$	–	–		κ_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		$3.40 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t\kappa_W$
$\sigma(bbH)$	–	–		κ_b^2
Partial decay width				
Γ^{ZZ}	–	–		κ_Z^2
Γ^{WW}	–	–		κ_W^2
$\Gamma^{\gamma\gamma}$	✓	t–W	κ_γ^2	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W\kappa_t$
$\Gamma^{\tau\tau}$	–	–		κ_τ^2
Γ^{bb}	–	–		κ_b^2
$\Gamma^{\mu\mu}$	–	–		κ_μ^2
Total width ($\mathrm{B_{BSM}} = 0$)				
Γ_H	✓	–	κ_H^2	$0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 +$ $0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 +$ $0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{(Z\gamma)}^2 +$ $0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$

A simple observation

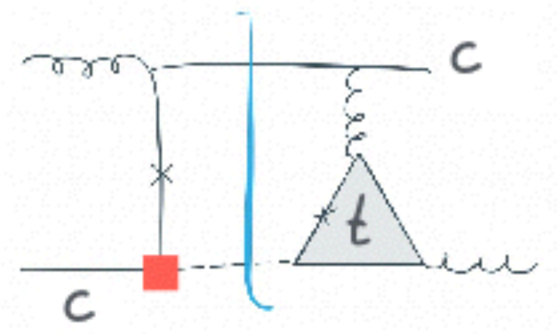
- In SM, interference between top & bottom loops does not only change total Higgs production cross section but also distributions in pp→hj such as $p_{T,h}$, y_h, $p_{T,j}$, …
- Measurements of shape of distributions at low to moderate p_T should allow to constrain modifications $\kappa_c = y_c/y_c^{SM}$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

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

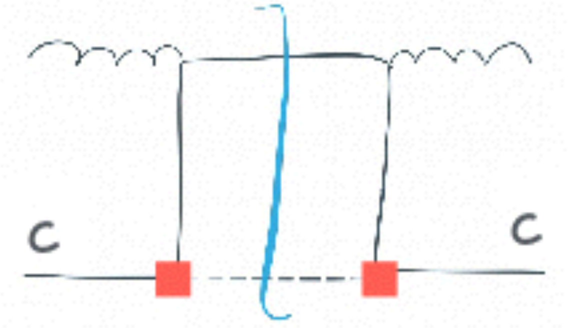
Charm contributions to pp→hj



$$\sim \alpha_s^3 \colorbox{red}{κ_c} \frac{m_c^2}{m_h^2} \ln^2\left(\frac{p_T^2}{m_c^2}\right)$$

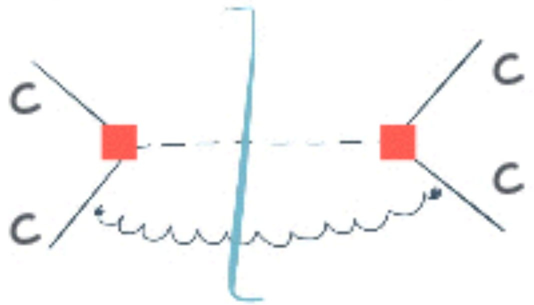


$$\sim \colorbox{green}{α_s} \alpha_s^2 \colorbox{red}{κ_c} \frac{m_c^2}{m_h^2} \qquad (= 0 \text{ in 4, 5 flavour scheme})$$



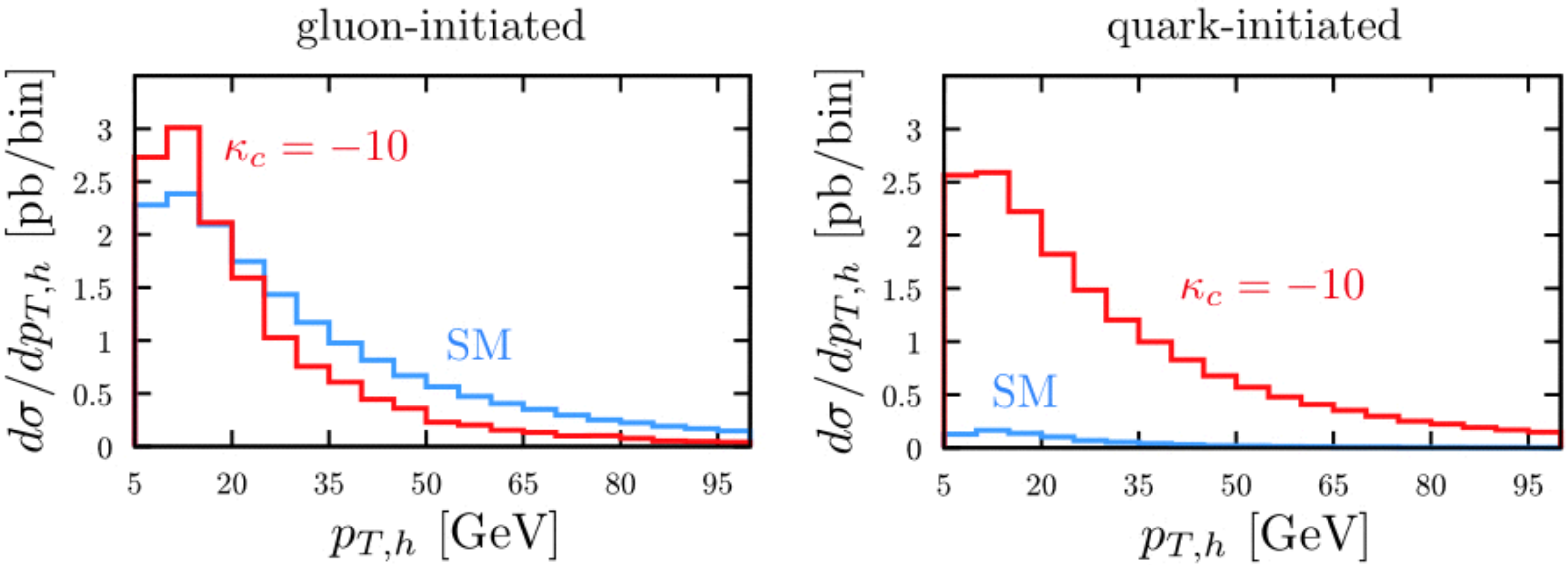
$$\sim \colorbox{green}{α_s} \alpha_s \colorbox{red}{κ_c^2} \frac{m_c^2}{m_h^2}$$

🟩 extra powers of α_s from charm PDF



$$\sim \colorbox{green}{α_s^2} \alpha_s \colorbox{red}{κ_c^2} \frac{m_c^2}{m_h^2}$$

Charm contributions to pp→hj

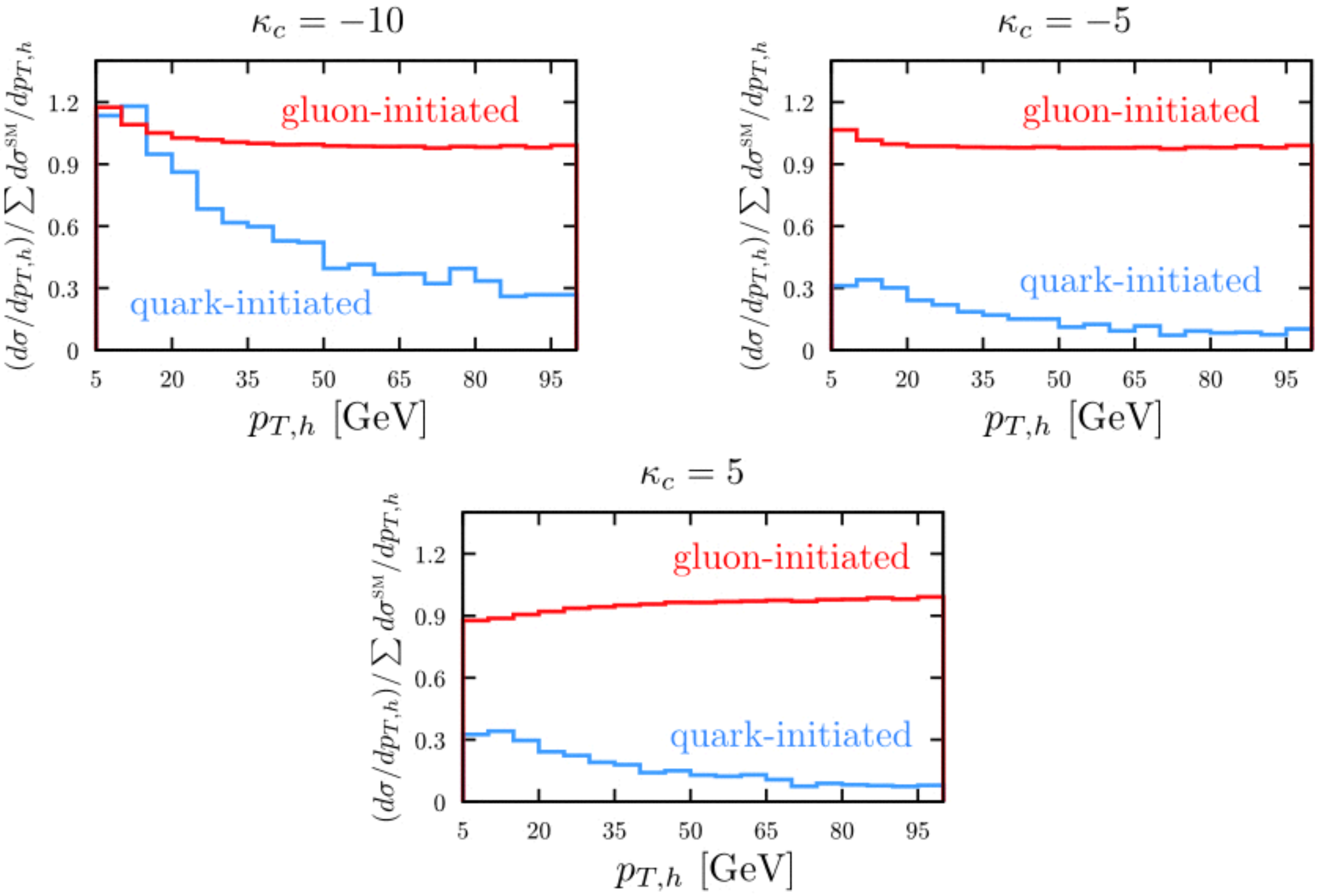


Bishara, unpublished

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 $|\kappa_{s,d,u}| \gg 10$

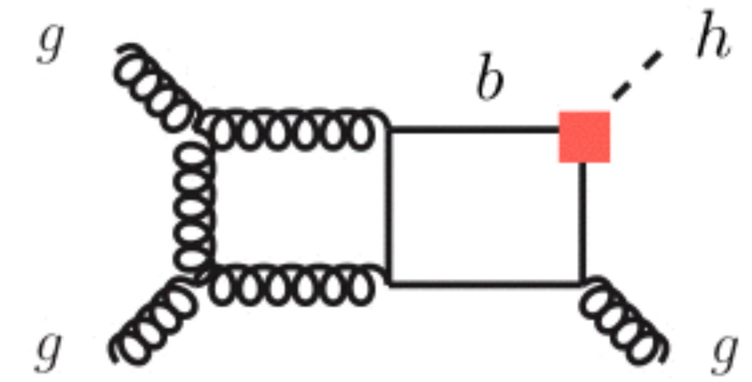
Bishara, UH, Monni & Re, 1606.09253; Soreq, Zhu & Zupan, 1606.09621

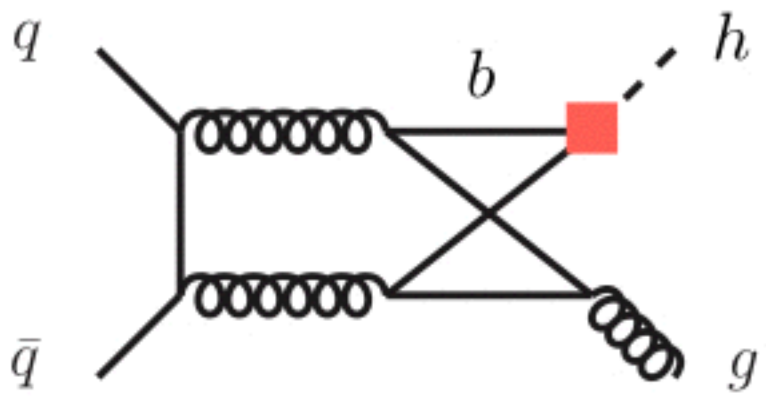
Charm contributions to pp→hj

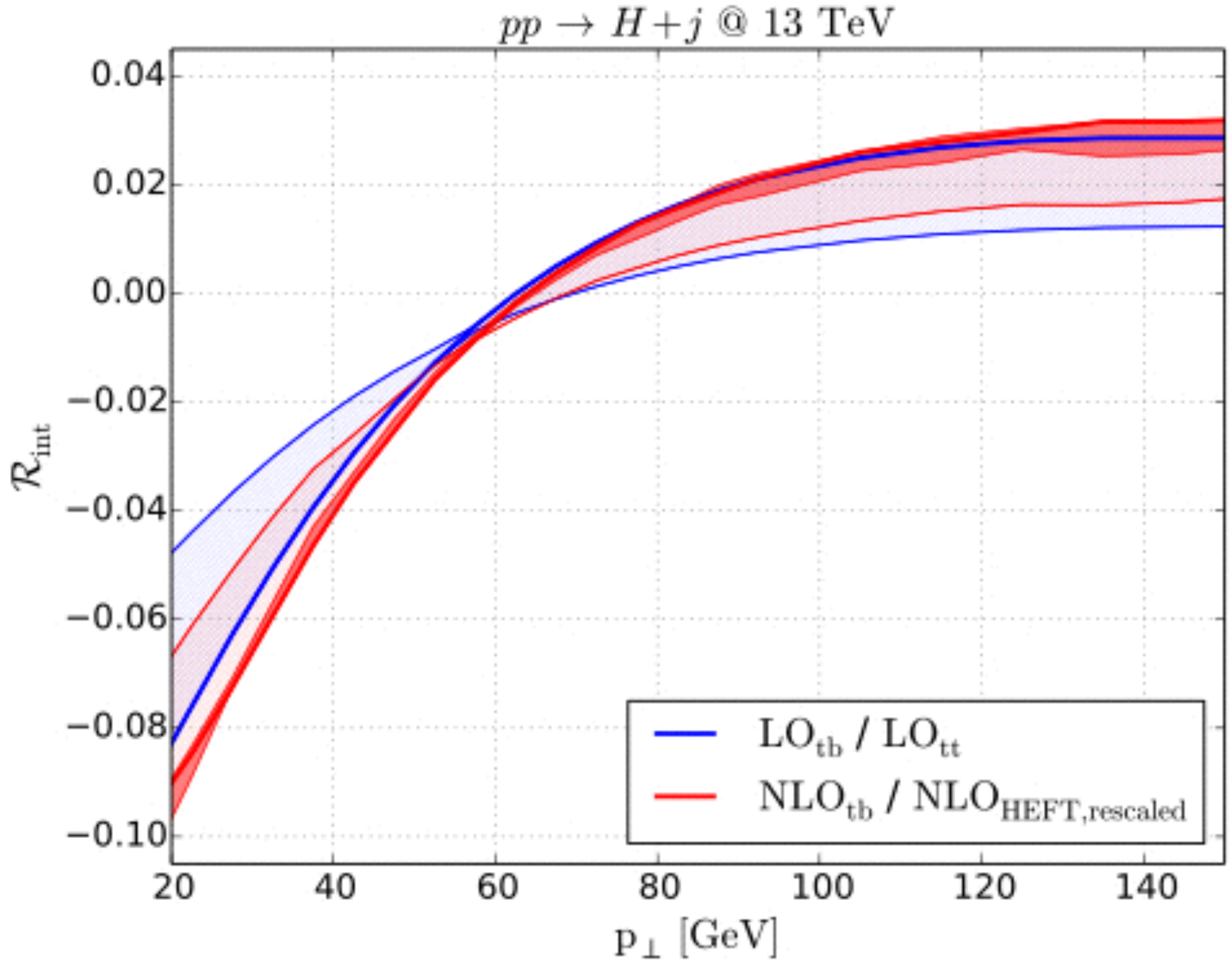


Bishara, unpublished

Top-bottom interference at NLO



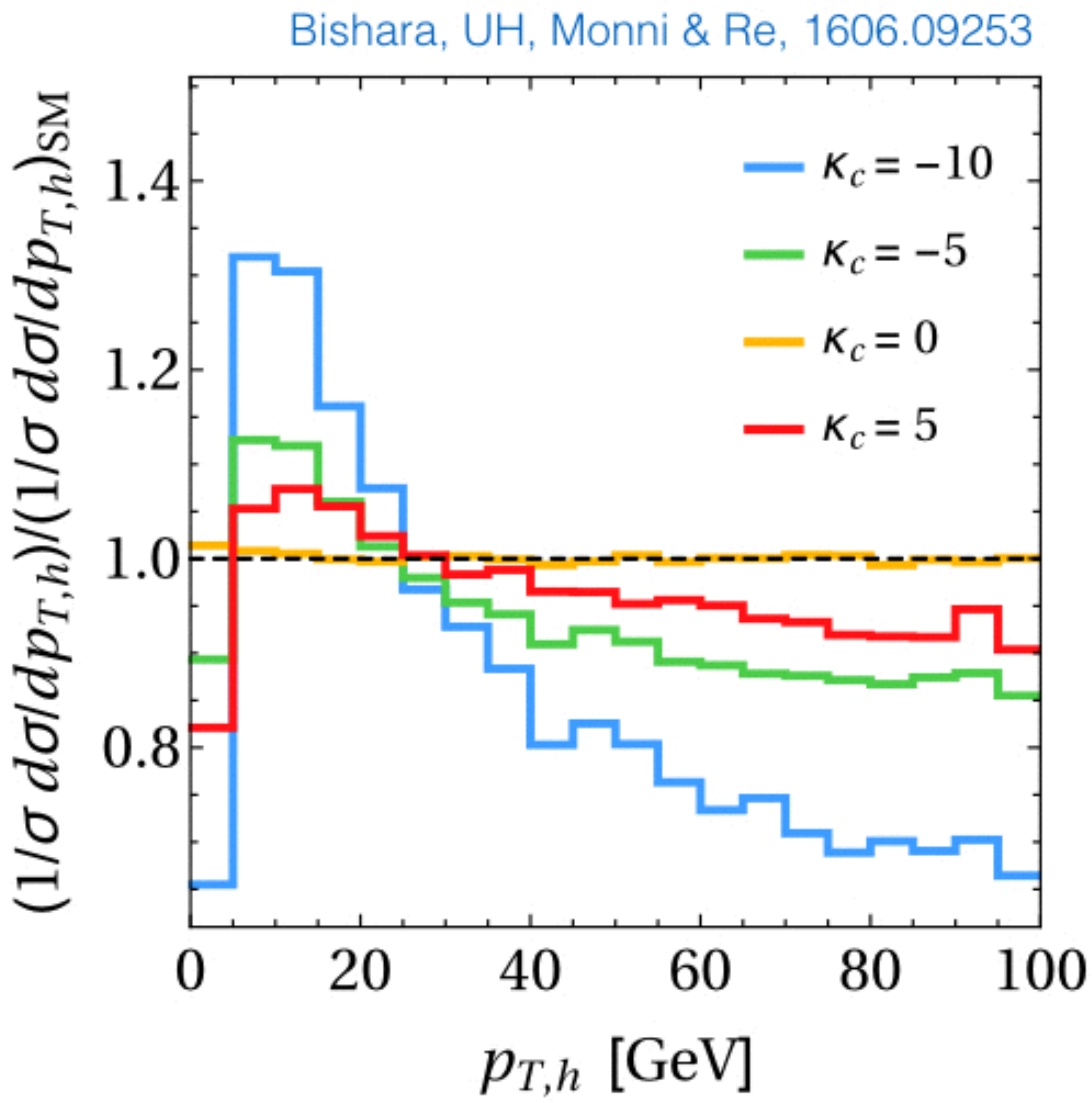




NLO corrections of O(50%) but closely track QCD effects to top-mediated contribution. For $p_T < 30$ GeV inclusion of NLO effects lead to a O(2) reduction of scheme ambiguity related to m_b

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

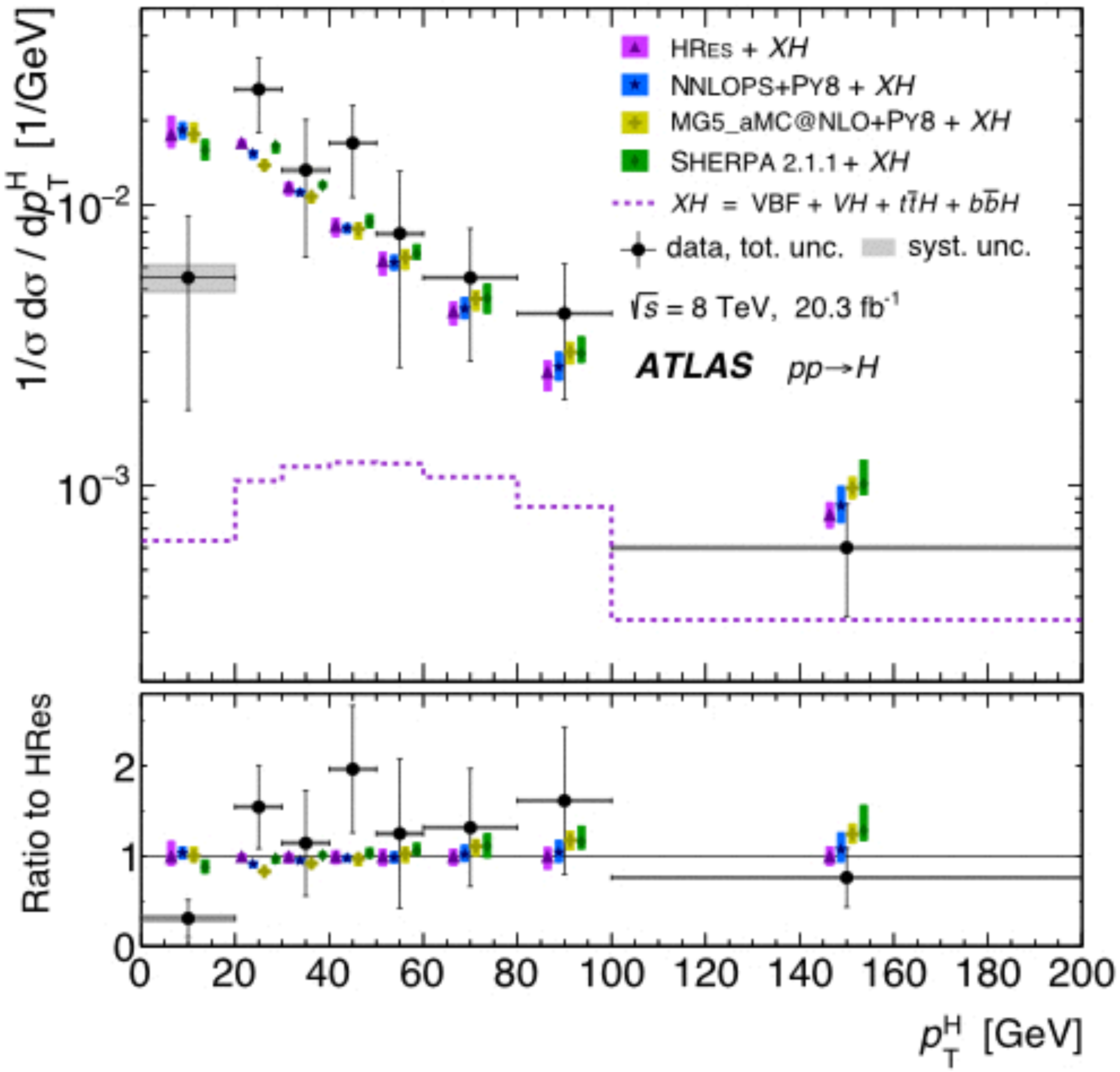
Normalised $p_{T,h}$ spectra at 8 TeV



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

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

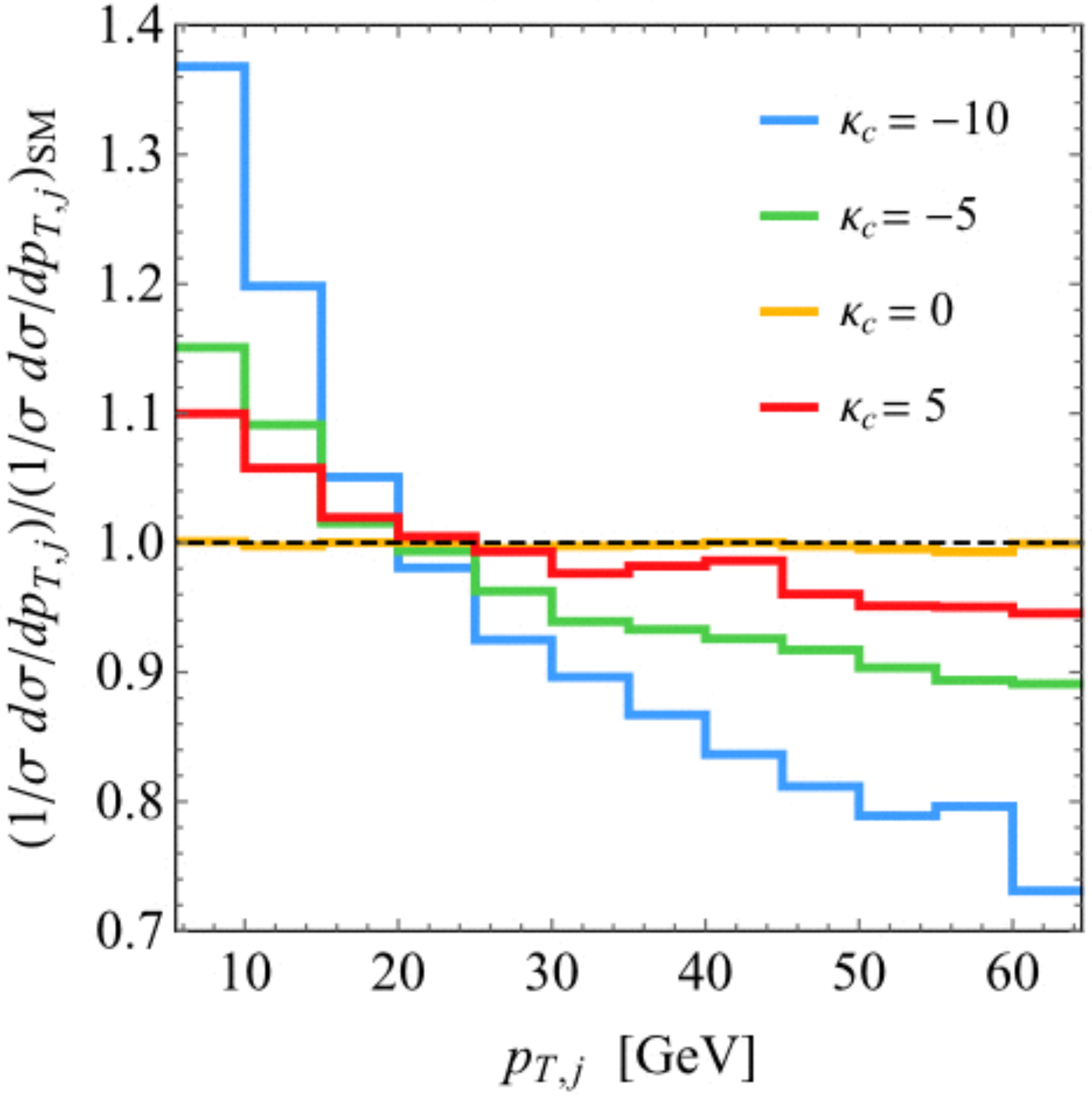
ATLAS, 1504.05833



Statistics limited & not in full agreement with theory predictions

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

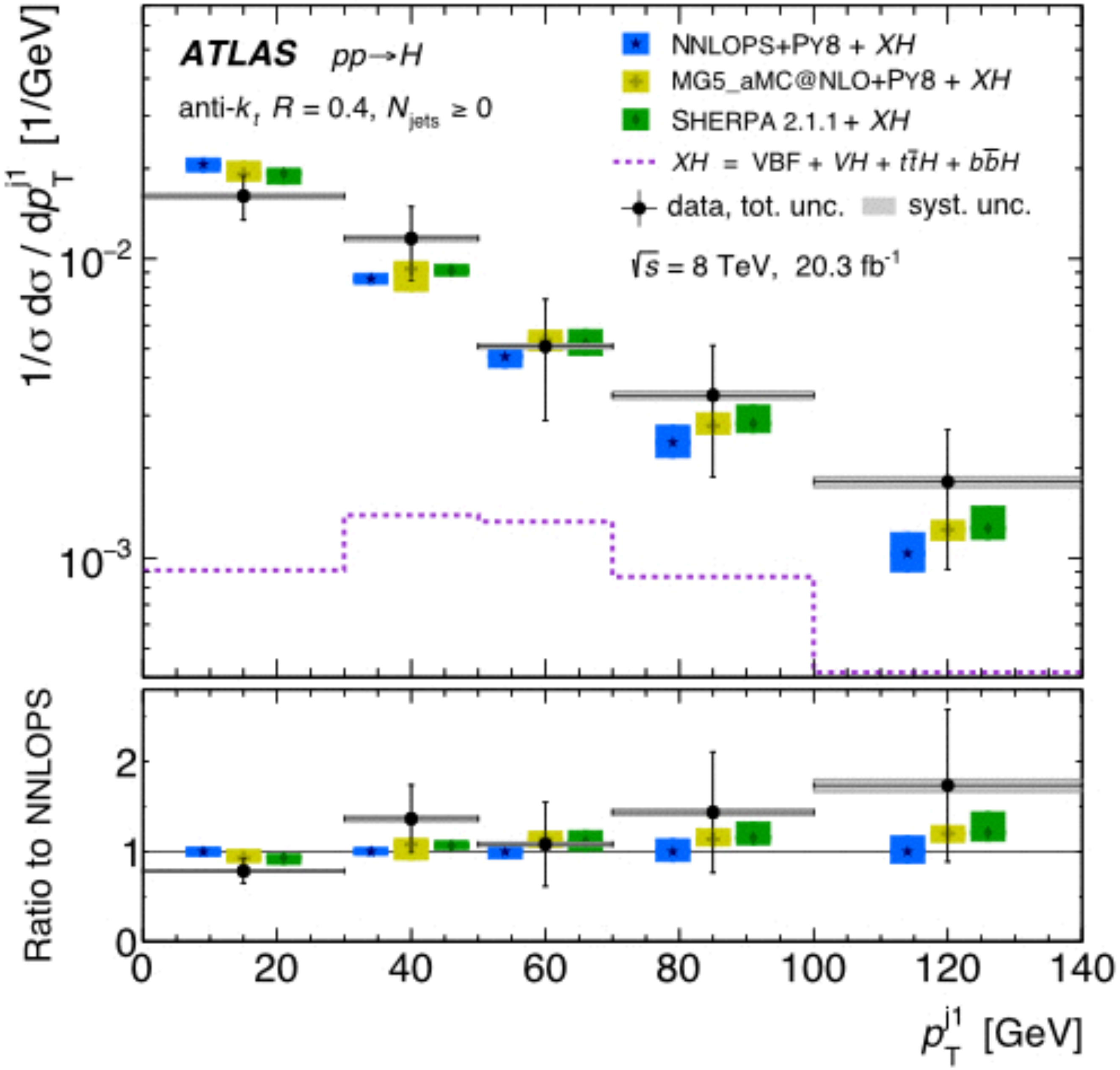
Bishara, UH, Monni & Re, 1606.09253



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

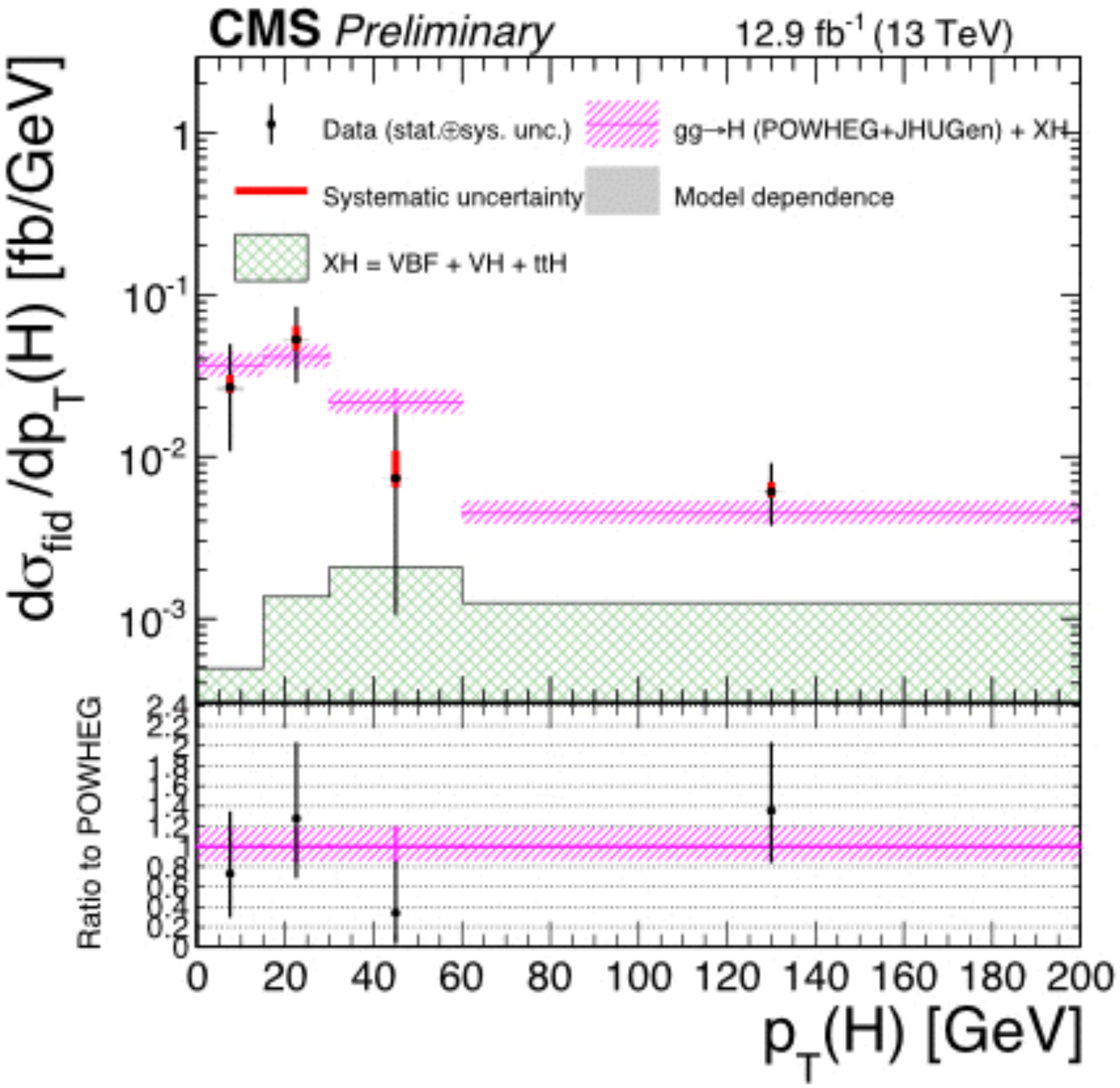
Measured $p_{T,j}$ spectrum at 8 TeV

ATLAS, 1504.05833

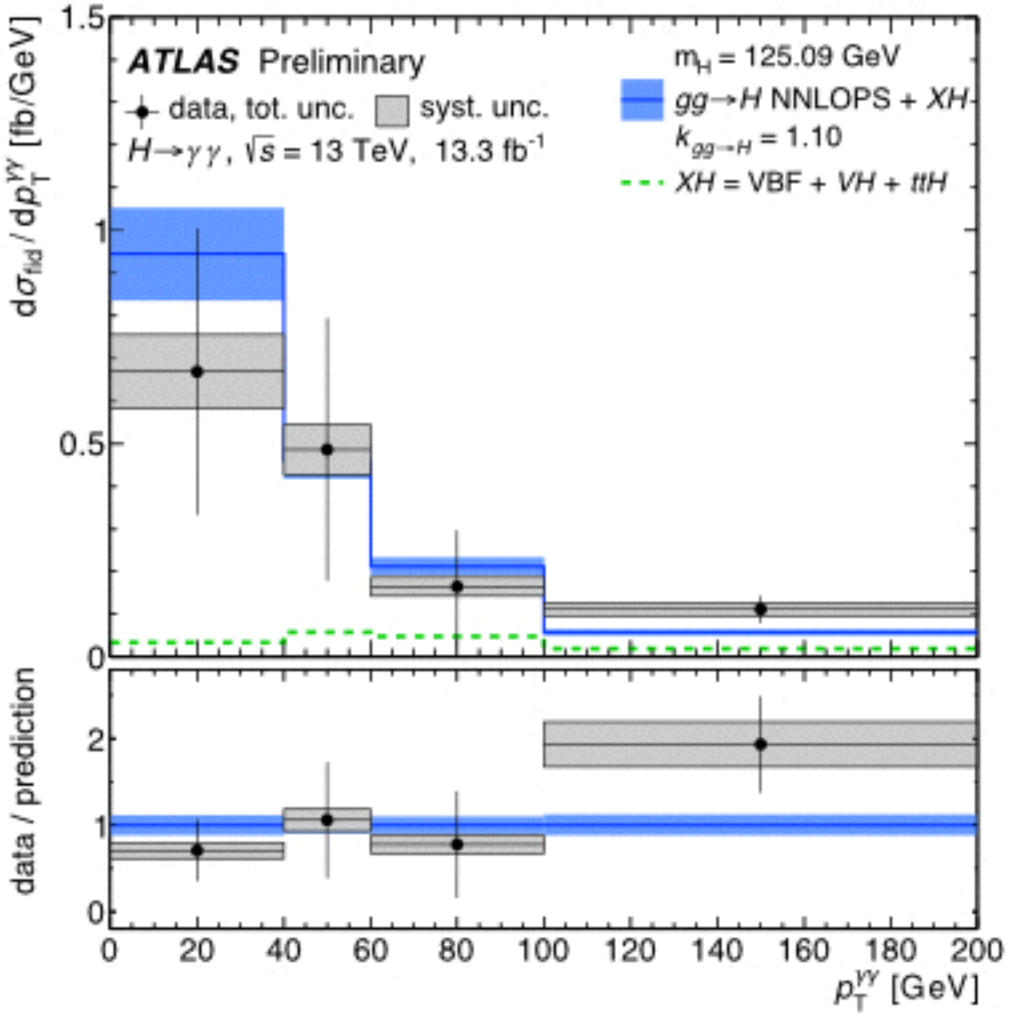


Statistics limited & in full agreement with theory predictions

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

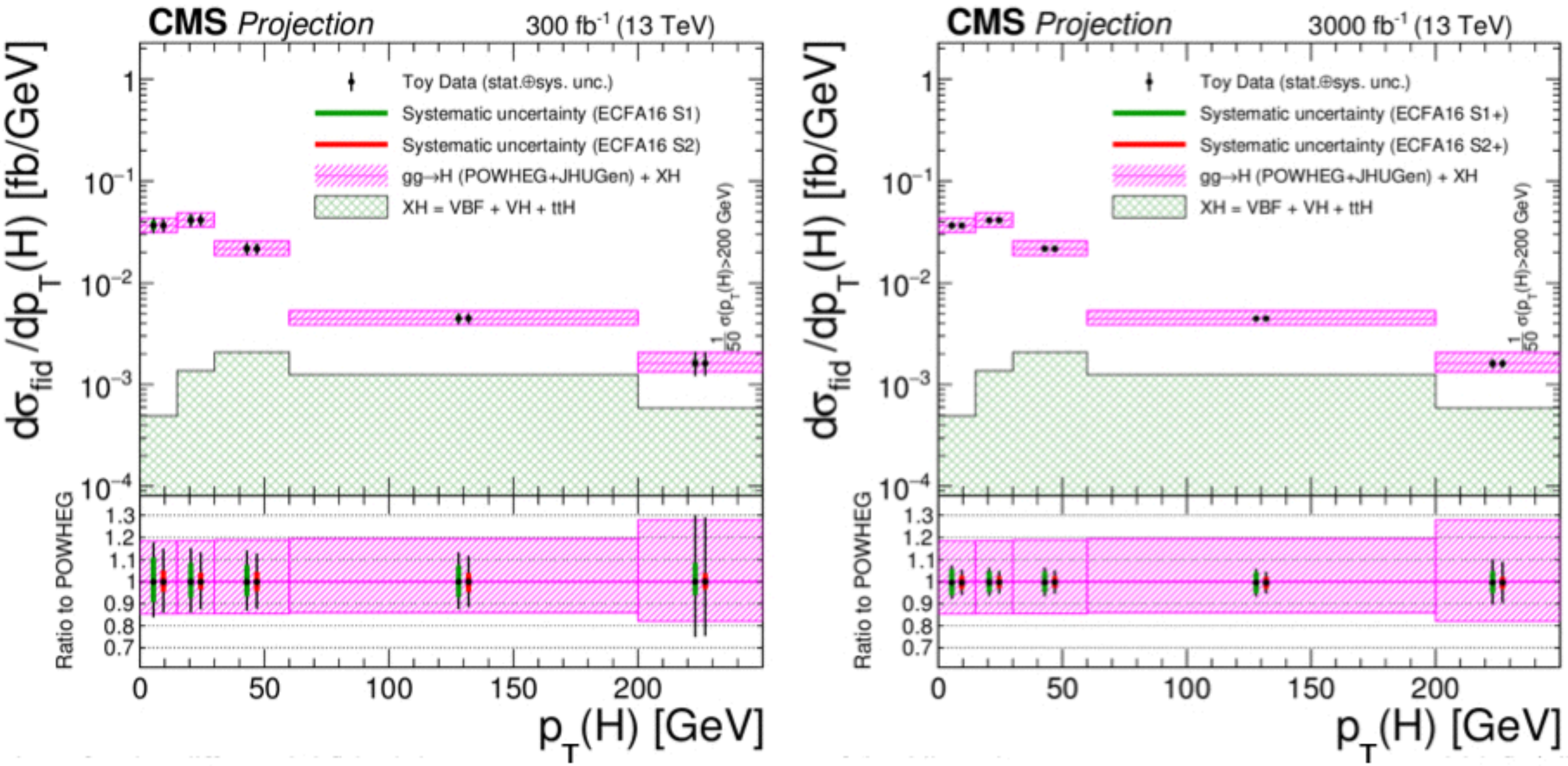


CMS PAS HIG-16-033



ATLAS-CONF-2016-067

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

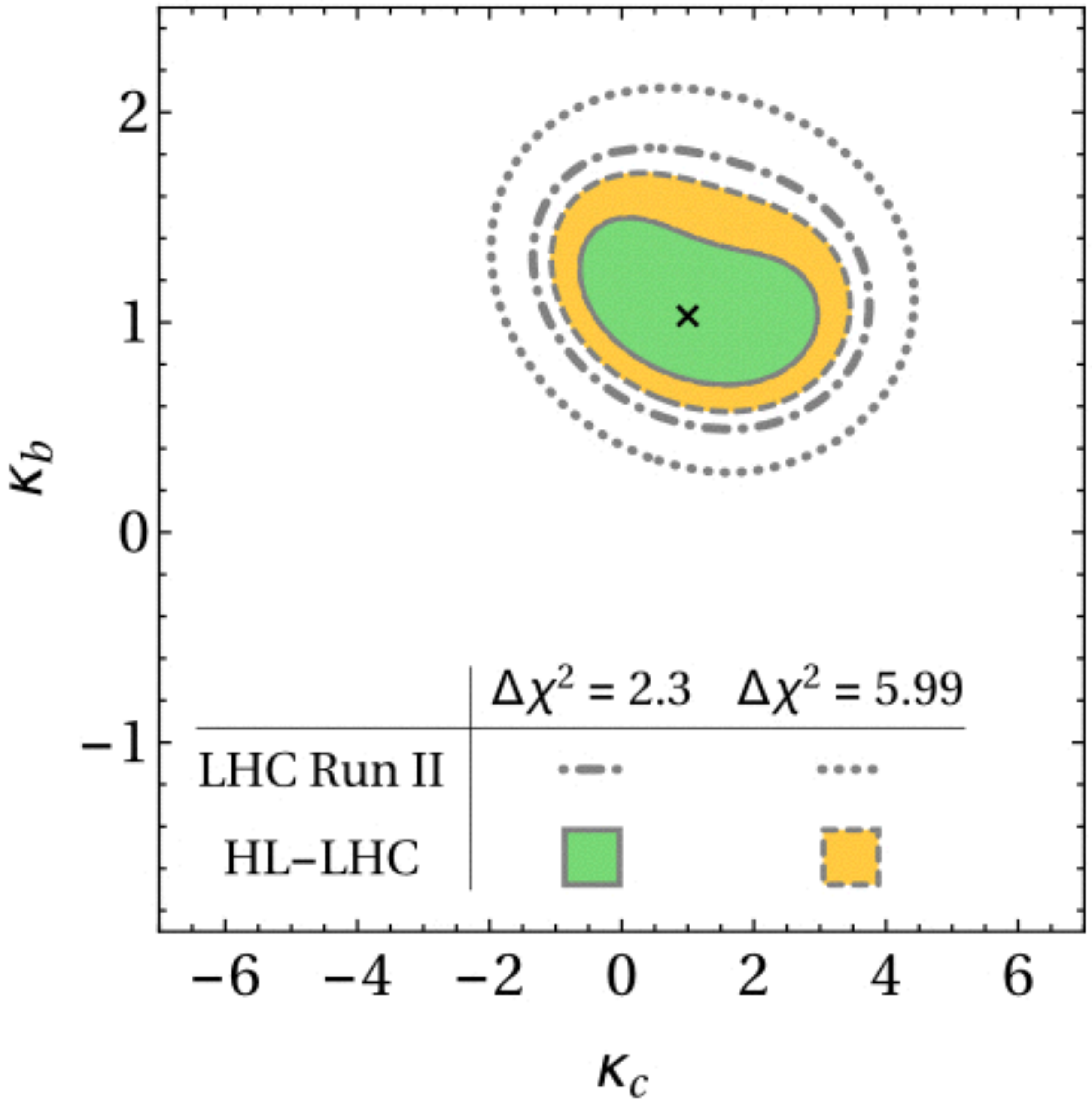


CMS-DP-2016-064

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

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

Bishara, UH, Monni & Re, 1606.09253



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

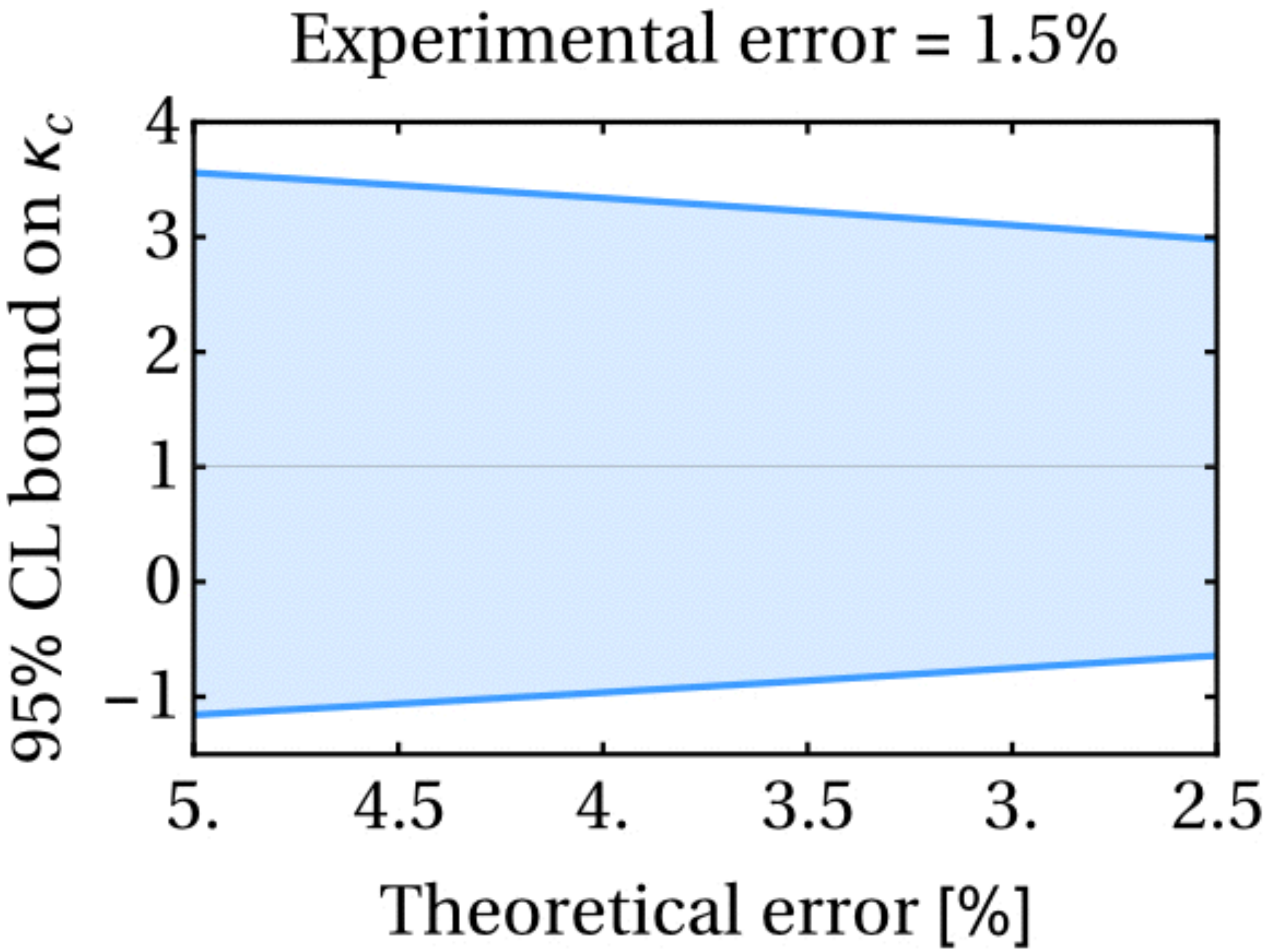
(LHC Run II)

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

(HL-LHC)

†95% CL after profiling over κ_b

Impact of theory error at HL-LHC



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