Measuring Higgs coupling to charm quark

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arXiv: 1503.00290 and 1505.06689

Higgs in Standard Model

Spin, Charge   Mass   Coupling

Higgs in Standard Model

Spin, Charge   Mass   Coupling

Neutral Scalar: Higgs?

Higgs in Standard Model

Spin, Charge   Mass   Coupling

Neutral Scalar: Higgs?

Measure Unknown SM parameter

Higgs in Standard Model

Spin, Charge   Mass   Coupling

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Higgs in Standard Model

Spin, Charge   Mass   Coupling

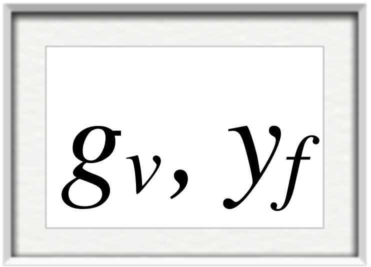
Neutral Scalar: Higgs?

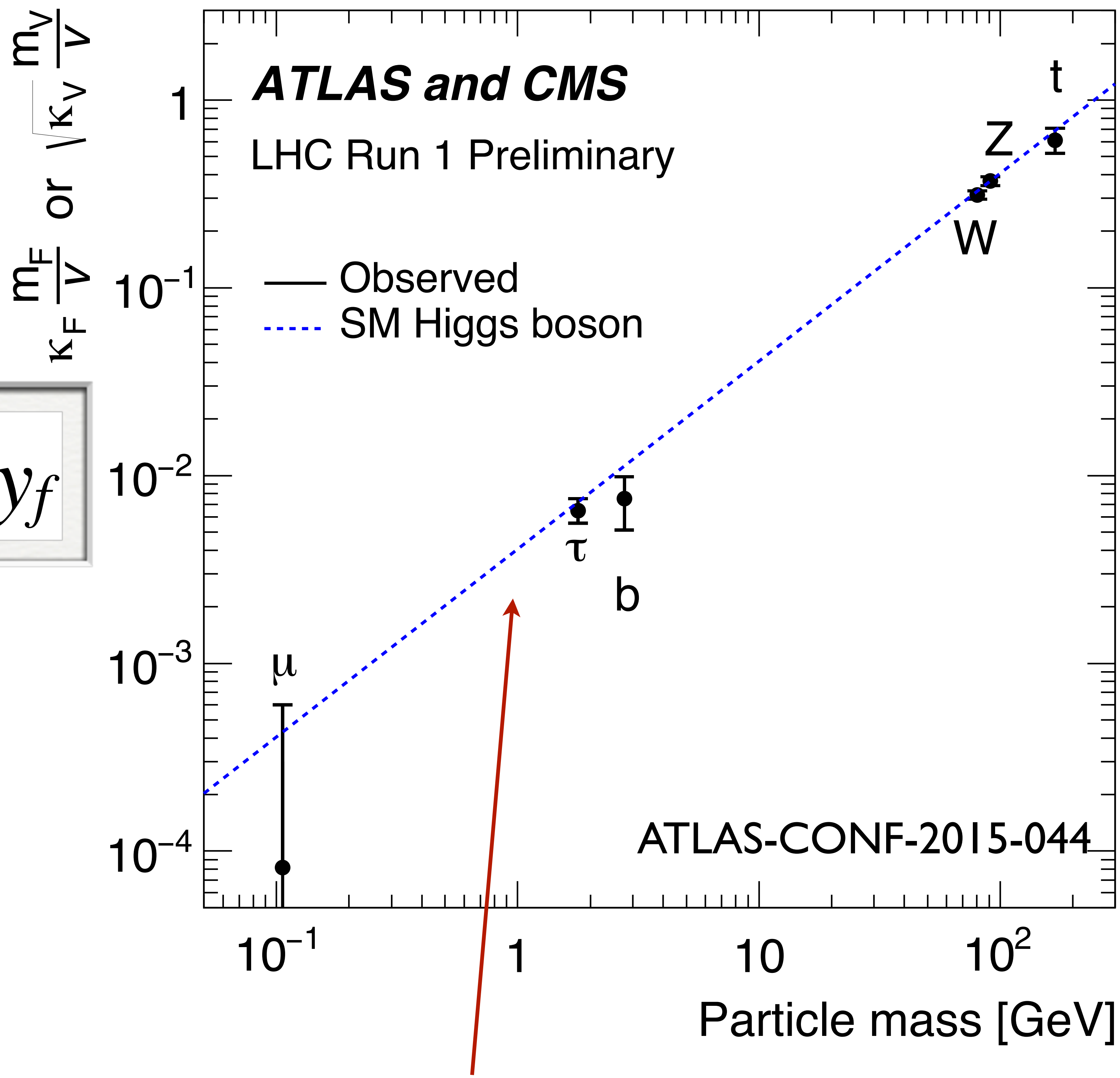
Measure Unknown SM parameter

Predicted as $y_X \simeq \sqrt{2}\frac{m_X}{v}$. Over-constraining SM

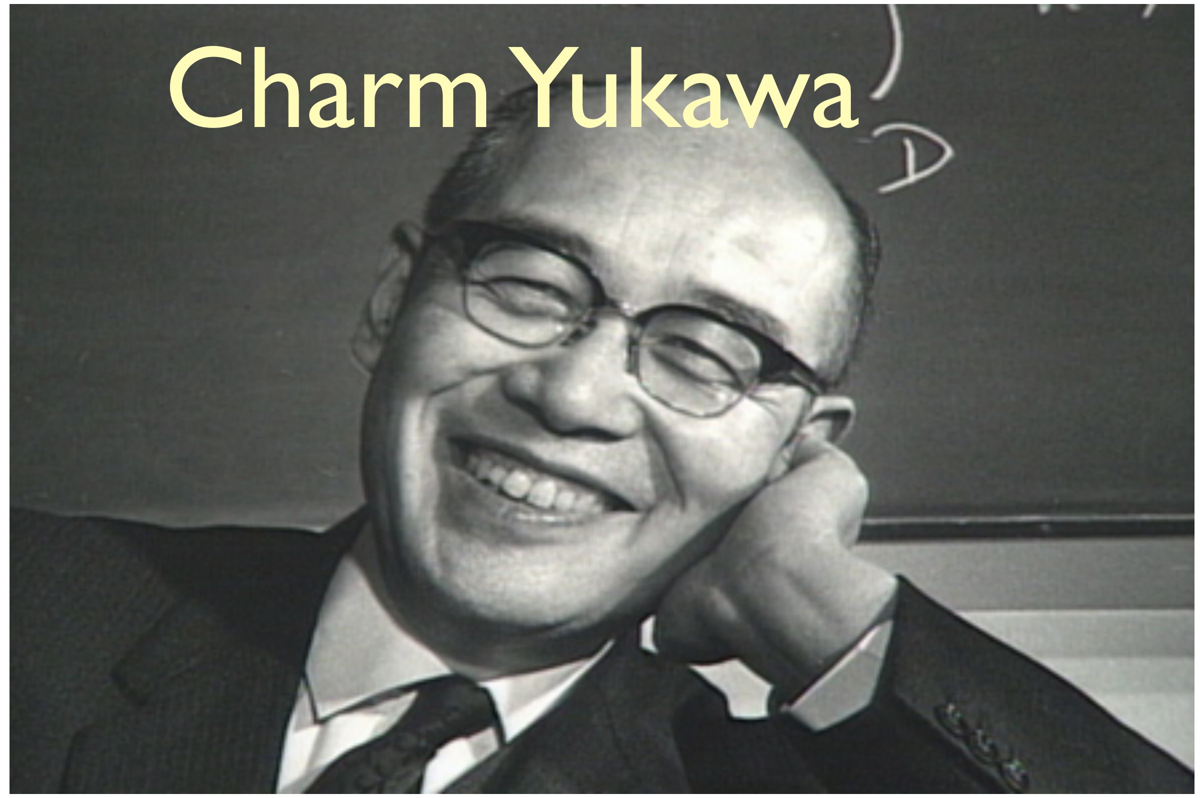
⇒Window of Beyond SM

Higgs Couplings at Run I





SM expects next strongest coupling is charm Yukawa



1. Inclusive

$h \to cc$

2. Exclusive

$h \to J/\psi + \gamma$

Inclusive

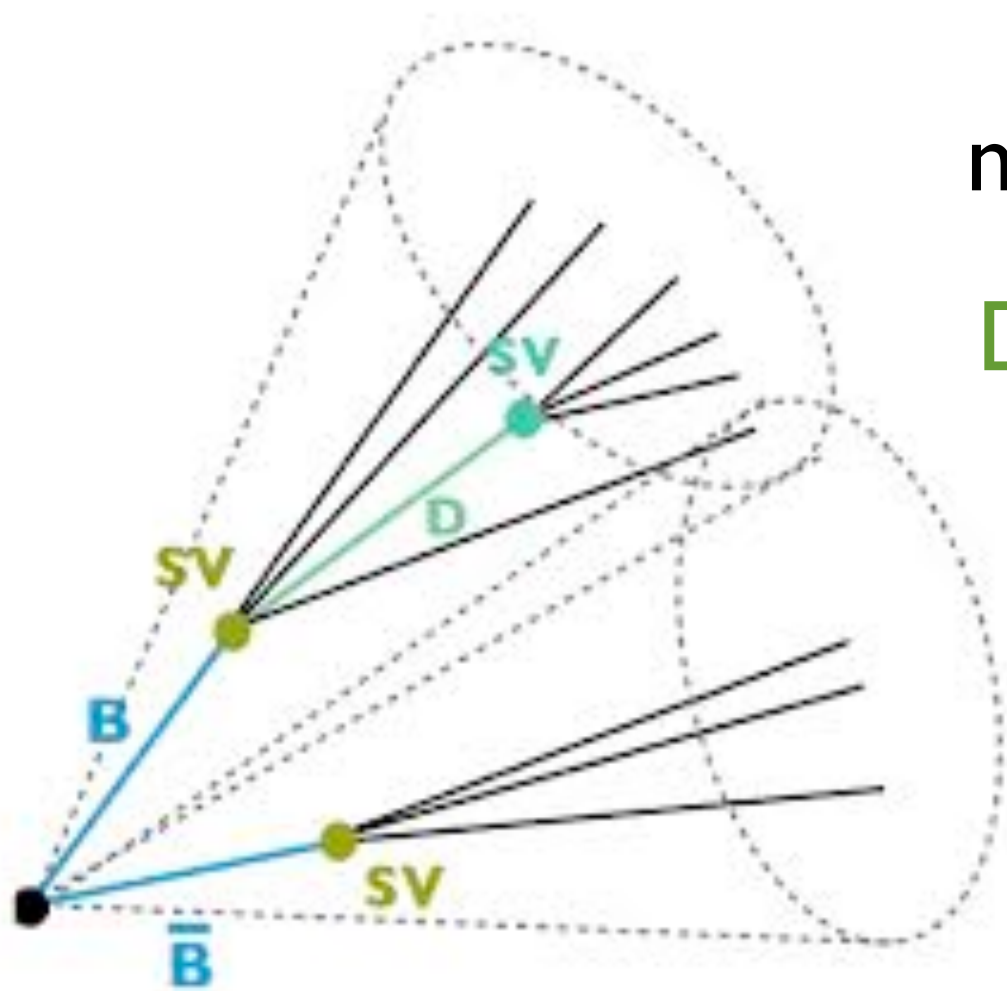
$h \to cc$

recasting $h \to bb$ analysis

b-tagging to study H→bb

b-jet is distinguished from other jets

Secondary Vertex: B-meson is long-lived ~440μm/c
fly in the detector

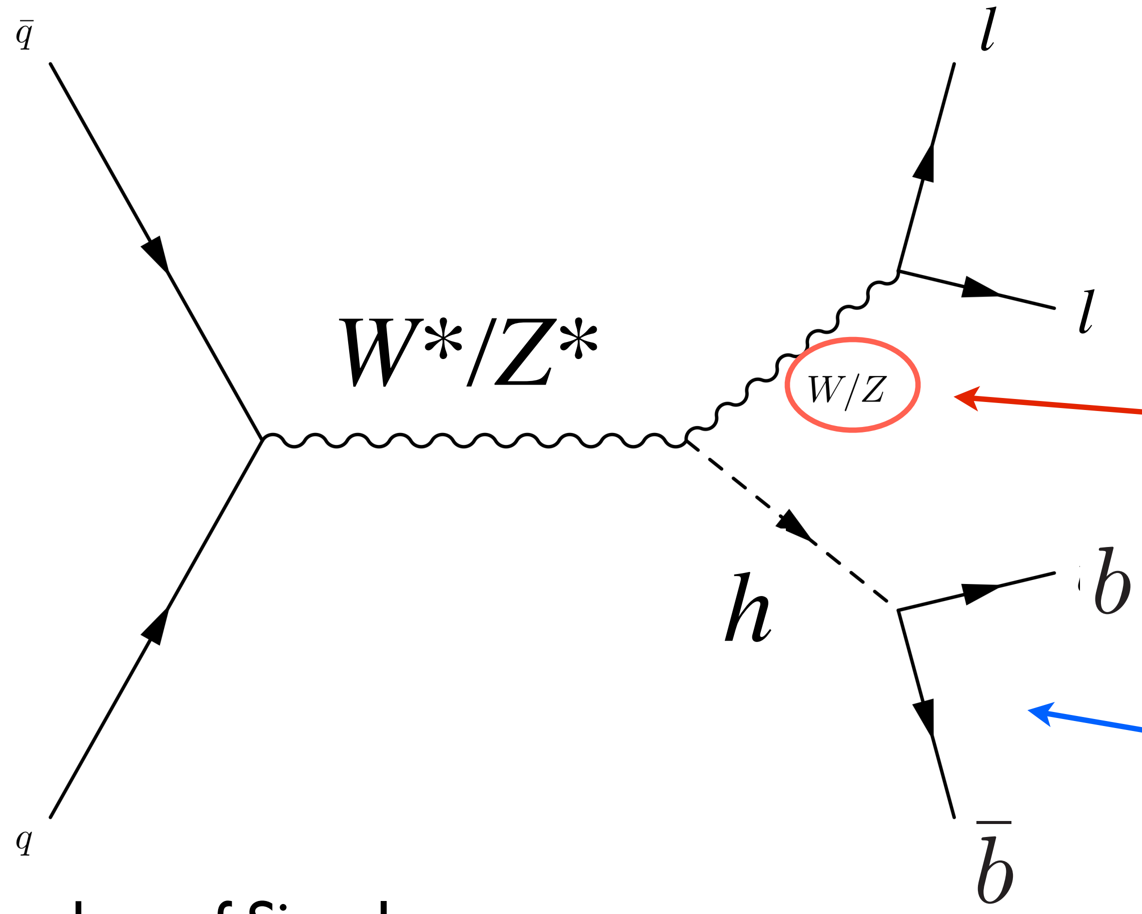


main *issue*: Mistag

D-meson, also long-lived
~120-310μm/c

c-jet 4-40%,
light jet: O(0.1-1)%

Vh (Associate) production



0, 1, 2 lep

W/Z reconstructed

2 b-tags required

ATLAS	Med	Tight	CMS	Loose	Med1	Med2	Med3
ϵ_b	70%	50%	ϵ_b	88%	82%	78%	71%
ϵ_c	20%	3.8%	ϵ_c	47%	34%	27%	21%

Number of Signal

$$S^{VH} = \mathcal{L} \cdot \sigma \cdot \mathrm{Br}_b \cdot \epsilon_{b_1} \epsilon_{b_2} \cdot \epsilon$$

Tagging Efficiency of b-jet

Signal strength

$$\mu_b = \frac{S^{VH}_{obs}}{S^{VH}_{exp}} = \frac{\mathcal{L} \cdot \sigma \cdot \mathrm{Br}_b \cdot \epsilon_{b_1} \epsilon_{b_2} \cdot \epsilon}{\mathcal{L} \cdot \sigma_{SM} \cdot \mathrm{Br}^{SM}_b \cdot \epsilon_{b_1} \epsilon_{b_2} \cdot \epsilon} = \frac{\sigma \cdot \mathrm{Br}_b}{\sigma_{SM} \cdot \mathrm{Br}^{SM}_b}$$

$\mu_b^{\mathrm{ATLAS}} = 0.52 \pm 0.32 \pm 0.24$ $\quad \mu_b^{\mathrm{CMS}} = 1.0 \pm 0.5$ $\Rightarrow$ **bottom Yukawa**

ATLAS [arXiv:1409.6212] CMS [arXiv:1310.3687]

What if H→cc is enhanced?

$$\mu_b = \frac{S^{VH}_{obs}}{S^{VH}_{exp}} = \frac{\cancel{\mathcal{L}} \cdot \sigma \cdot \mathrm{Br}_b \cdot \epsilon_{b_1}\epsilon_{b_2} \cdot \cancel{\epsilon}}{\cancel{\mathcal{L}} \cdot \sigma_{SM} \cdot \mathrm{Br}_b^{SM} \cdot \epsilon_{b_1}\epsilon_{b_2} \cdot \cancel{\epsilon}}$$

$$\Rightarrow \frac{\sigma \cdot \mathrm{Br}_b \cdot \epsilon_{b_1}\epsilon_{b_2} + \sigma \cdot \mathrm{Br}_c \cdot \epsilon_{c_1}\epsilon_{c_2}}{\sigma_{SM} \cdot \mathrm{Br}_b^{SM} \cdot \epsilon_{b_1}\epsilon_{b_2}}$$

$$= \mu_b + \frac{\mathrm{Br}_c^{SM}}{\mathrm{Br}_b^{SM}} \frac{\epsilon_{c_1}\epsilon_{c_2}}{\epsilon_{b_1}\epsilon_{b_2}} \mu_c$$

$$\mu_b + (0.05\,\epsilon_{c/b})\mu_c$$

$$\mathrm{Br}^{\mathrm{SM}}(h \to c\bar{c}) = 2.9\%$$

$$\mathrm{Br}^{\mathrm{SM}}(h \to b\bar{b}) = 58\%$$

$$\epsilon_{c/b} \equiv \frac{\epsilon_{c1}\epsilon_{c2}}{\epsilon_{b1}\epsilon_{b2}}$$

Large $\epsilon_{c/b}$, more sensitive to μ_c

but only constrain a combination (degeneracy)

⇒ Need very different working points $\epsilon_{c/b}$

Collect info from ATLAS, use S/B>2.5%

ATLAS [arXiv:1409.6212]

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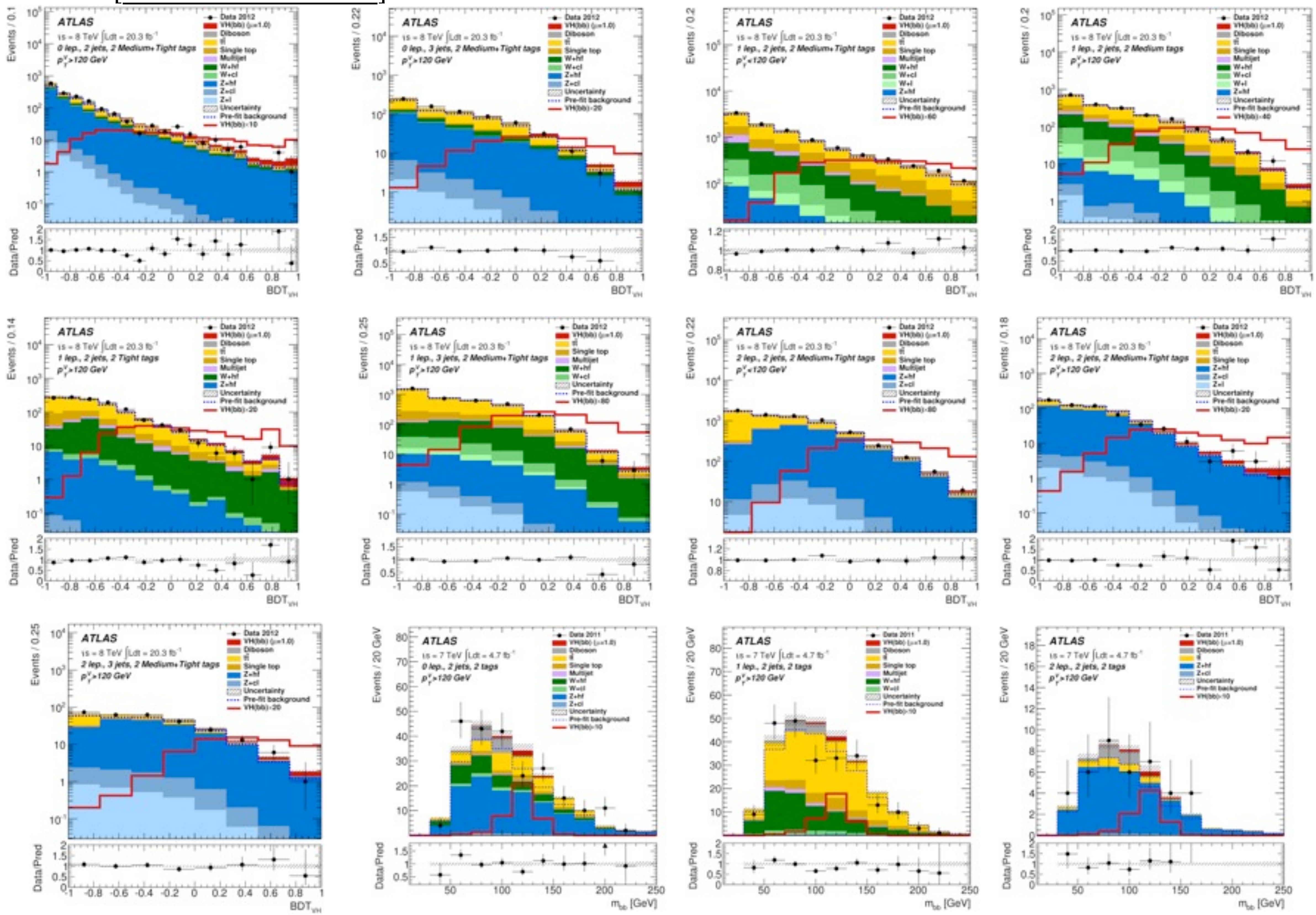
ATLAS [arXiv:1409.6212]



Collect info from CMS, use S/B>2.5%

CMS [arXiv:1310.3687] Phys.Rev. **D89** (2014) 012003

Please provide table or keep good resolution...

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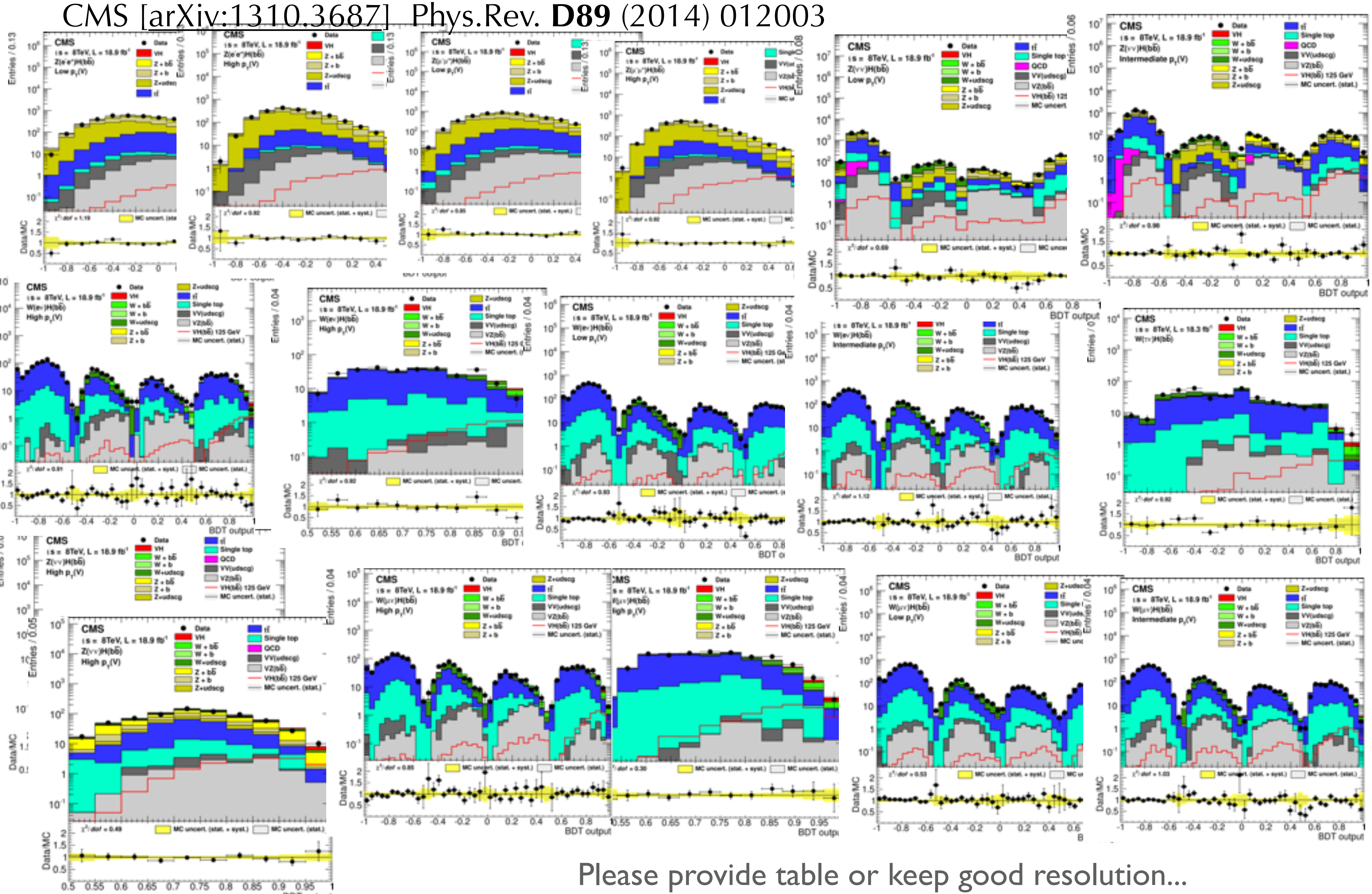

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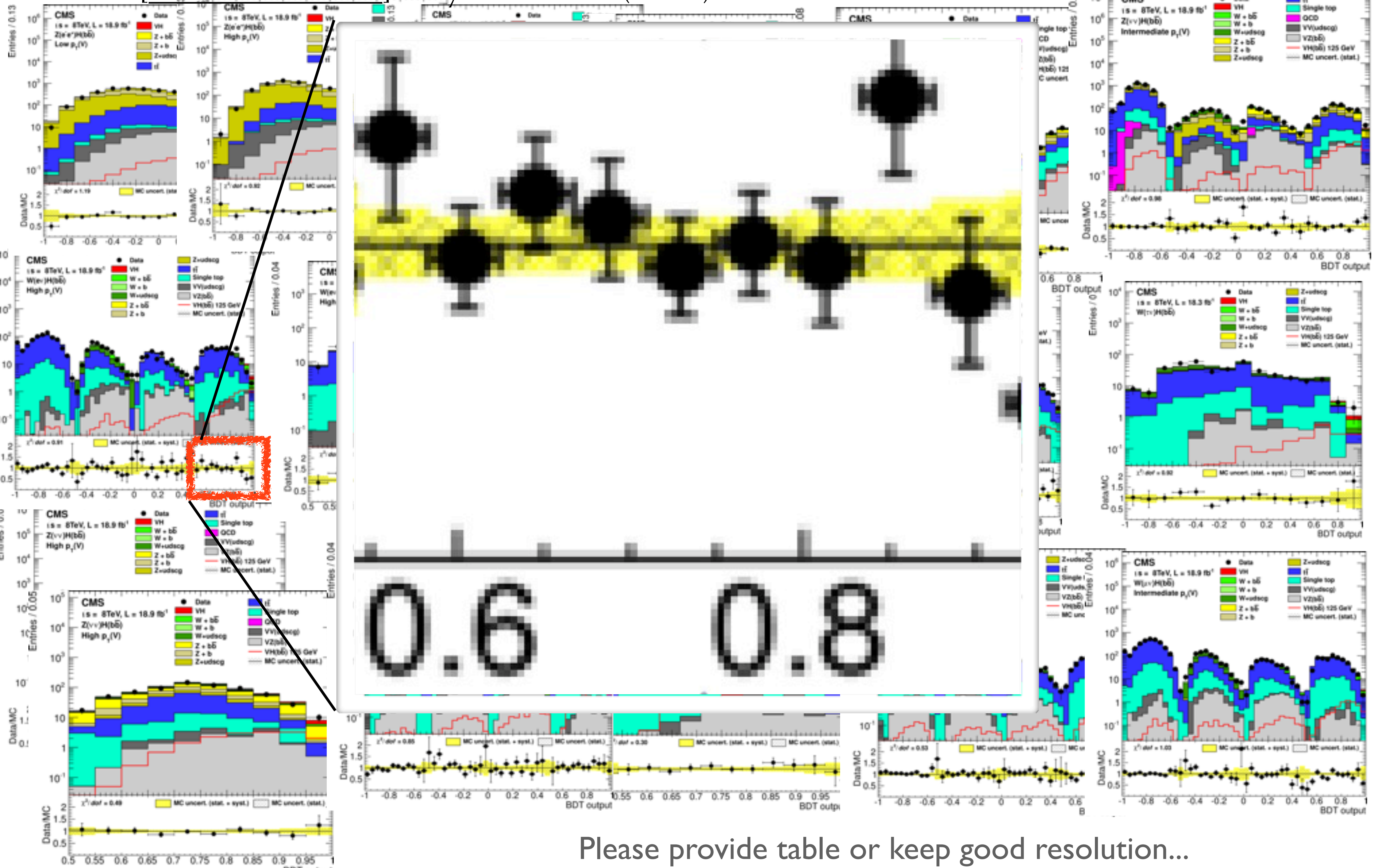

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Disentangle degeneracy

$\mu_b + (0.05\ \epsilon_{c/b})\mu_c$ ATLAS&CMS have different working points

	1st Tag	2nd Tag	$\epsilon_{c/b}$
(a)ATLAS	Med	Med	8.2×10^{-2}
(b)ATLAS	Tight	Tight	5.9×10^{-3}
(c)CMS	Med1	Med1	0.18
(d)CMS	Med2	Loose	0.19
(e)CMS	Med1	Loose	0.23
(f)CMS	Med3	Loose	0.16

$$L(\mu) = \prod_i P_{poiss}(k_i, N^{BG}_{SM,i} + \mu N^{signal}_{SM,i}).$$

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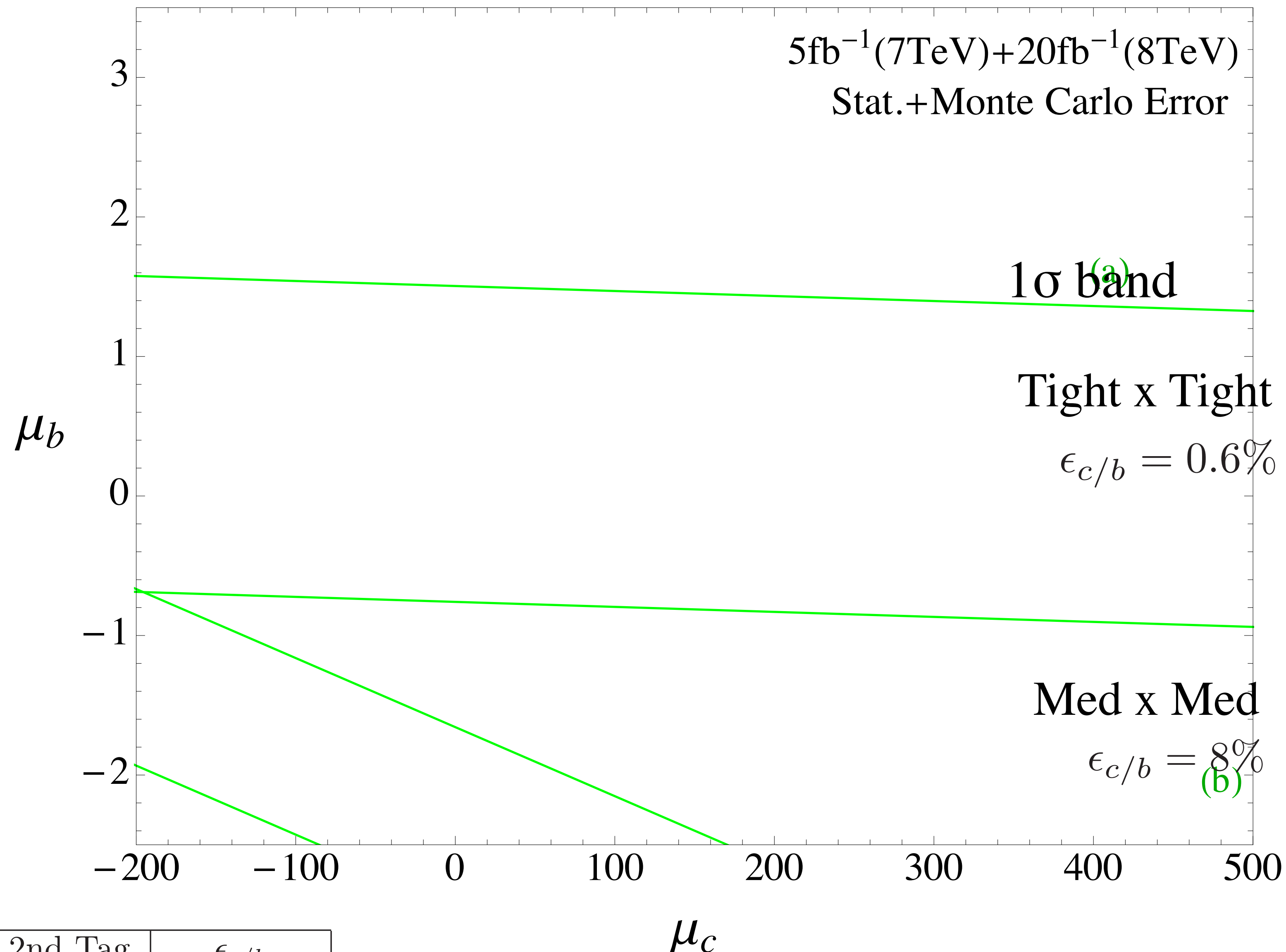

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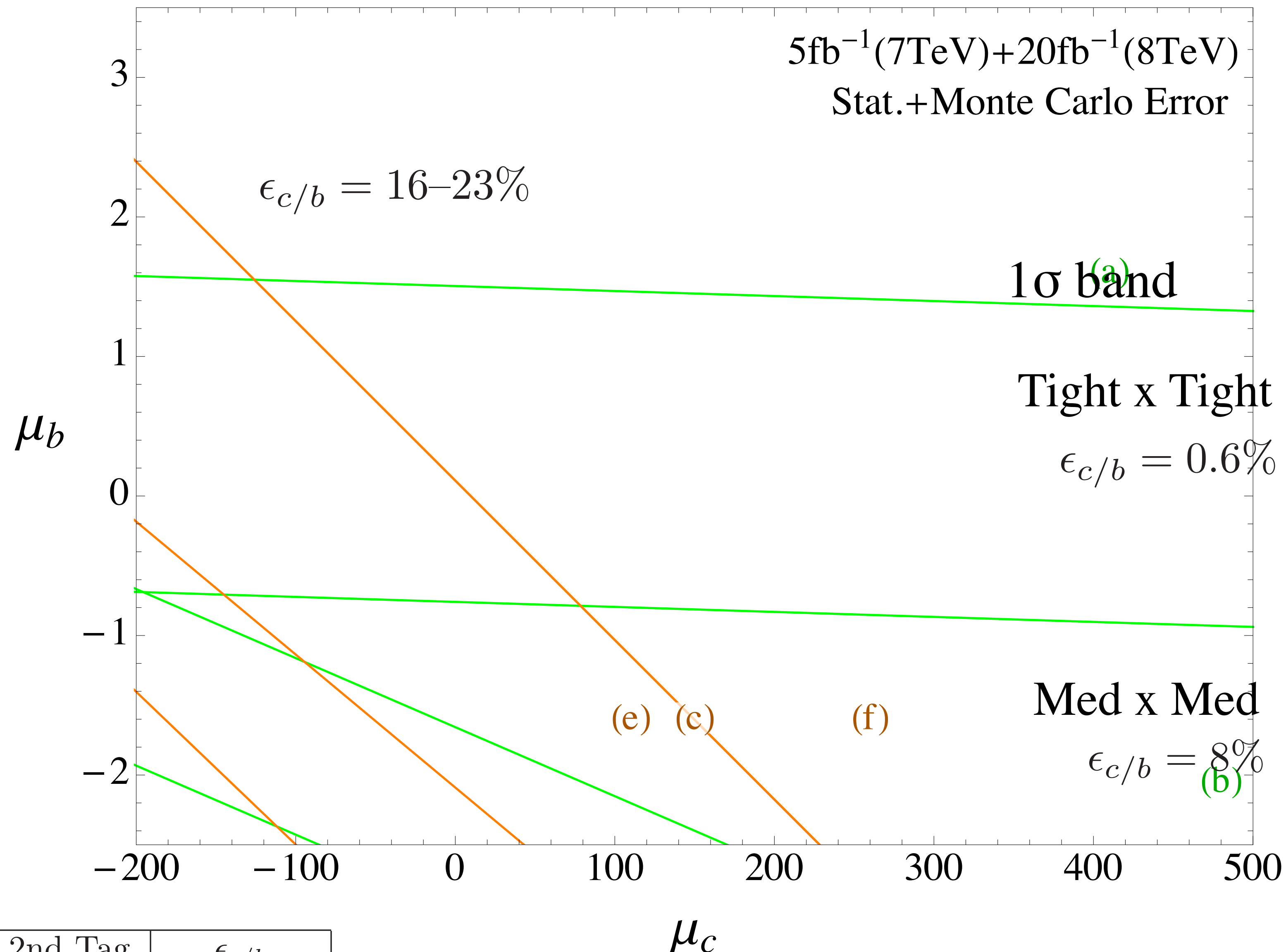

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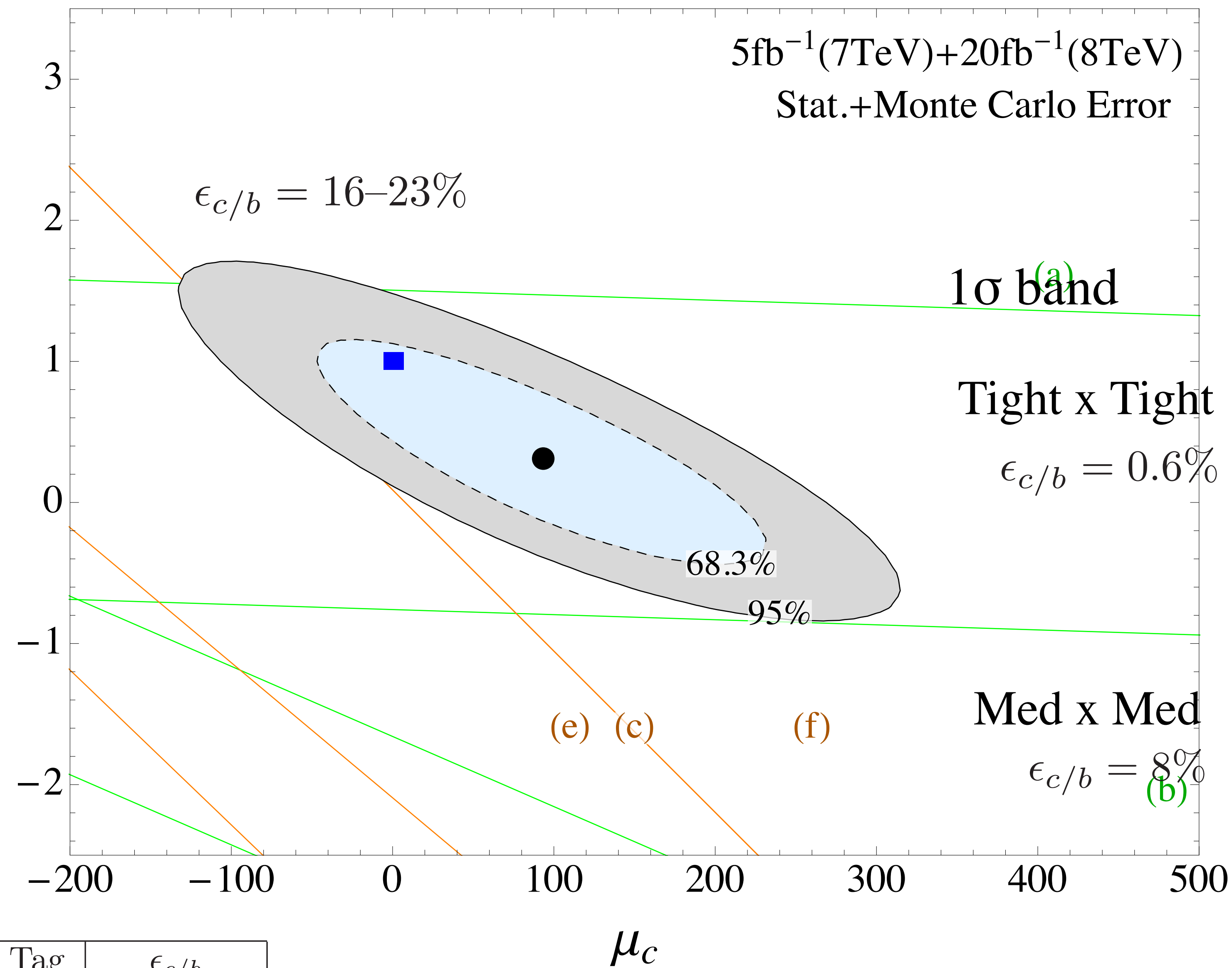

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$$L(\mu) = \prod_i P_{poiss}(k_i, N_{SM,i}^{BG} + \mu N_{SM,i}^{signal}).$$

Disentangle degeneracy

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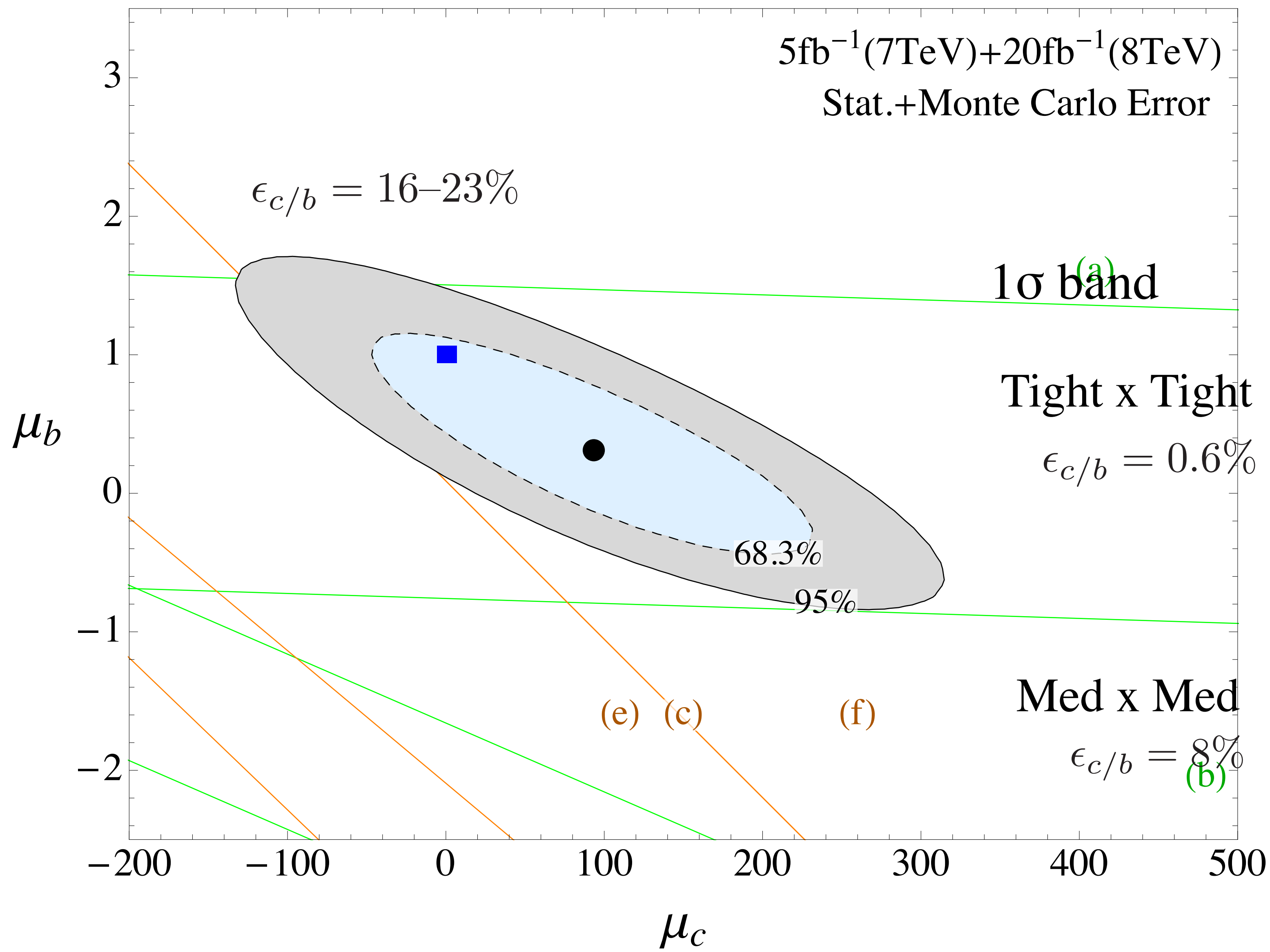


profiled μ_b

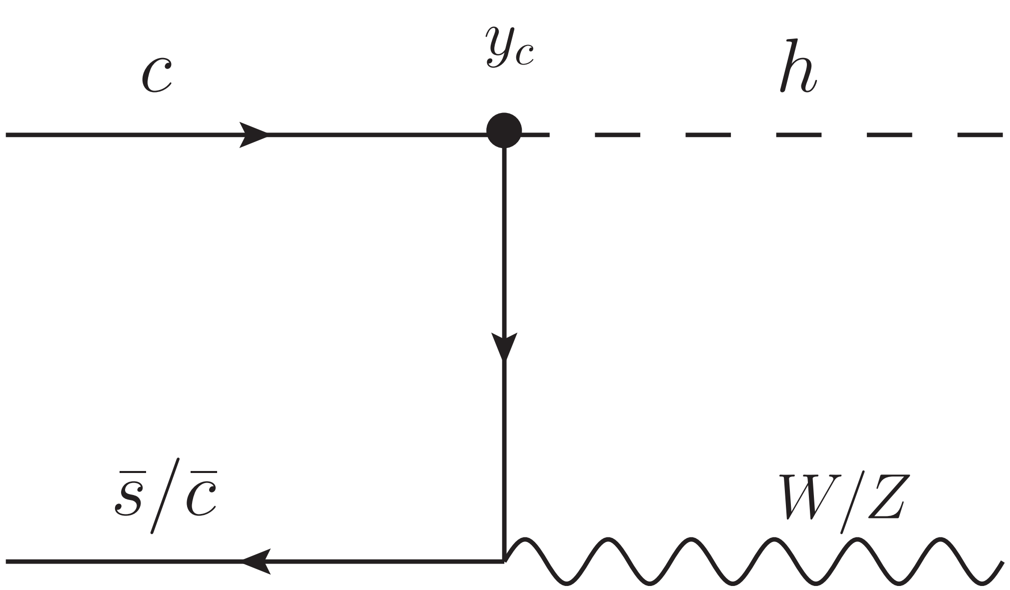
$$\mu_c = 95^{+90(175)}_{-95(180)} \text{ at } 68.3(95)\% \text{ CL.}$$

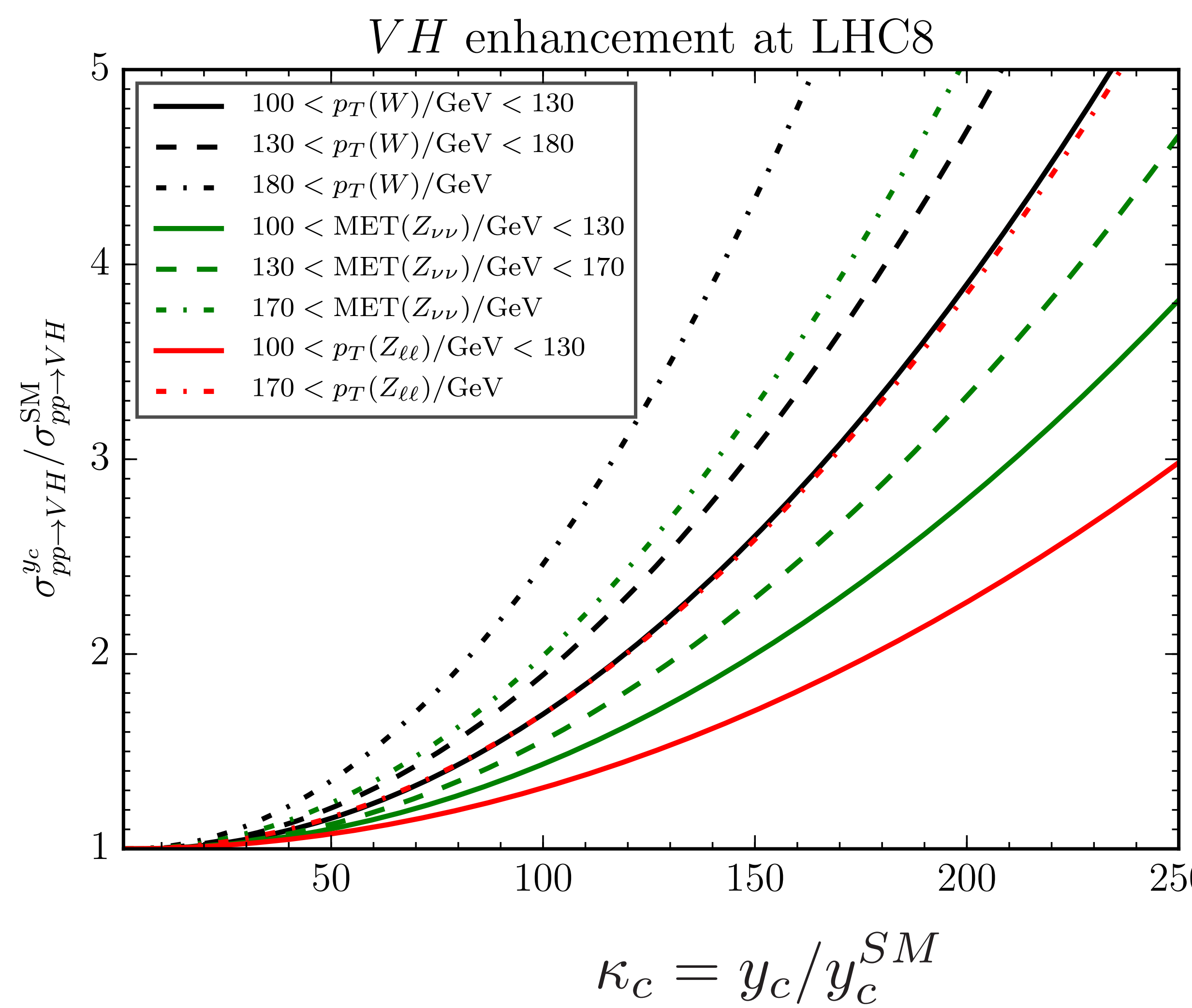
First bound on signal strength!

New Production by large Yukawa

Decay Br(H→cc)=100%, still μ_c=34

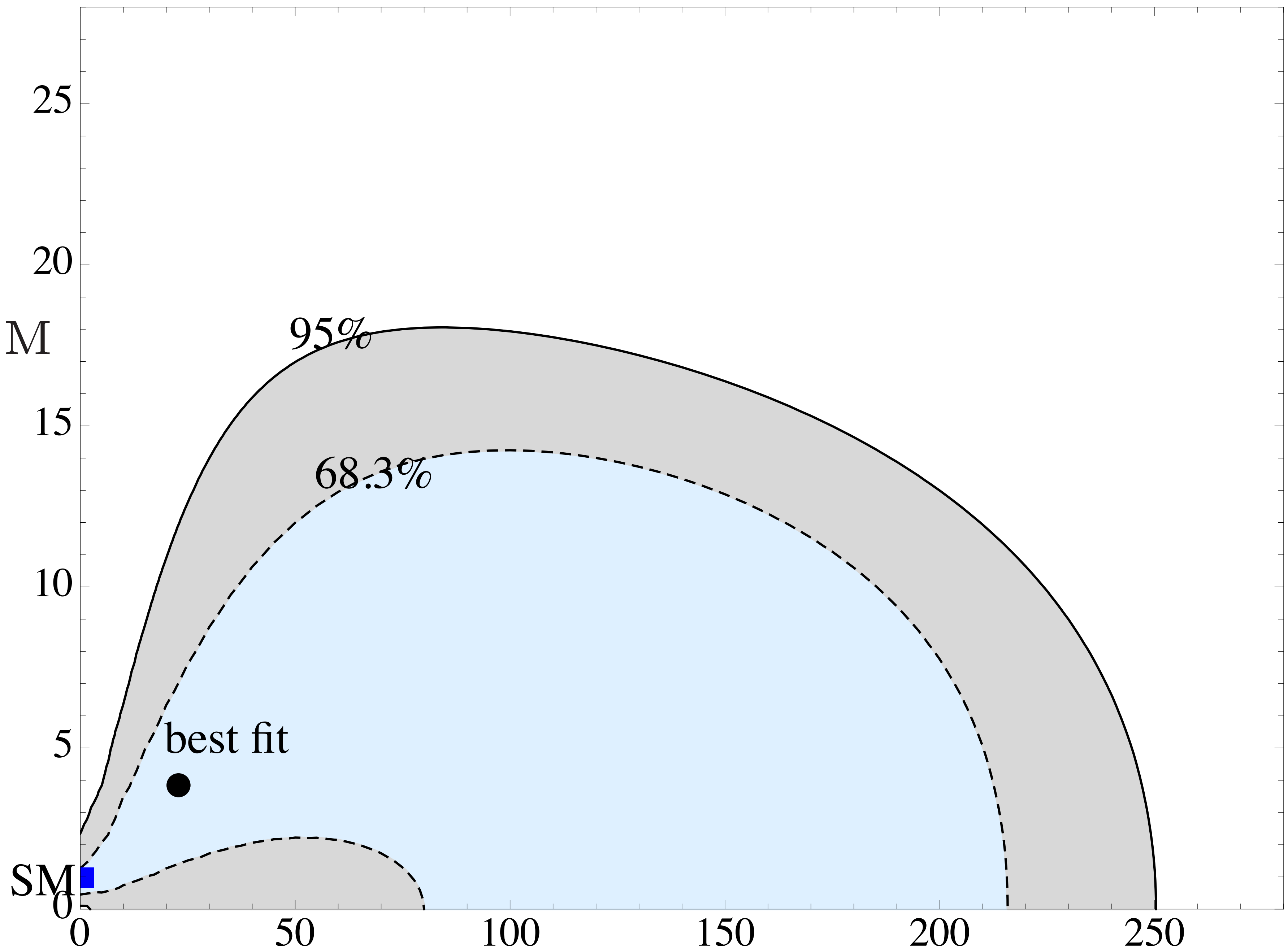
At large coupling $\kappa_c = y_c/y_c^{SM}$ ~100
switch on new production





Related work **[Brivio, Goertz, Isidori ('15)]**

First Bound on Coupling



$\kappa_b \equiv y_b / y_b^{\mathrm{SM}}$

$\kappa_c \equiv y_c / y_c^{\mathrm{SM}}$ $\kappa_c \lesssim 234$

combining with tth

$y_t \neq y_c$ Exclude Higgs-quark coupling universality

Inclusive channel at Future LHC

1. More Statistics

Better sensitivity of Vh→bb

$\Delta\mu_b \sim 0.5$ @ATLAS 8TeV

$\Delta\mu_b = 0.14$ @ATLAS Med (3000fb^{-1})

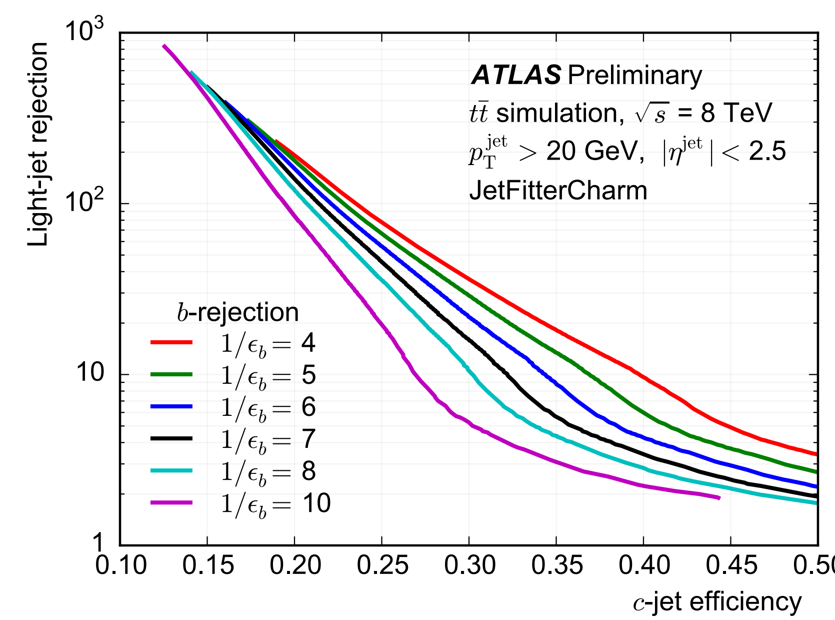
ATL-PHYS-PUB-2014-011 (1- and 2-lep channels)

Thanks for ATLAS for providing tables!

2. New Technology: Charm tagging

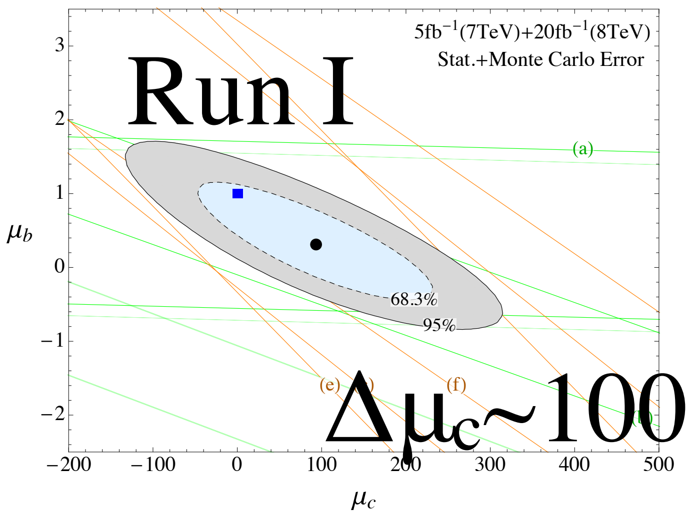
	ϵ_b	ϵ_c	$\epsilon_{\rm light}$	
Med:	70,	20,	1.25	(%)
	↓	↓	↓	
C-tag:	13,	19,	0.5	

Scharm study[arXiv:1501.01325]



Inclusive channel at Future LHC

More data and charm-tagging to disentangle μ_c



	ϵ_b	ϵ_c	ϵ_{light}		
C-tag:	13,	19,	0.5	(%)	$\epsilon_{c/b} \sim 2.13$

Inclusive channel at Future LHC

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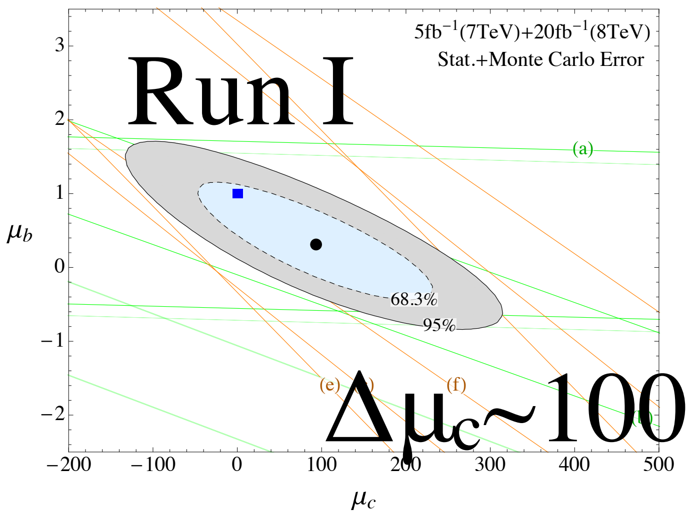

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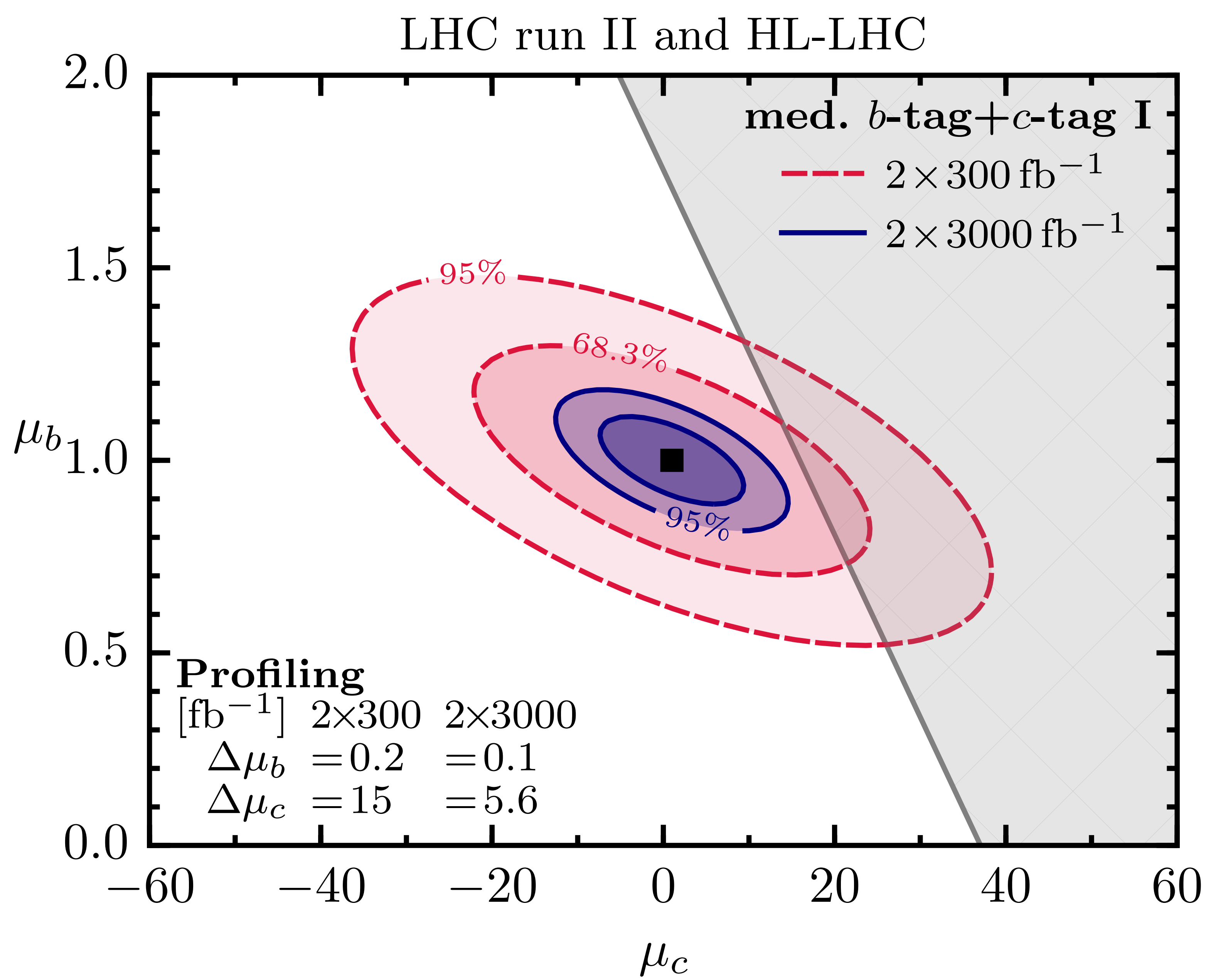
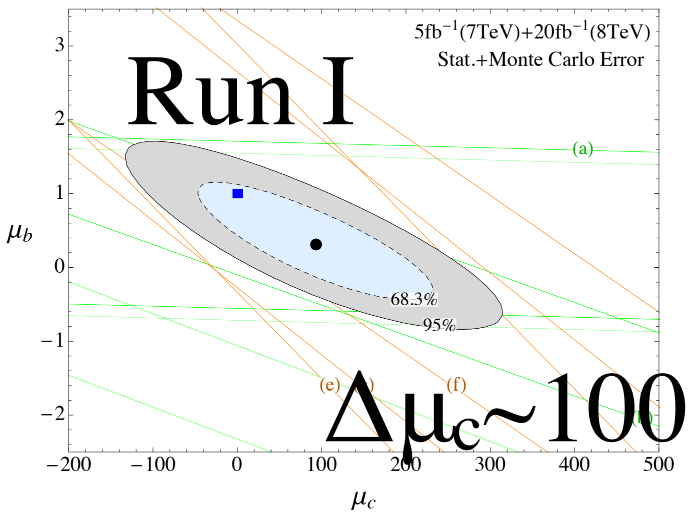


68%CL

$\Delta\mu_c$=15 (2x300fb^{-1})
=5.6 (2x3000fb^{-1})

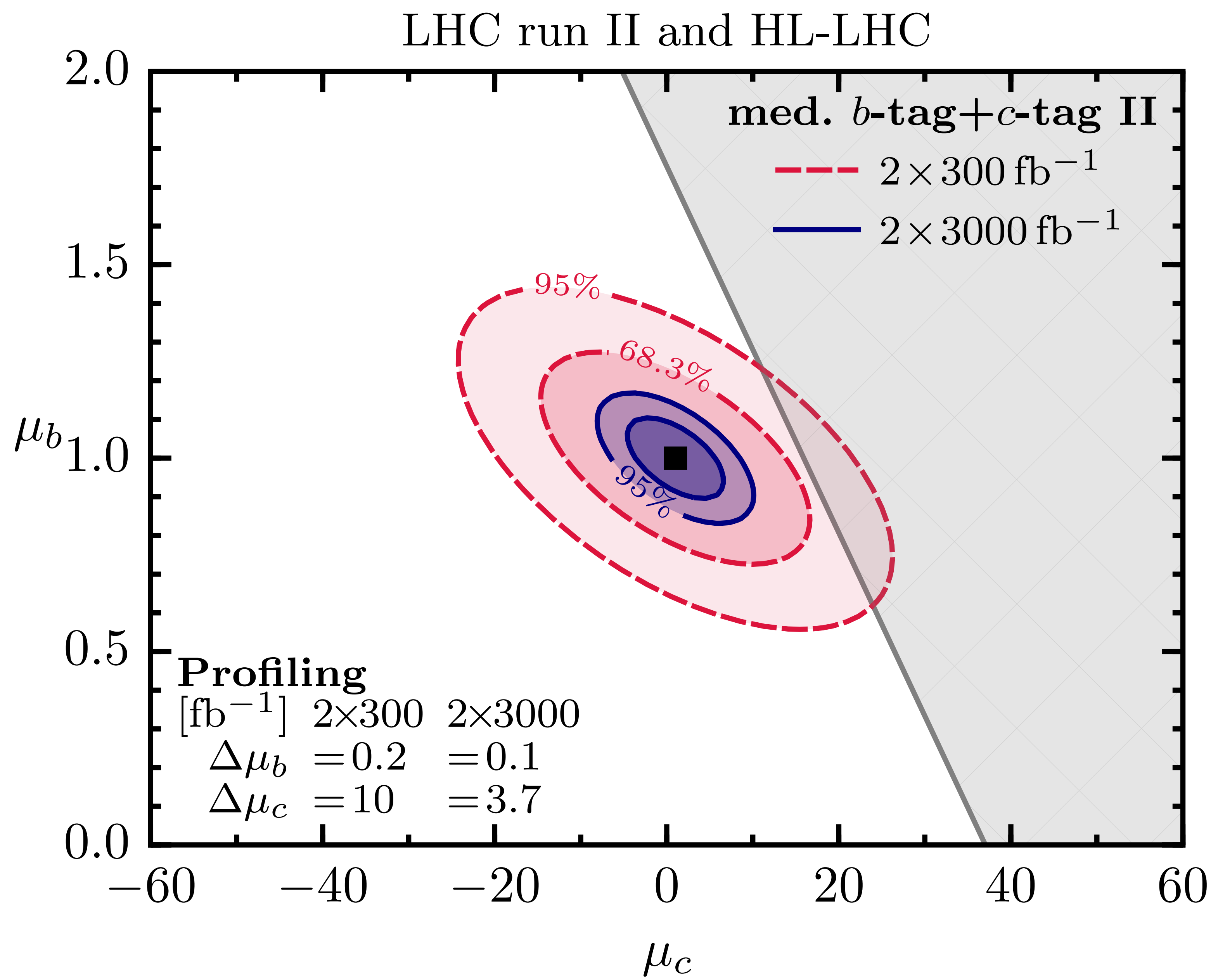
Inclusive channel at Future LHC

More data and charm-tagging to disentangle μ_c



Thanks to IBL

C-tag: ϵ_b 20, ϵ_c 30, ϵ_{light} 0.5 (%) $\epsilon_{c/b} \sim 2.25$

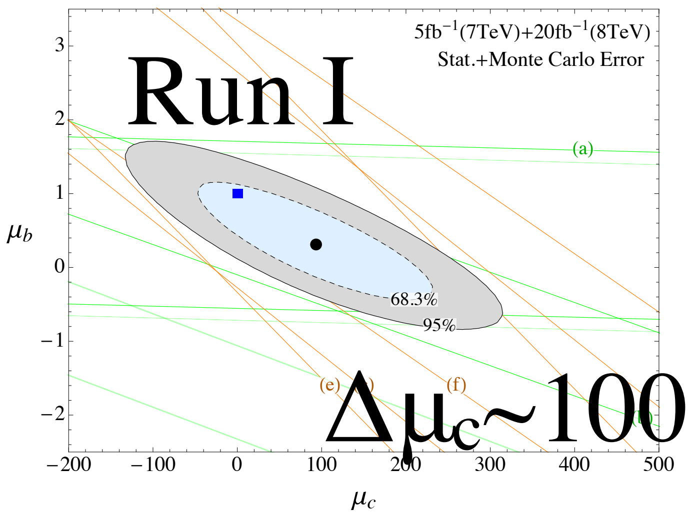


68%CL

$\Delta\mu_c$=10 ($2\text{x}300\text{fb}^{-1}$)
=3.7 ($2\text{x}3000\text{fb}^{-1}$)

Inclusive channel at Future LHC

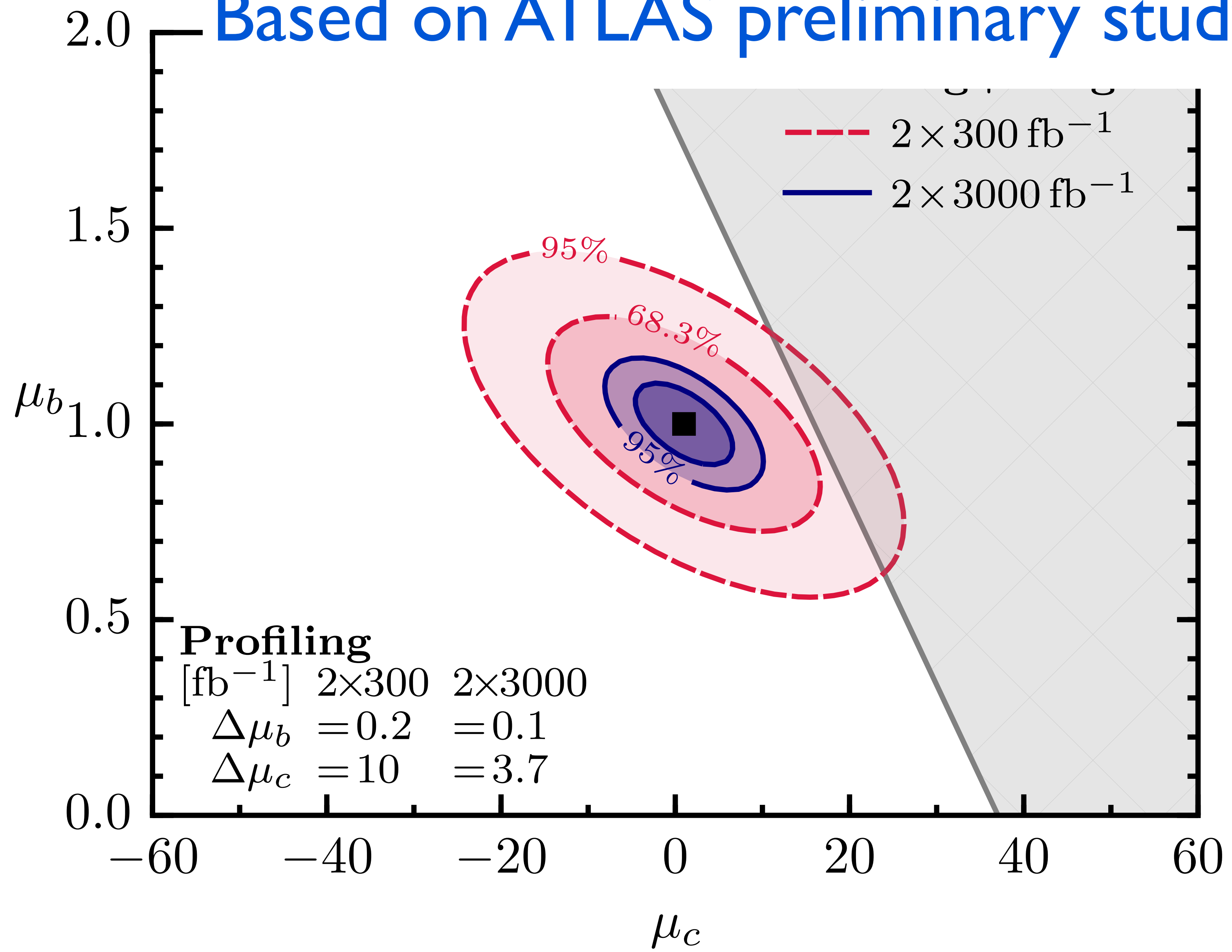
More data and charm-tagging to disentangle μ_c



Thanks to IBL

C-tag: ϵ_b 5, ϵ_c 20, ϵ_{light} 0.5 (%) $\epsilon_{c/b} \sim 16!$

Based on ATLAS preliminary study

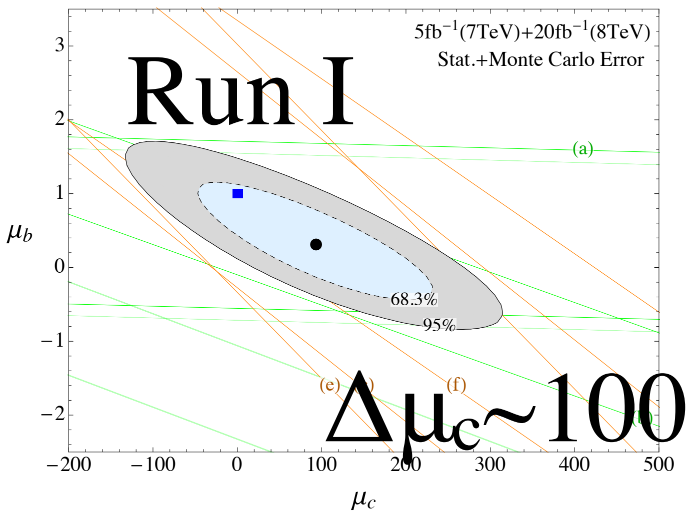


68%CL

$\Delta\mu_c$=10 (2x300fb^{-1})
=3.7 (2x3000fb^{-1})

Inclusive channel at Future LHC

More data and charm-tagging to disentangle μ_c



Thanks to IBL

C-tag: ϵ_b 5, ϵ_c 20, $\epsilon_{\rm light}$ 0.5 (%)

$\epsilon_{c/b} \sim 16!$

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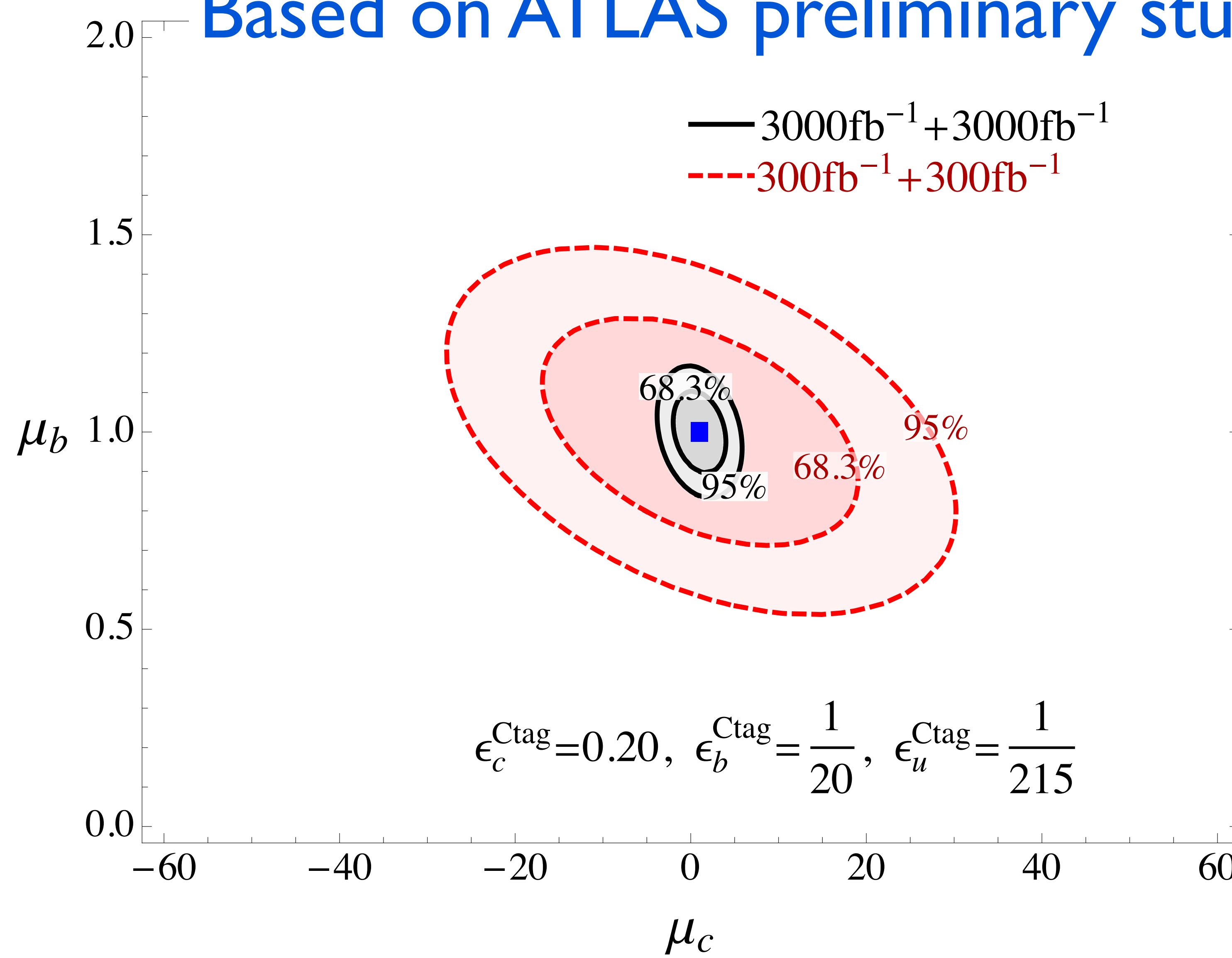


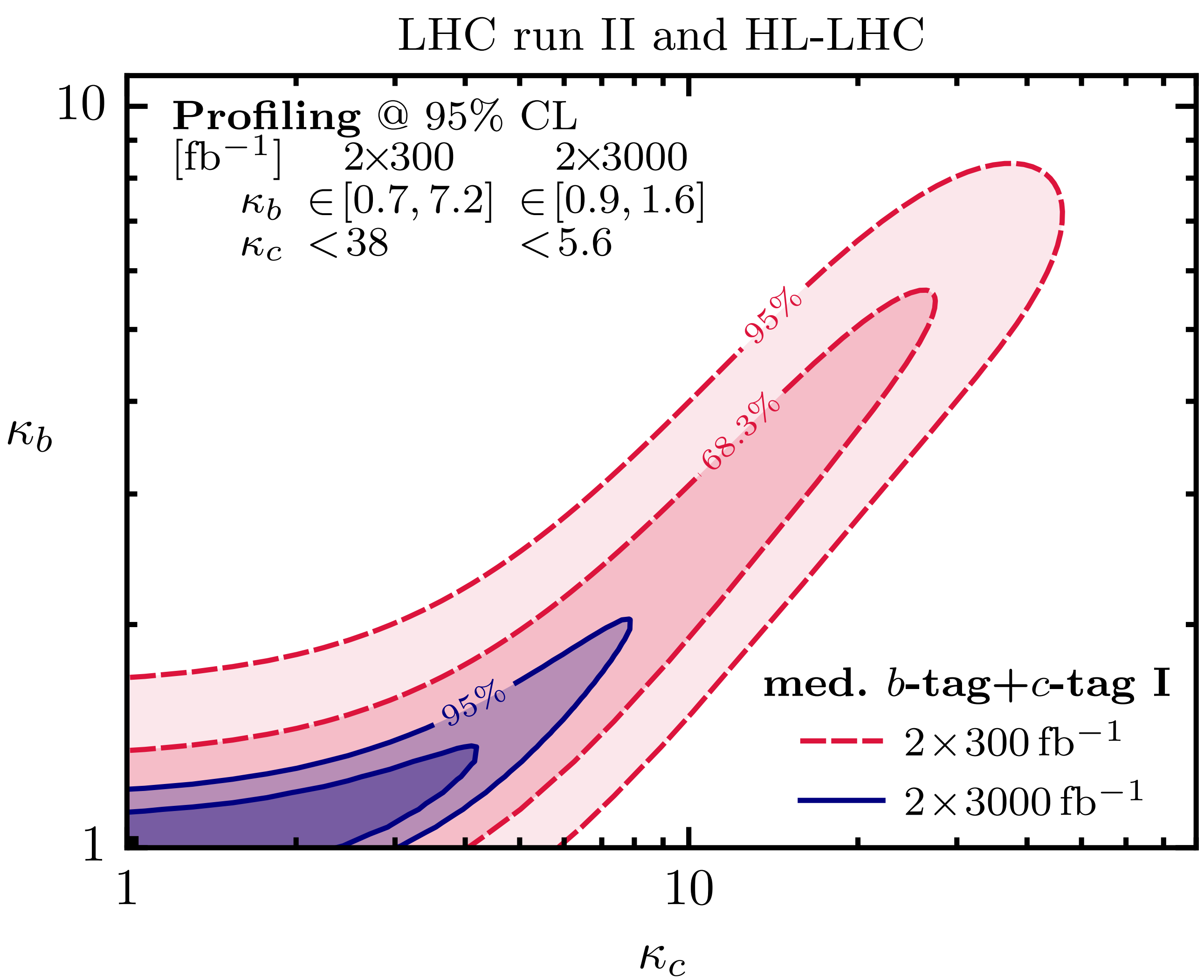
68%CL

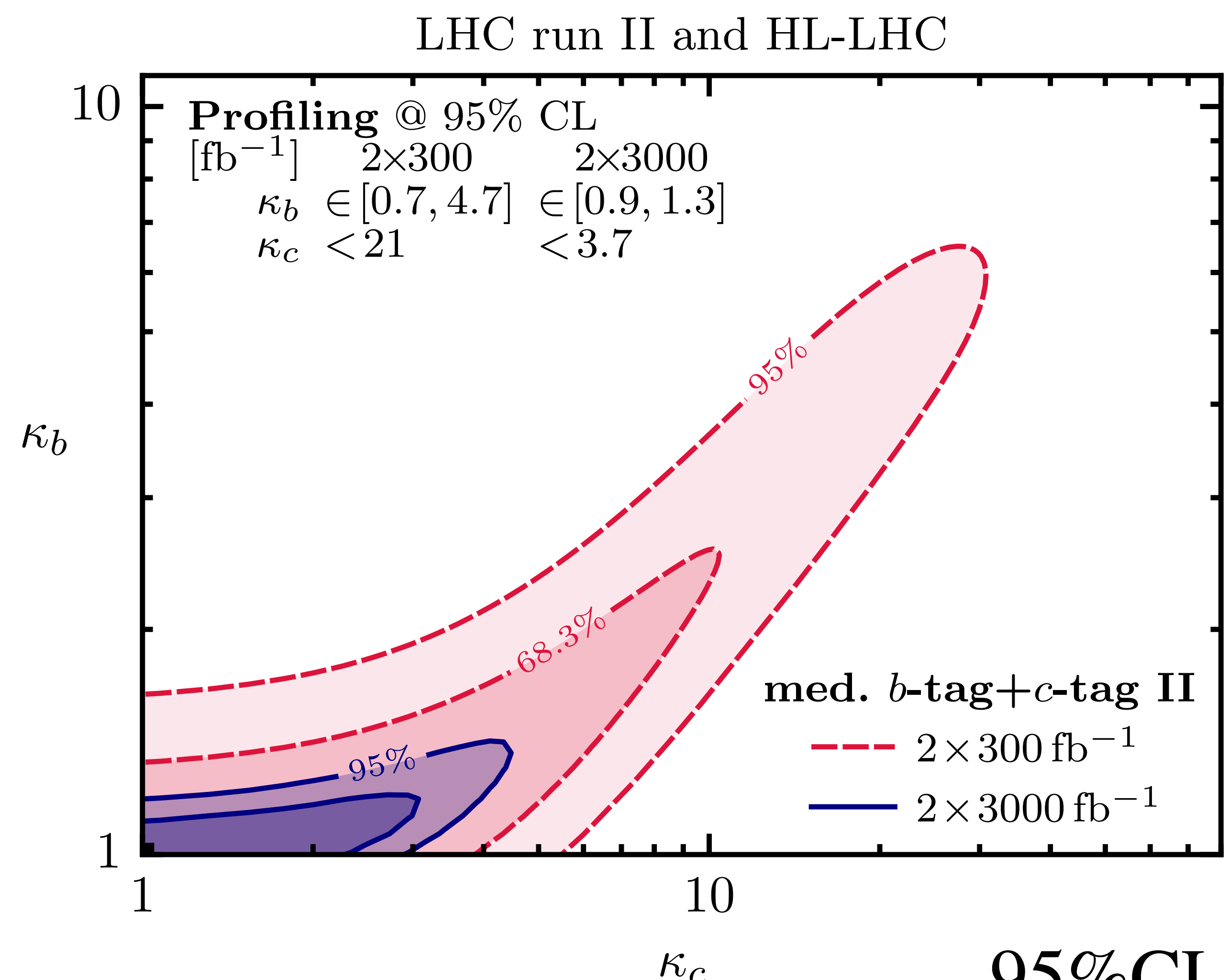
$\Delta\mu_c=2.8$ (2x3000fb^{-1})

Inclusive channel at Future LHC

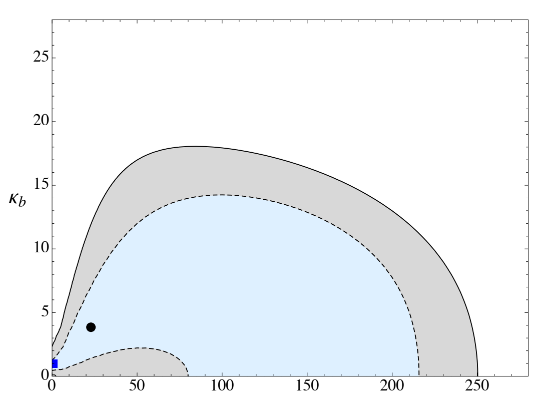
C-tag: ϵ_b ϵ_c ϵ_{light}: 13, 19, 0.5 (%)

ϵ_b ϵ_c ϵ_{light}: 20, 30, 0.5 (%)





95%CL



Run I

$\kappa_c \lesssim 234$

$\kappa_c < 21$ (2x300fb^{-1})

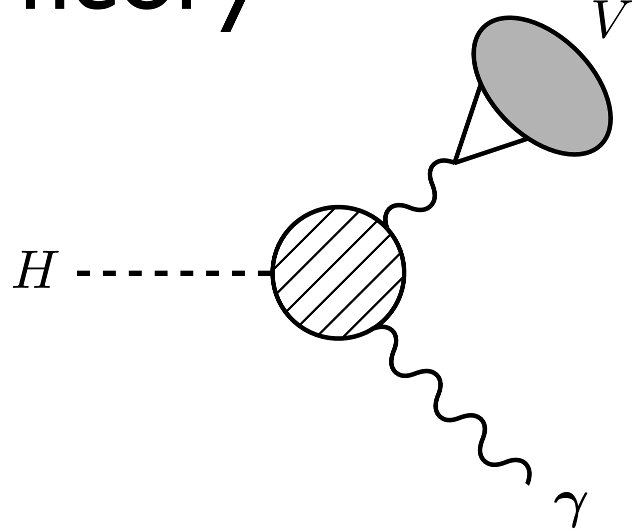
< 3.7 (2x3000fb^{-1})

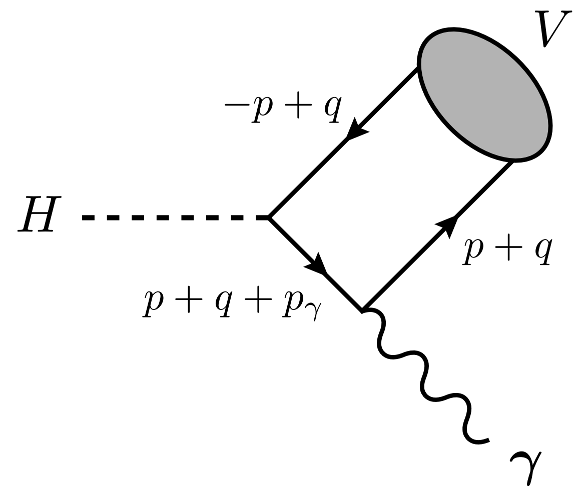
Exclusive

$h \to J/\psi + \gamma$

Exclusive J/ψ+γ channel

1.Theory

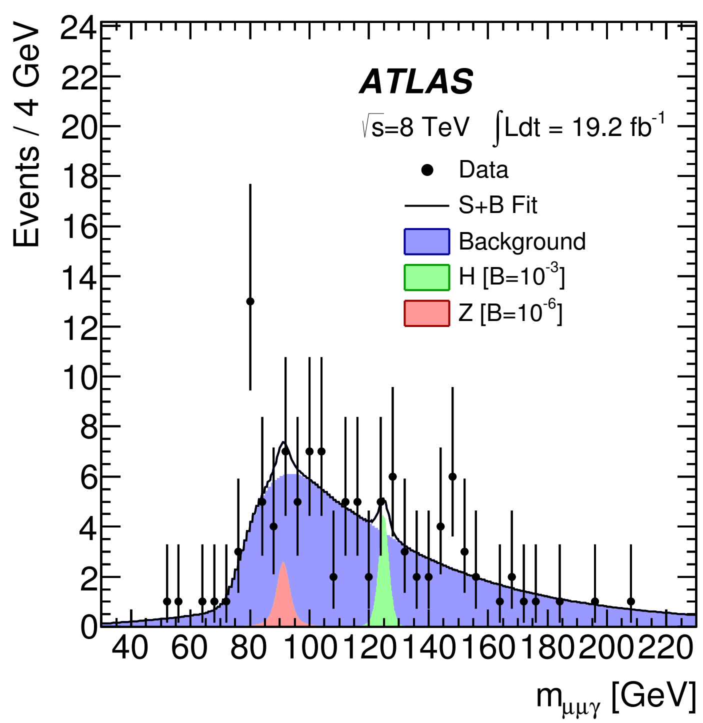




Bodwin, Petriello, Stoynev, Velasco ('13)
Bodwin, Chung, Ee, Lee, Petriello ('14)
Koenig, Neubert ('15)

$$\Gamma(H \to J/\psi + \gamma) = \left|(11.9 \pm 0.2) - (1.04 \pm 0.14)\kappa_c\right|^2 \times 10^{-10}\ \mathrm{GeV}$$

2.Measurement



$$\sigma \cdot \mathrm{Br}(H \to J/\psi\gamma) < 33\mathrm{fb}^{-1}$$

[95%CL upper bound]

2.5×10^{-6} [SM]

ATLAS [arXiv:1501.03276]
CMS [arXiv:1507.03031]

$$\mu^{95}_{J/\psi,8} = 515$$

Exclusive J/ψ+γ channel

3.Combine with $h\to 4l$ *or* $\gamma\gamma$

cancel total width and cross section dependence

$$\frac{\sigma(pp\to h)\times \mathrm{BR}_{h\to J/\psi\gamma}}{\sigma(pp\to h)\times \mathrm{BR}_{h\to ZZ^*\to 4\ell}} = \frac{\Gamma_{h\to J/\psi\gamma}}{\Gamma_{h\to ZZ^*\to 4\ell}} = 2.79\frac{(\kappa_\gamma - 0.087\kappa_c)^2}{\kappa_V^2}\times 10^{-2} < 9.3$$

$$-210\kappa_V + 11\kappa_\gamma < \kappa_c < 210\kappa_V + 11\kappa_\gamma$$

Calculation updated+$h\to\gamma\,\gamma$

[arXiv: 1505.03870]
Koenig, Neubert

$$\kappa_c \lesssim 430$$

due to smaller κ_c coefficient

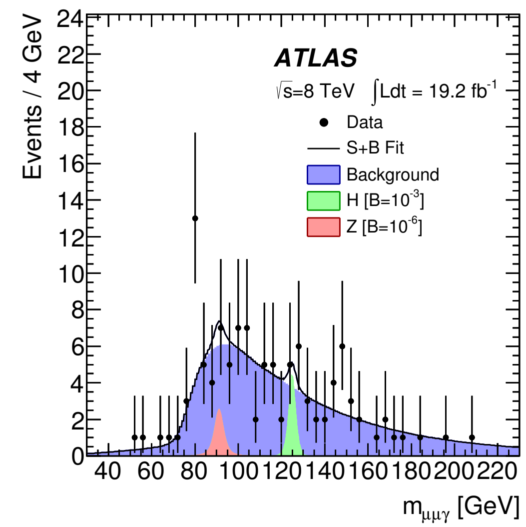
J/ψ+γ Channel at Future LHC

$$11\kappa_\gamma - 10\kappa_V \left(\frac{\mu^{95}_{J/\psi\gamma,E}}{\mu_{ZZ^*}}\right)^{1/2} < \kappa_c < 11\kappa_\gamma + 10\kappa_V \left(\frac{\mu^{95}_{J/\psi\gamma,E}}{\mu_{ZZ^*}}\right)^{1/2}$$

$$\mu^{95}_{J/\psi,8} = 515$$

We learned BG is large

$$\frac{S^{95}_E}{\sqrt{B_E}} \approx \frac{S^{95}_8}{\sqrt{B_8}} \quad (\sim 2\sigma)$$



Naive rescaling

$$R_E \equiv \frac{S^{\rm SM}_E / B_E}{S^{\rm SM}_8 \,/\, B_8}$$

$$\mu^{95}_{J/\psi\gamma,E} = \frac{S^{95}_E}{S^{\rm SM}_E} \approx \left(\frac{B_E}{B_8}\frac{S^{\rm SM}_8}{S^{\rm SM}_E}\right)^{1/2}\left(\frac{S^{\rm SM}_8}{S^{\rm SM}_E}\right)^{1/2}\frac{S^{95}_8}{S^{\rm SM}_8} = \frac{1}{R_E^{1/2}}\left(\frac{\sigma^{\rm SM}_{h,8}\ \mathcal{L}_8}{\sigma^{\rm SM}_{h,E}\ \mathcal{L}_E}\right)^{1/2}\mu^{95}_{J/\psi\gamma,8}$$

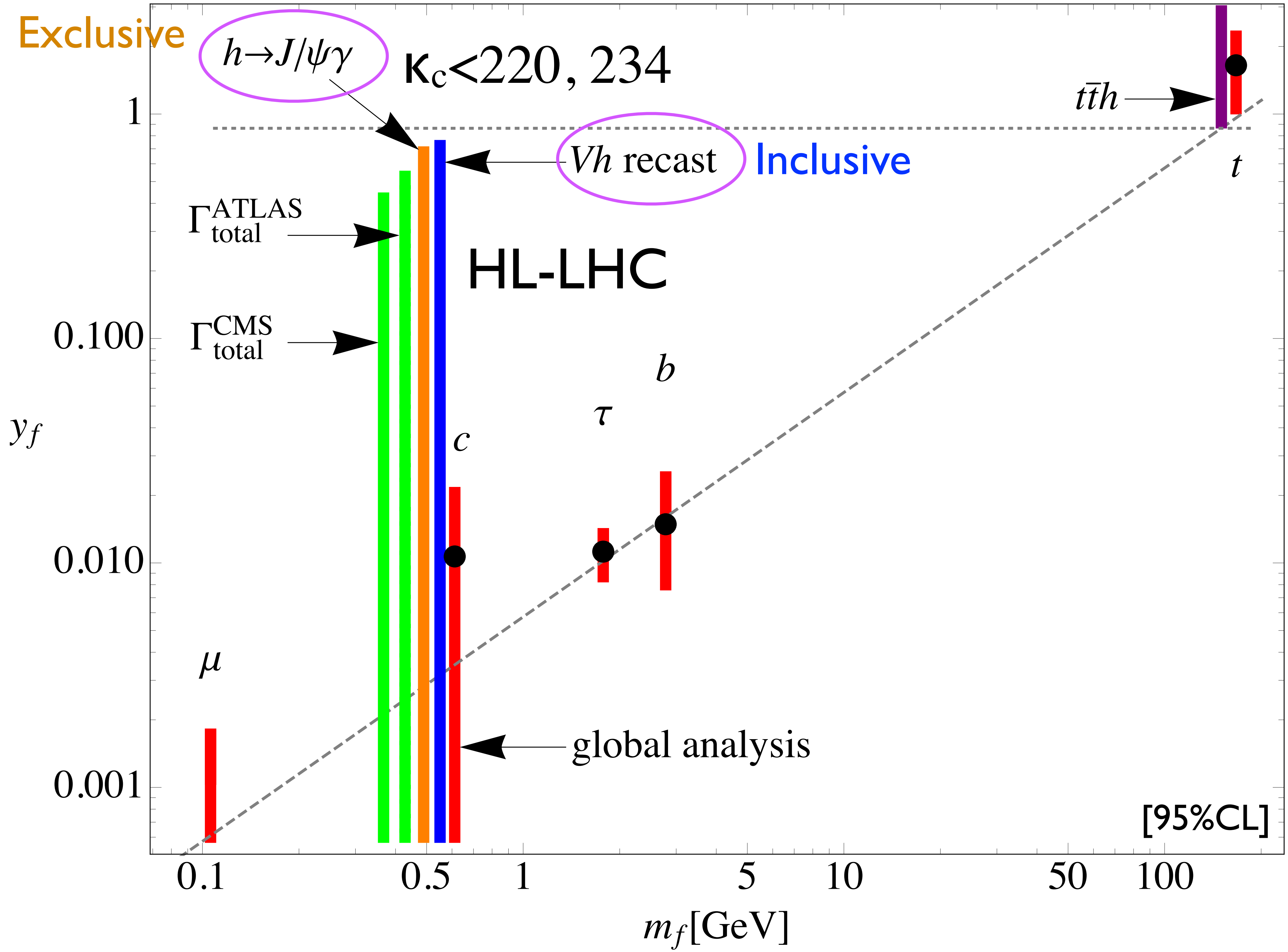
$$11 - 45\left(\frac{1}{R_{14}}\frac{\sigma^{\rm SM}_{h,8}}{\sigma^{\rm SM}_{h,14}}\frac{2\times 3000{\rm fb}^{-1}}{\mathcal{L}_{14}}\right)^{1/4} < \kappa_c < 11 + 45\left(\frac{1}{R_{14}}\frac{\sigma^{\rm SM}_{h,8}}{\sigma^{\rm SM}_{h,14}}\frac{2\times 3000{\rm fb}^{-1}}{\mathcal{L}_{14}}\right)^{1/4}$$

$(\kappa_V = \kappa_\gamma = \mu_{ZZ^*} = 1)$

$$-30 \lesssim \kappa_c \lesssim 50 \quad \text{[95\%CL]}$$

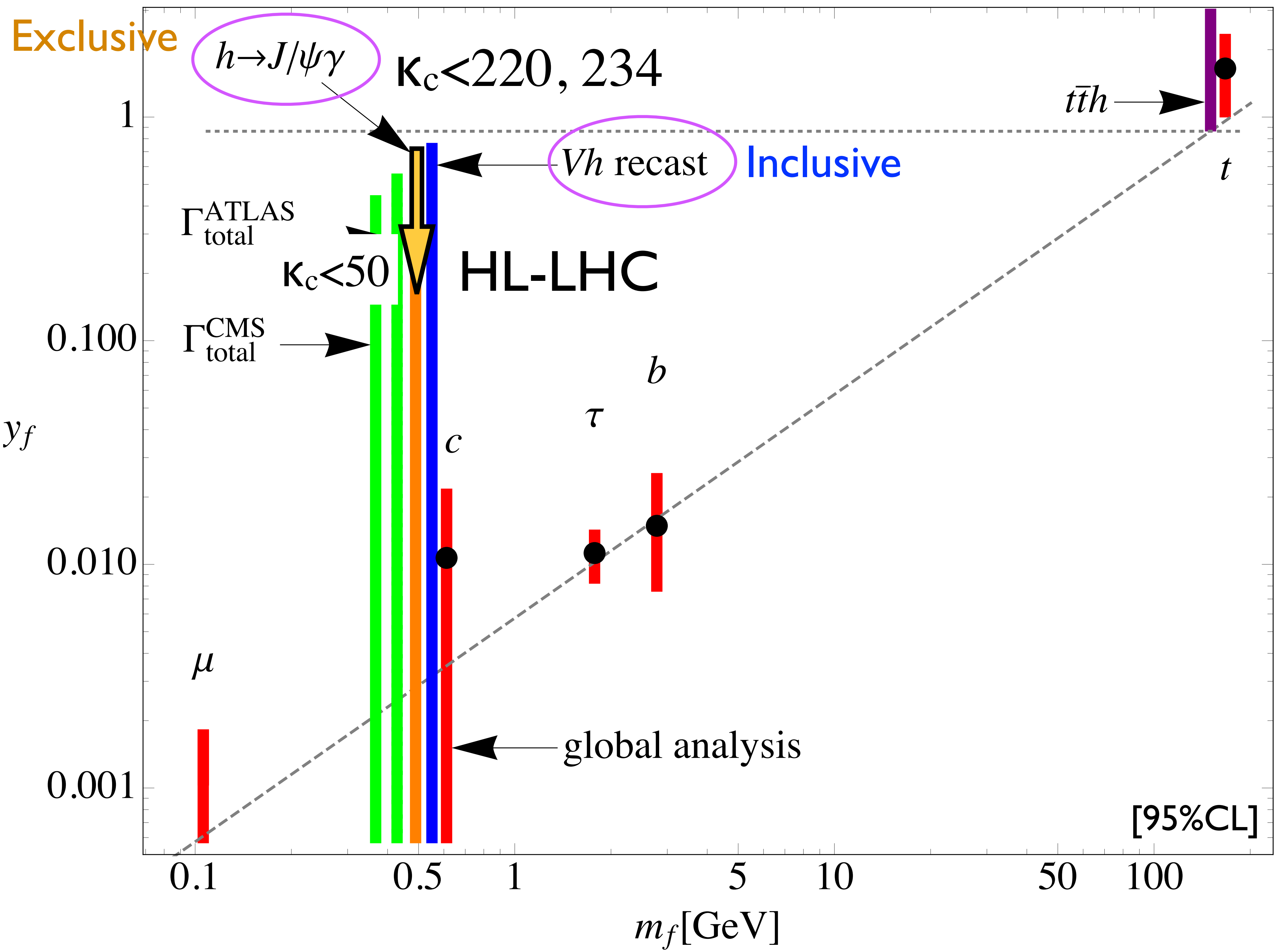
much weaker reach even at HL-LHC!

Summary



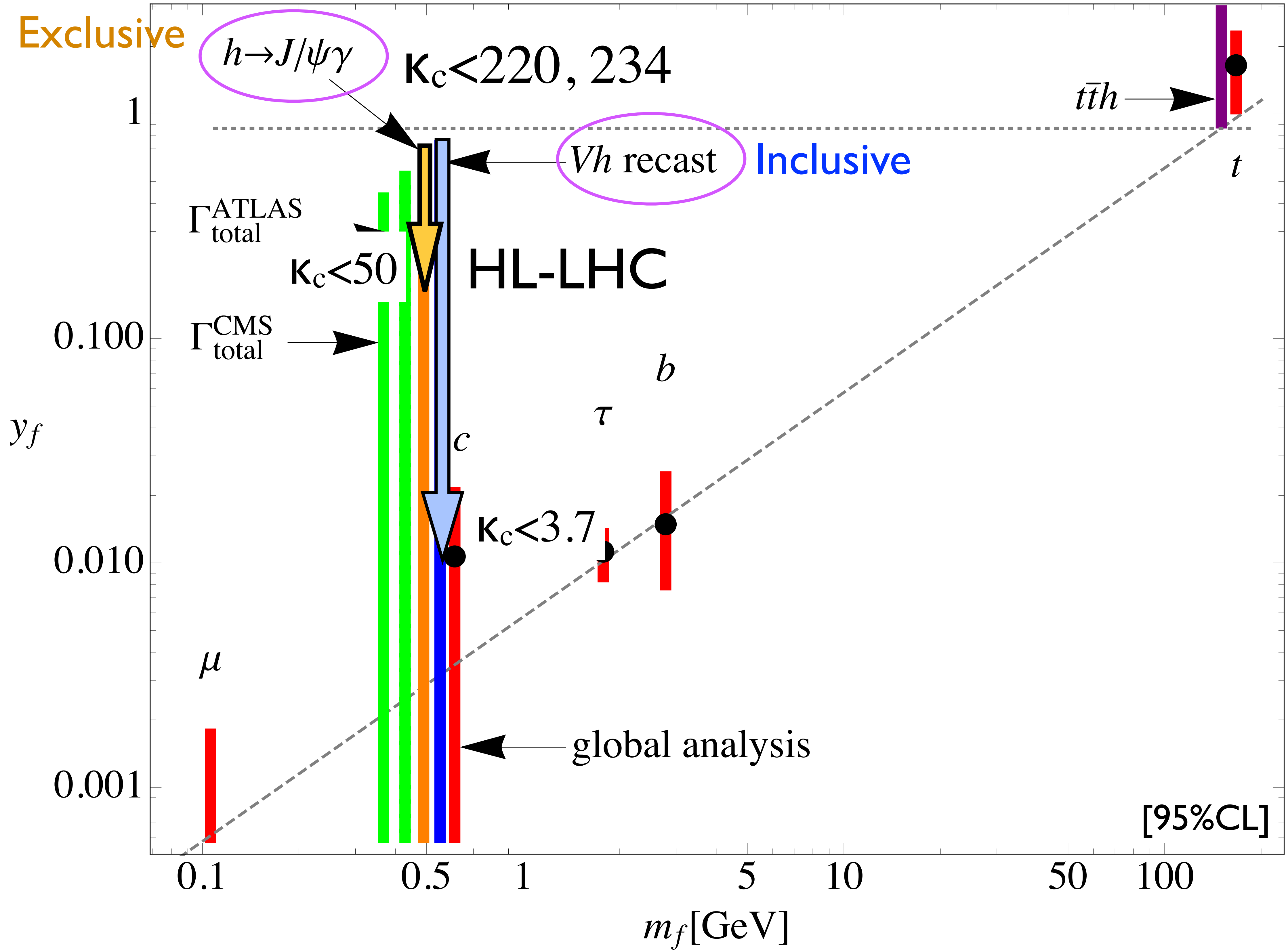
Exclusive
$h \to J/\psi\gamma$
κ_c<220, 234
$t\bar{t}h$
1
Vh recast
Inclusive
t
$\Gamma^{\rm ATLAS}_{\rm total}$
HL-LHC
0.100
$\Gamma^{\rm CMS}_{\rm total}$
b
y_f
τ
c
0.010
μ
global analysis
0.001
[95%CL]
0.1
0.5
1
5
10
50
100
m_f[GeV]

Summary



Exclusive
h→J/ψγ
κc<220, 234
1
Vh recast
Inclusive
t
tt̄h
Γ^ATLAS_total
κc<50
HL-LHC
0.100
Γ^CMS_total
yf
b
τ
c
0.010
μ
global analysis
0.001
[95%CL]
0.1
0.5
1
5
10
50
100
mf[GeV]

Summary



Exclusive
h→J/ψγ
κc<220, 234
Vh recast
Inclusive
Γ total ATLAS
κc<50
HL-LHC
Γ total CMS
tt̄h
t
b
τ
c
κc<3.7
μ
global analysis
[95%CL]
1
0.100
0.010
0.001
yf
0.1
0.5
1
5
10
50
100
mf[GeV]

Thank you