

$B \rightarrow D^{(*)} \tau \nu_\tau$ in two-Higgs-doublet models

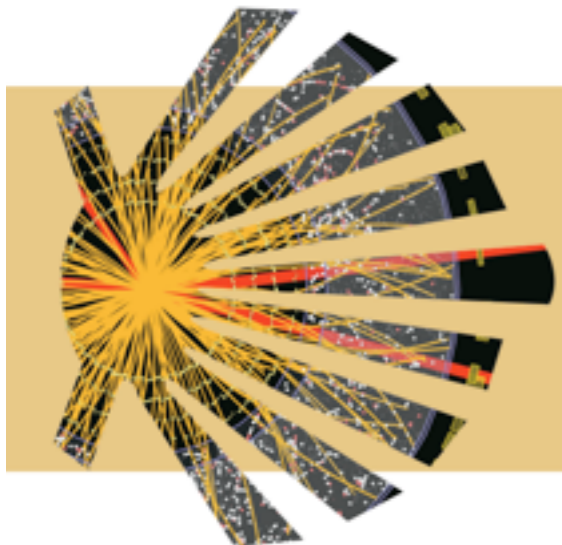
Alejandro Celis

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for details [JHEP 1301 \(2013\) 054](#) and [arXiv:1302.5992](#)

for those of you browsing the slides, all quoted refs. are hyperlinks

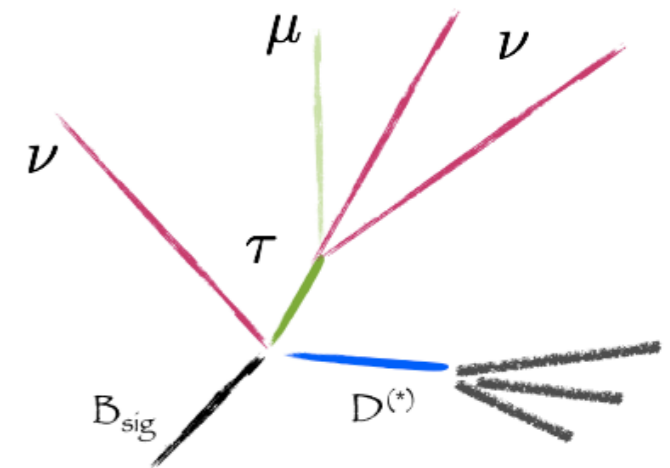


V CPAN DAYS

Centro Nacional de Física de Partículas, Astropartículas y Nuclear
Proyecto Consolider-Ingenio 2010

Santiago de Compostela

25 - 27 November 2013

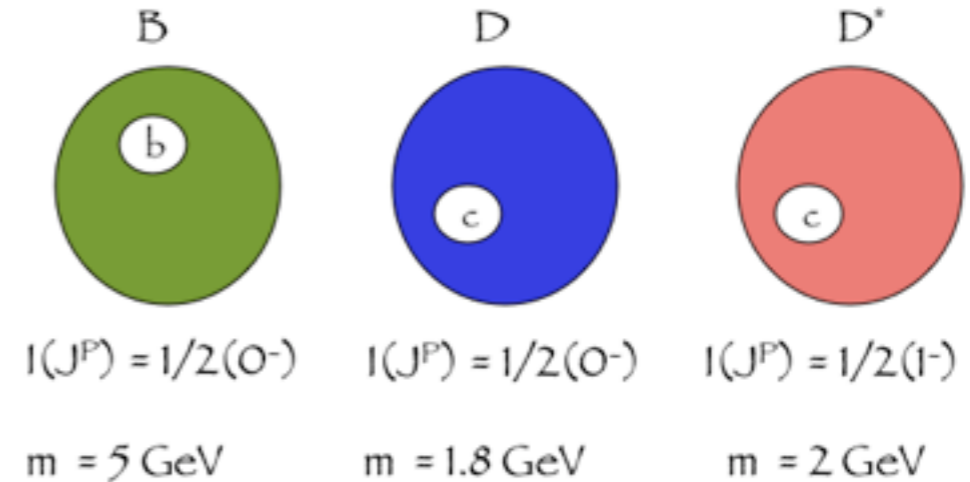
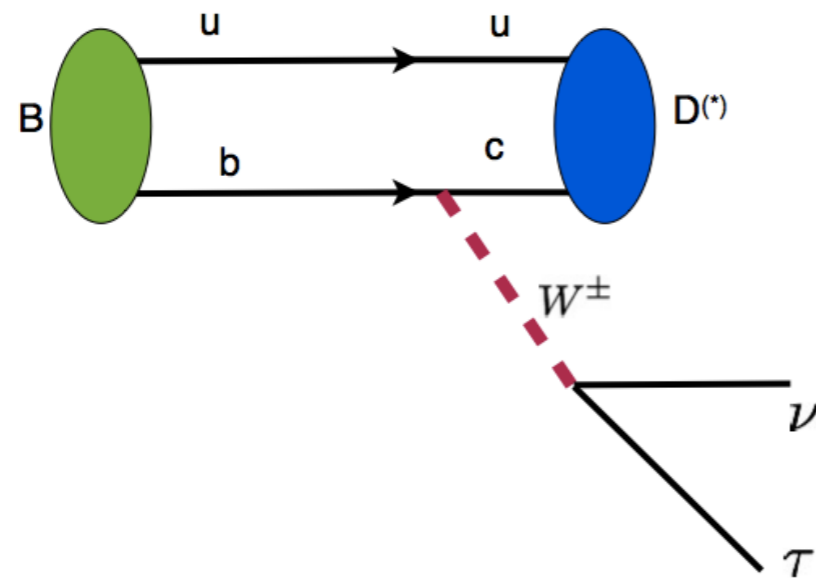


The basics

$$B \rightarrow D^{(*)} \ell \nu$$

if interested, check these recent lectures on $B \rightarrow D^{()}$ tau nu transitions*

[Svetlana Fajfer Lectures on Helmholtz International School "Physics of Heavy Quarks", July \(2013\)](#)



Some motivations for the study of $b \rightarrow c \ell \nu$ transitions

- ★ determination of $|V_{cb}|$ *seminal work by Korner & Schuler (1987)*
- ★ tests of lepton flavour universality *(Belle-II)*
- ★ 3-body decay, tau and D^* polarization (disentangle new physics)
- ★ new physics can enter at tree-level
- ★ non-perturbative QCD \Rightarrow Form Factors

The basics

$$B \rightarrow D \ell \nu$$

Parametrization of the hadronic amplitude

$$f_+(0) = f_0(0)$$

$$\bullet \quad \langle D(p_D) | \bar{c} \gamma^\mu b | \bar{B}(p_B) \rangle = f_+(q^2) \left[(p_B + p_D)^\mu - \frac{m_B^2 - m_D^2}{q^2} q^\mu \right] + f_0(q^2) \frac{m_B^2 - m_D^2}{q^2} q^\mu$$

$$q^2 = (p_B - p_D)^2$$

vector form factor

scalar form factor

Charged Higgs enters through scalar current

$$\langle D(p_D) | \bar{c} b | \bar{B}(p_B) \rangle = \frac{m_B^2 - m_D^2}{\bar{m}_b - \bar{m}_c} f_0(q^2)$$

Determination of the form factors based on:

Heavy Quark Effective Theory (HQET)

Lattice QCD

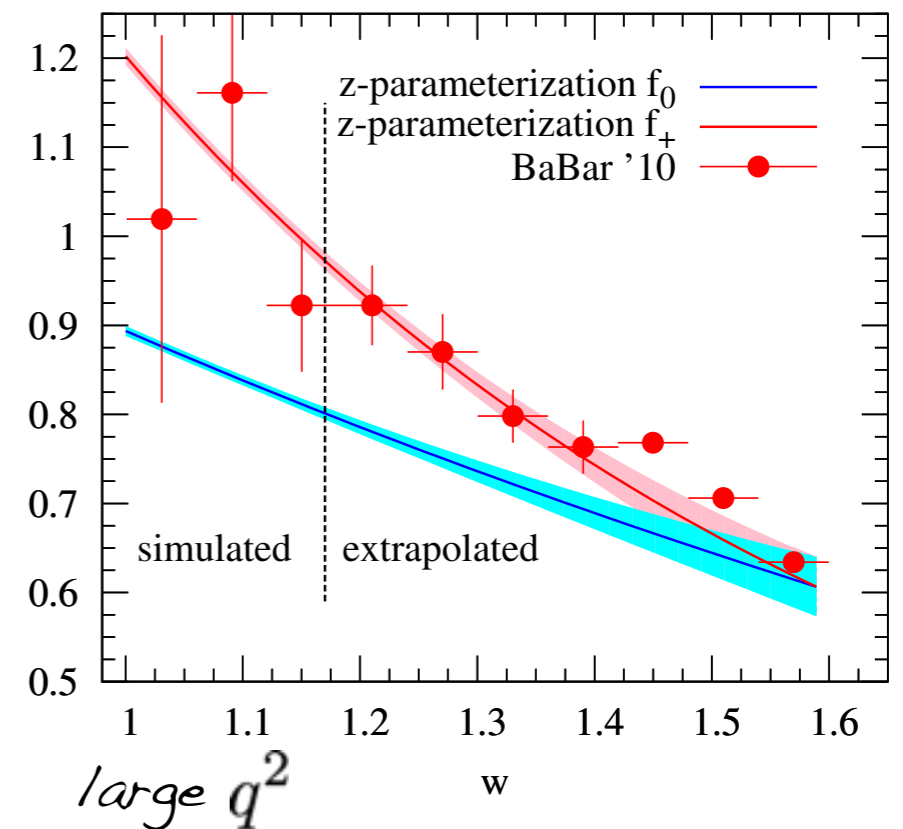
Differential distribution for $B \rightarrow D \ell \nu$ ($\ell = e, \mu$)

$d\Gamma$ does not depend on scalar form factor for $m_\ell = 0$

input from Lattice QCD very important

Lattice QCD

arXiv:1206.4992



$$w = \frac{m_B^2 + m_D^2 - q^2}{2m_B m_D}$$

The basics

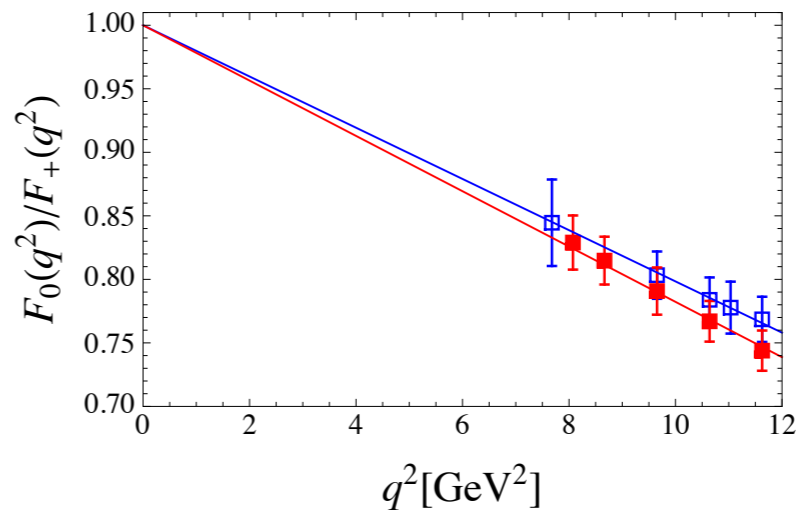
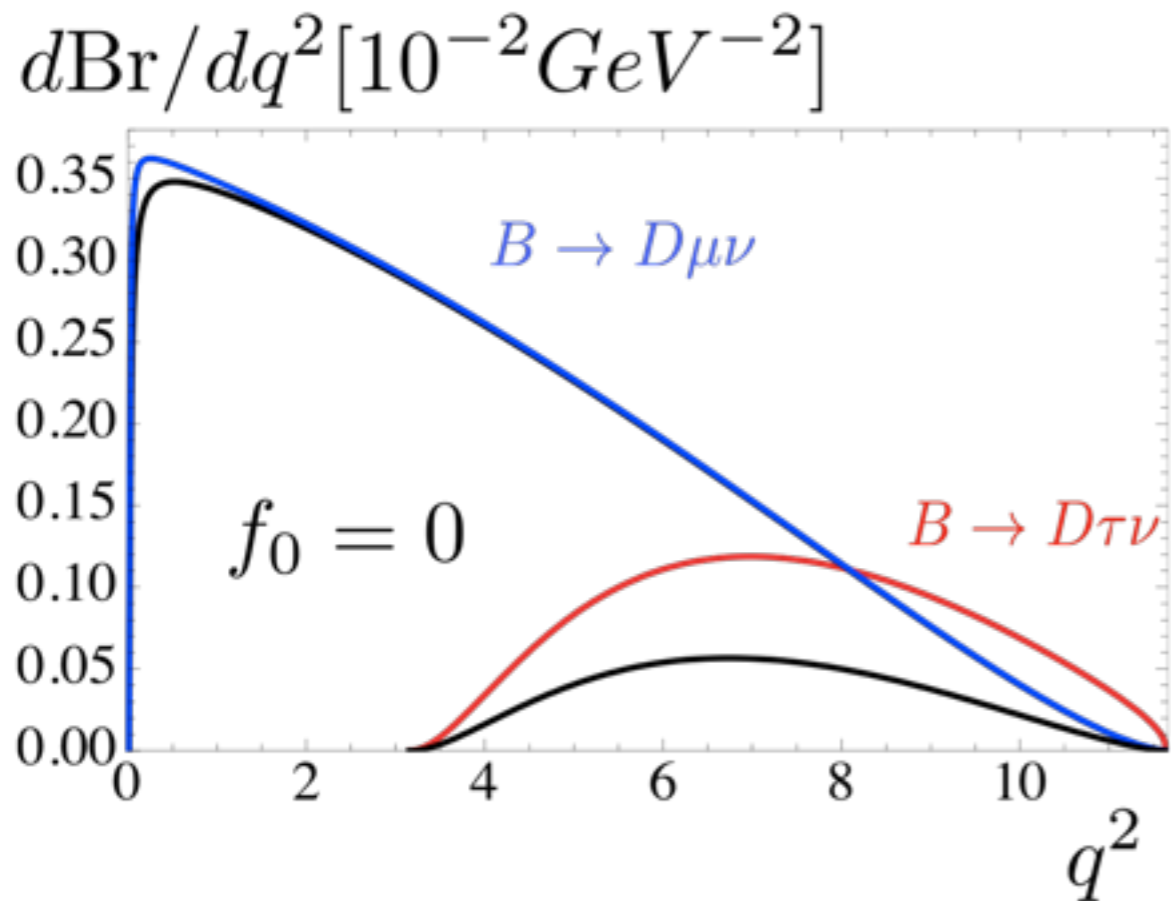
$B \rightarrow D\ell\nu$

how important is the determination of the scalar form factor?

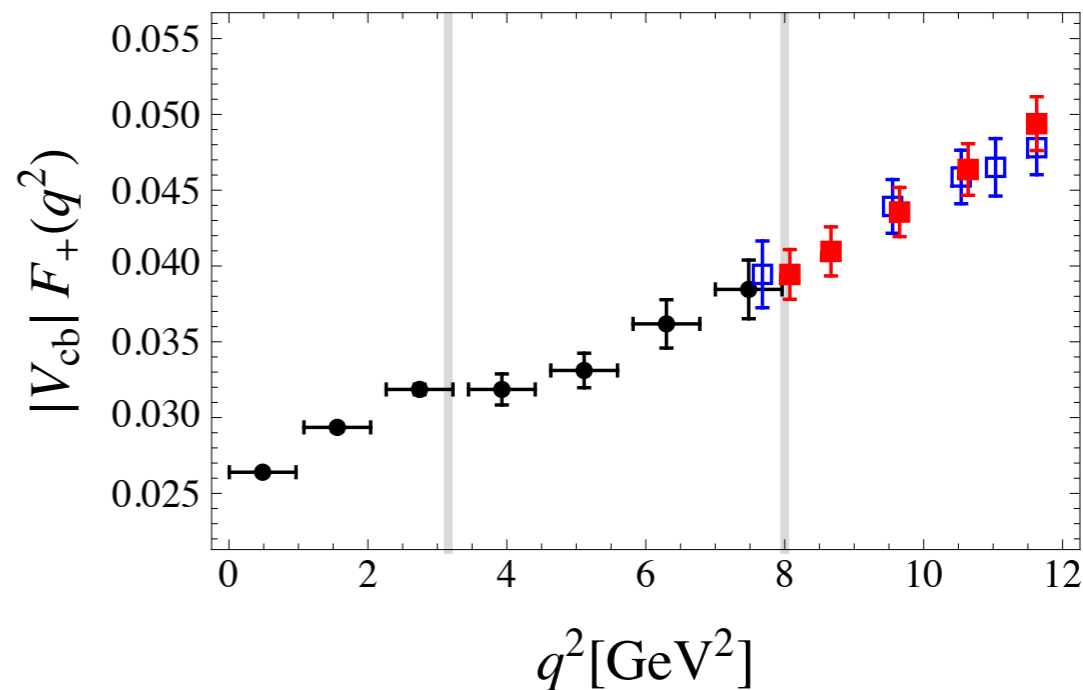
Proposal:

$B \rightarrow D\ell\nu$ with minimal theory input.

Becirevic, Kosnik, Tayduganov [arXiv:1206.4977](https://arxiv.org/abs/1206.4977)



scalar form factor has large impact for tau final state



$$\frac{d\text{Br}(B \rightarrow D\ell\nu)}{dq^2} \propto |f_+(q^2)|^2 \left[\underbrace{c_+^\ell(q^2)}_{\text{phase space}} + \underbrace{c_0^\ell(q^2)}_{\text{phase space}} \left| \frac{f_0(q^2)}{f_+(q^2)} \right|^2 \right]$$

$$c_0^\ell(q^2) \propto m_\ell^2$$

robust th. prediction for:

$$\frac{\text{Br}(B \rightarrow D\tau\bar{\nu}_\tau)}{\text{Br}(B \rightarrow D\mu\bar{\nu}_\mu)} \Big|_{q^2 \leq 8 \text{ GeV}^2}$$

The basics

$$B \rightarrow D^* \ell \nu$$

- $\langle D^*(p_{D^*}, \epsilon^*) | \bar{c} \gamma_\mu b | \bar{B}(p_B) \rangle$, $V(q^2)$
- $\langle D^*(p_{D^*}, \epsilon^*) | \bar{c} \gamma_\mu \gamma_5 b | \bar{B}(p_B) \rangle$ $A_0(q^2), A_1(q^2), A_2(q^2)$

Charged Higgs enters through pseudoscalar current

$$\langle D^*(p_{D^*}, \epsilon^*) | \bar{c} \gamma_5 b | \bar{B}(p_B) \rangle = -\frac{2m_{D^*}}{\bar{m}_b + \bar{m}_c} A_0(q^2) \epsilon^* \cdot q$$

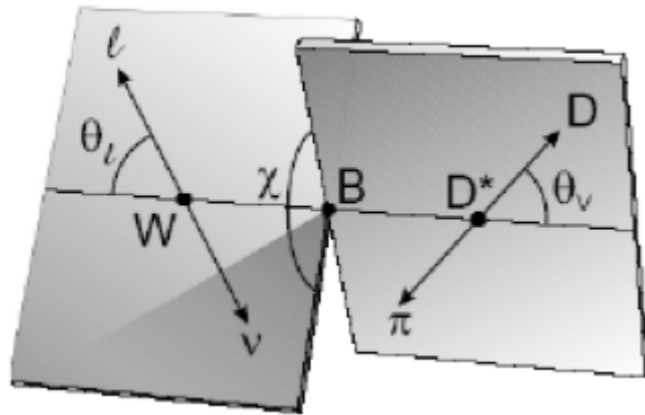
Determination of the form factors based on:

Heavy Quark Effective Theory (HQET)

[Falk, Neubert \(1992\)](#)

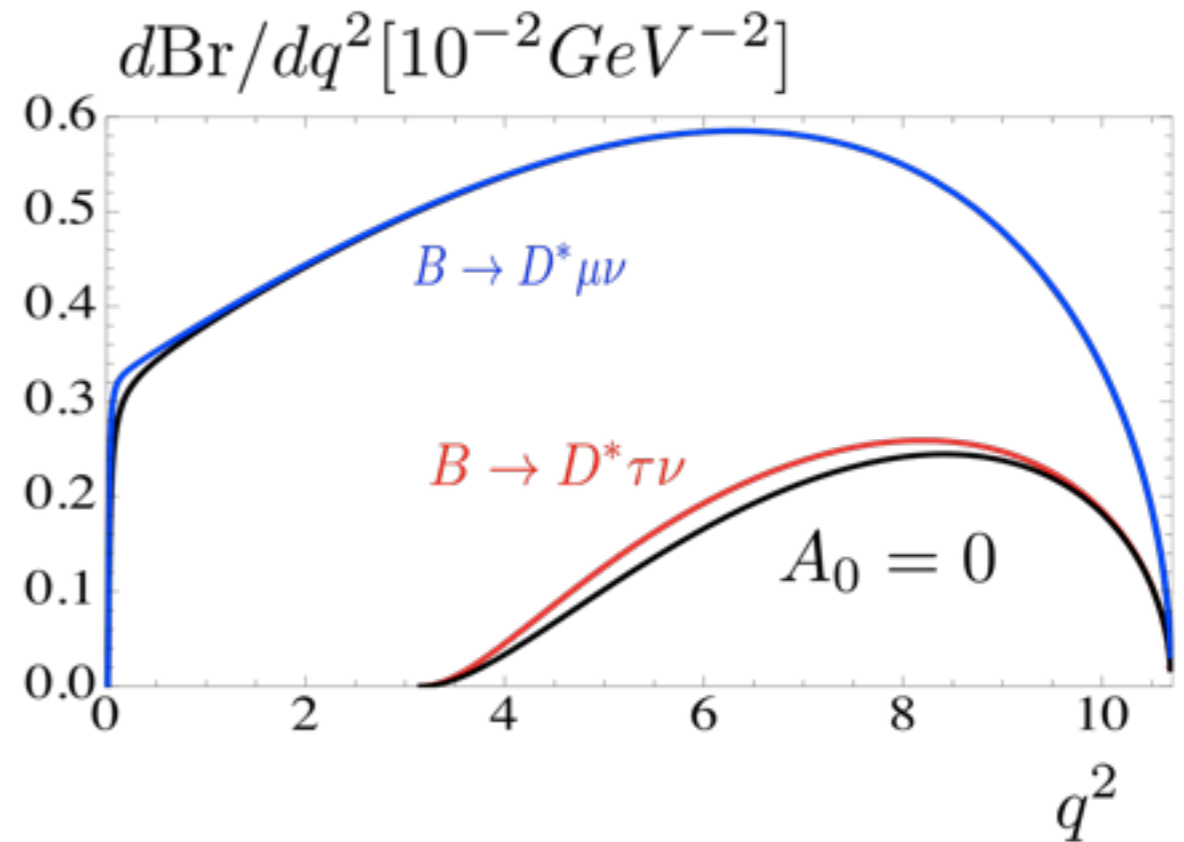
[Caprini, Lellouch, Neubert \(1997\)](#)

Differential distribution for $B \rightarrow D^* \ell \nu_\ell$ ($\ell = e, \mu$)



HFAG

how important is the determination of the scalar form factor?



scalar form factor has a small impact

Lattice QCD results would be useful here.

[Fermilab Lattice and MILC Collaborations](#)

(only at zero recoil)

looking for new physics

$$B \rightarrow D^{(*)} \tau \nu$$

much of the literature focused on two-Higgs-doublet models, why?

- ★ Discovery of a Higgs-like boson around 126 GeV

extra Higgs doublets (and singlets) keep $\rho \simeq 1$

- ★ Can lead to LFU violations in a natural way

avoid large

FCNC's \Rightarrow Higgs coupling to fermions \propto mass

() to learn more check the [Higgs hunter's guide \(Gunion et al.\)](#)*

What is the two-Higgs-doublet model?

the SM of electroweak interactions

- ★ fermion content
- ★ Gauge symmetries \Rightarrow interactions
- ★ scalar sector \Rightarrow

spontaneous breaking of EW symmetry

enlarge by adding a
second Higgs doublet

looking for new physics

$$B \rightarrow D^{(*)} \tau \nu$$

What is the two-Higgs-doublet model?

2 complex Higgs doublets
 \Rightarrow 8 real *d.o.f.*
 = 3 Goldstone bosons + ...

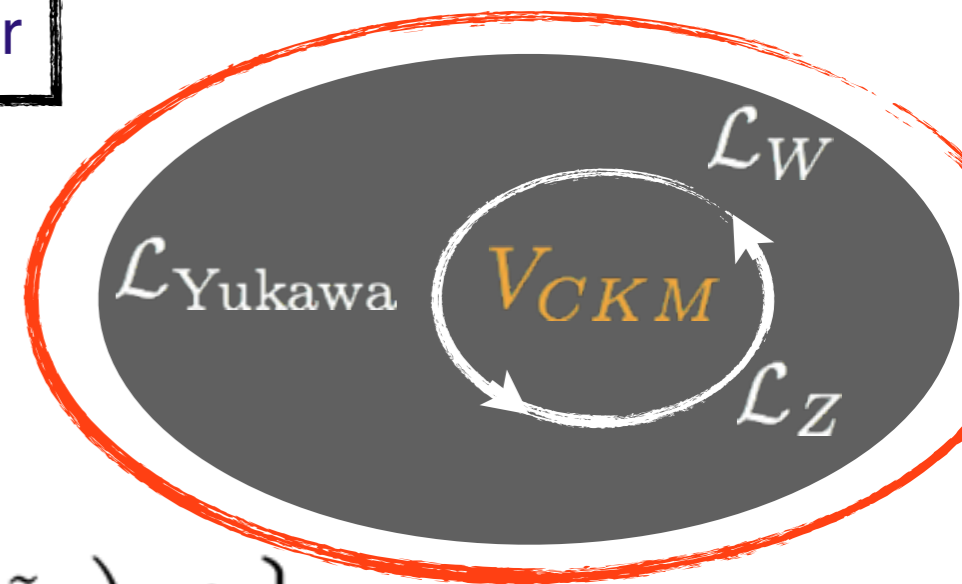
scalar spectrum:
 3 neutral Higgs
 +
 a charged scalar

~~CP~~

tree-level FCNCs

$$\mathcal{L}_Y = -\frac{\sqrt{2}}{v} \left\{ \bar{L}'_L (M'_\ell \Phi_1 + \Pi'_\ell \Phi_2) \ell'_R + \bar{Q}'_L (M'_d \Phi_1 + \Pi'_d \Phi_2) d'_R + \bar{Q}'_L (M'_u \tilde{\Phi}_1 + \Pi'_u \tilde{\Phi}_2) u'_R \right\} + \text{h.c.}$$

(primes \Rightarrow generic weak basis)



In the Higgs basis:

$$\Phi_1 = \begin{bmatrix} G^+ \\ \frac{1}{\sqrt{2}} (v + S_1 + iG^0) \end{bmatrix} \quad \Phi_2 = \begin{bmatrix} H^+ \\ \frac{1}{\sqrt{2}} (S_2 + iS_3) \end{bmatrix}$$

looking for new physics

$$B \rightarrow D^{(*)} \tau \nu$$

avoiding tree-level
FCNC's

Natural Flavour Conservation

Glashow, Weinberg (1976)
E. A. Paschos (1976)

the assumption that only one-Higgs field can couple to a given fermion species.

=> no tree-level FCNC's and no ~~CP~~ beyond CKM-phase

Aligned 2HDM

consider the lepton sector

$$\mathcal{L}_Y = -\frac{\sqrt{2}}{v} \left\{ \bar{L}'_L (M'_\ell \Phi_1 + \Pi'_\ell \Phi_2) \ell'_R \right\} + \text{h.c.}$$

$$\Pi_{d,l} = \zeta_{d,l} M_{d,l}, \quad \Pi_u = \zeta_u^* M_u$$

$\zeta_f \rightarrow$ new sources of CP violation
Flavor Universal (the same for each family)

charged Higgs interactions

$$\mathcal{L}_Y \supset -\frac{\sqrt{2}}{v} H^+ \left\{ \bar{u} [\zeta_d V M_d \mathcal{P}_R - \zeta_u M_u^\dagger V \mathcal{P}_L] d + \zeta_l \bar{\nu} M_l \mathcal{P}_R l \right\}$$

Model	ζ_d	ζ_u	ζ_l
Type I	$\cot \beta$	$\cot \beta$	$\cot \beta$
Type II	$-\tan \beta$	$\cot \beta$	$-\tan \beta$
Type X	$\cot \beta$	$\cot \beta$	$-\tan \beta$
Type Y	$-\tan \beta$	$\cot \beta$	$\cot \beta$
Inert	0	0	0

*particular limits
of the 2HDM*

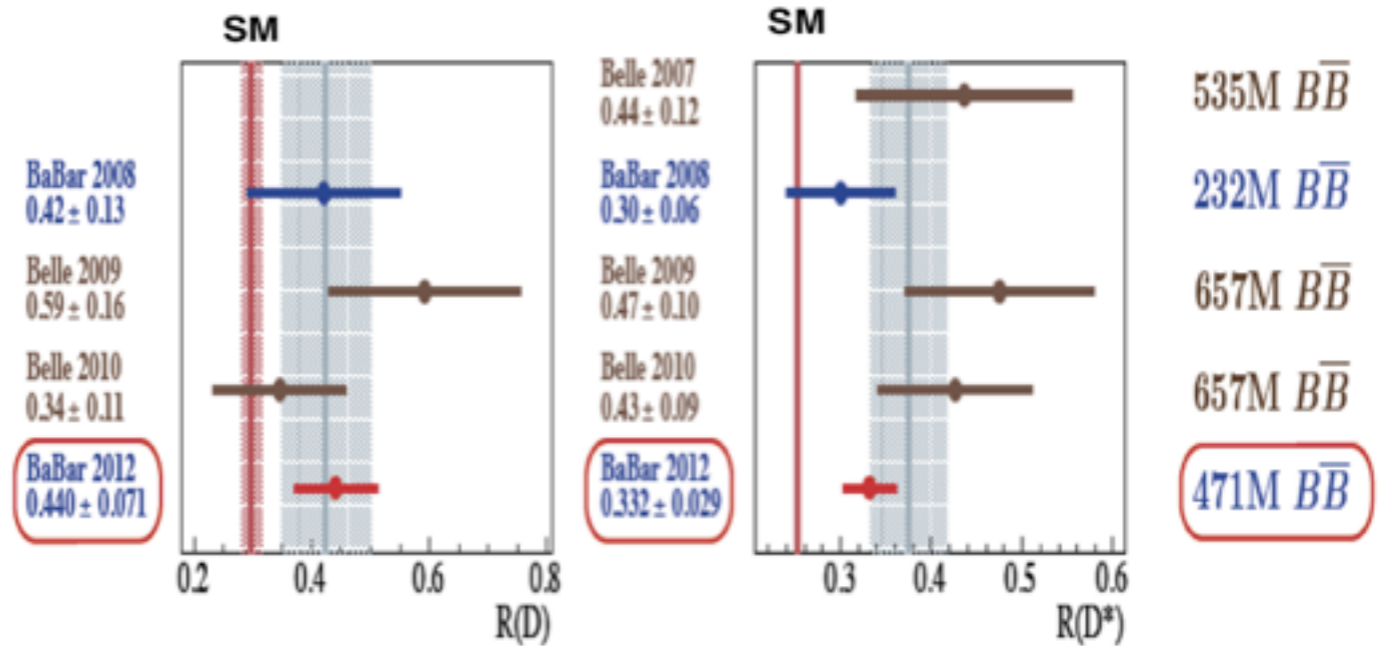
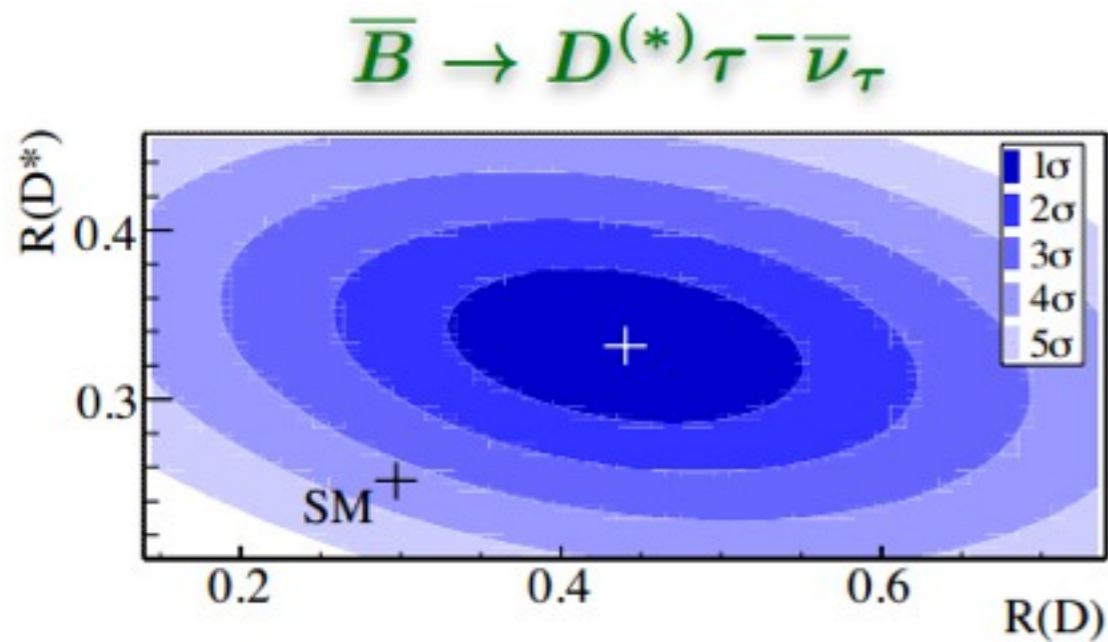
looking for new physics

$$B \rightarrow D^{(*)} \tau \nu$$

$$R(D^{(*)}) = \frac{\Gamma(B \rightarrow D^{(*)} \tau \nu)}{\Gamma(B \rightarrow D^{(*)} l \nu)}$$

some sources of uncertainty cancel in the ratio, $|V_{cb}|$ for example

BaBar Collaboration, Phys.Rev. D88 (2013)

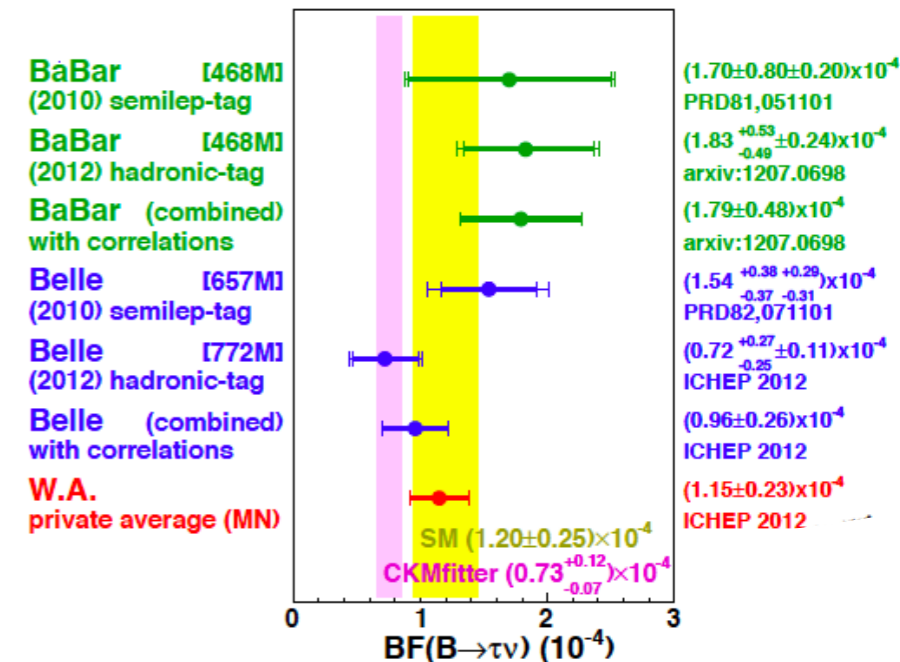


but remember the $B \rightarrow \tau \nu$ latest measurements

$$R(D) = \left\{ \begin{array}{l} 0.440 \pm 0.072 \text{ BABAR} \\ 0.297 \pm 0.017 \text{ SM} \end{array} \right\} \left. \begin{array}{l} 2.0\sigma \\ \\ 3.4\sigma \end{array} \right\}$$

$$R(D^*) = \left\{ \begin{array}{l} 0.332 \pm 0.030 \text{ BABAR} \\ 0.252 \pm 0.003 \text{ SM} \end{array} \right\} \left. \begin{array}{l} 2.7\sigma \\ \\ 3.4\sigma \end{array} \right\}$$

~ 1 sigma
[arXiv:1206.4992](https://arxiv.org/abs/1206.4992)
[arXiv:1206.4977](https://arxiv.org/abs/1206.4977)



SM predictions:

[Kamenik, Mescia \(2008\)](#)

[Fajfer, Kamenik, Nisandzic \(2012\)](#)

looking for new physics

$$B \rightarrow D^{(*)} \tau \nu$$

$$\mathcal{L}_Y \supset -\frac{\sqrt{2}}{v} H^+ \left\{ \bar{u} [\zeta_d V M_d \mathcal{P}_R - \zeta_u M_u^\dagger V \mathcal{P}_L] d + \zeta_l \bar{\nu} M_l \mathcal{P}_{Rl} \right\}$$

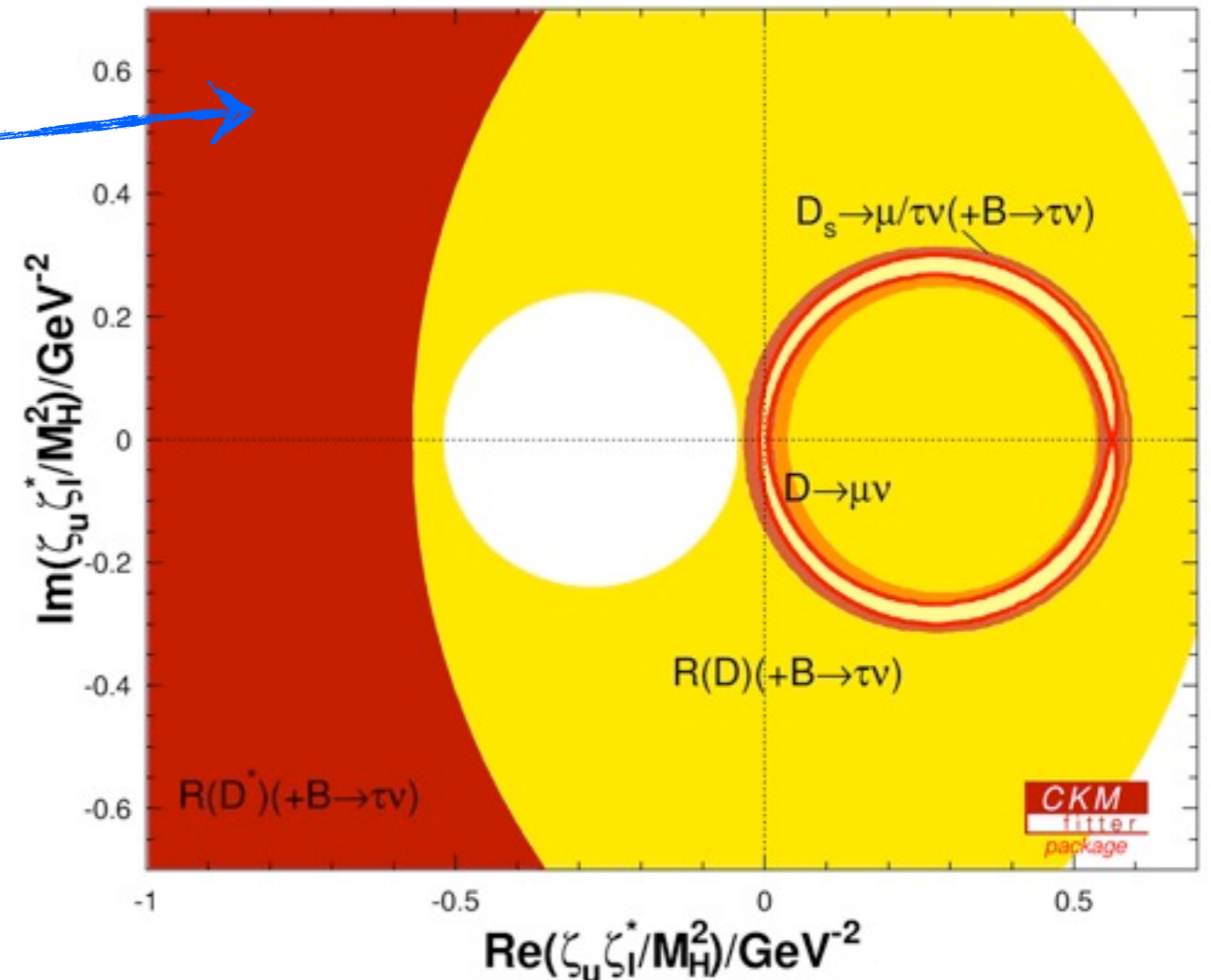
at 95 % CL

AC, Jung, X-Q. Li, Pich (2012)

$$R(D^*)(+B \rightarrow \tau \nu)$$

$$\rightarrow |\zeta_u \zeta_l| / M_{H^\pm}^2 \sim \mathcal{O}(1) \text{ GeV}^{-2}$$

big tension between
D_(s) leptonic decays,
R(D^{*}) and B → Tau Nu



by-product of the analysis

None of the 2HDM with NFC can accommodate the excess in R(D^{*})

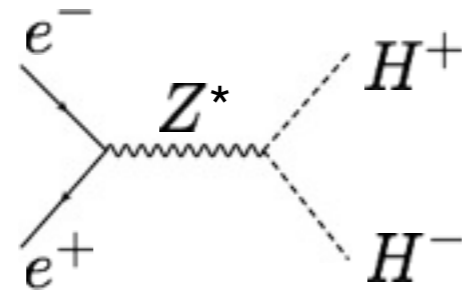
analysis within the Type III 2HDM (with tree-level FCNCs) has been done by [Crivellin et al.](#)

looking for new physics

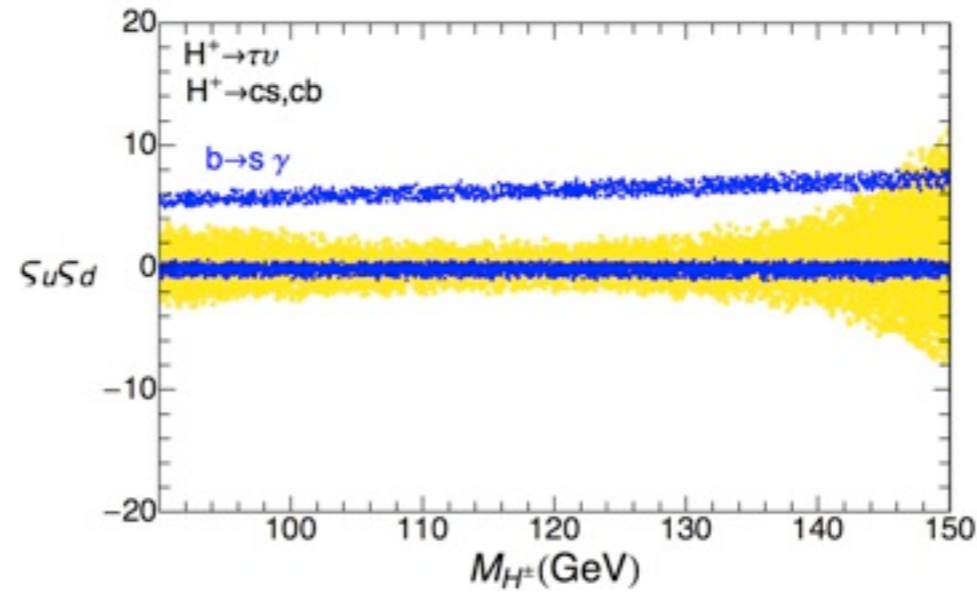
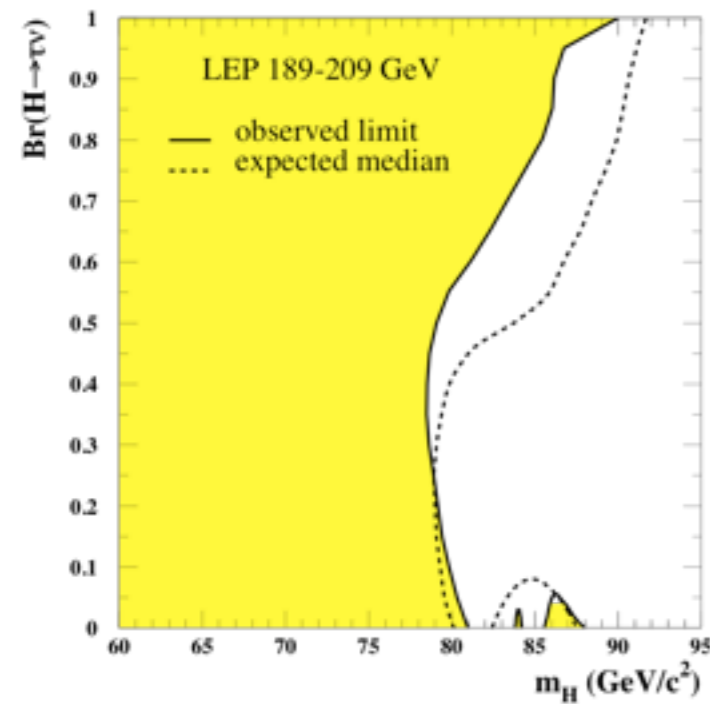
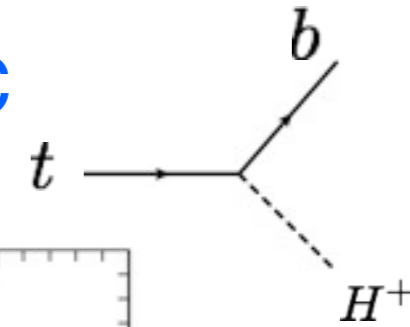
$$B \rightarrow D^{(*)} \tau \nu$$

$$\mathcal{L}_Y \supset -\frac{\sqrt{2}}{v} H^+ \left\{ \bar{u} \left[\varsigma_d V M_d \mathcal{P}_R - \varsigma_u M_u^\dagger V \mathcal{P}_L \right] d + \varsigma_l \bar{\nu} M_l \mathcal{P}_R \right\}$$

at LEP



at the LHC



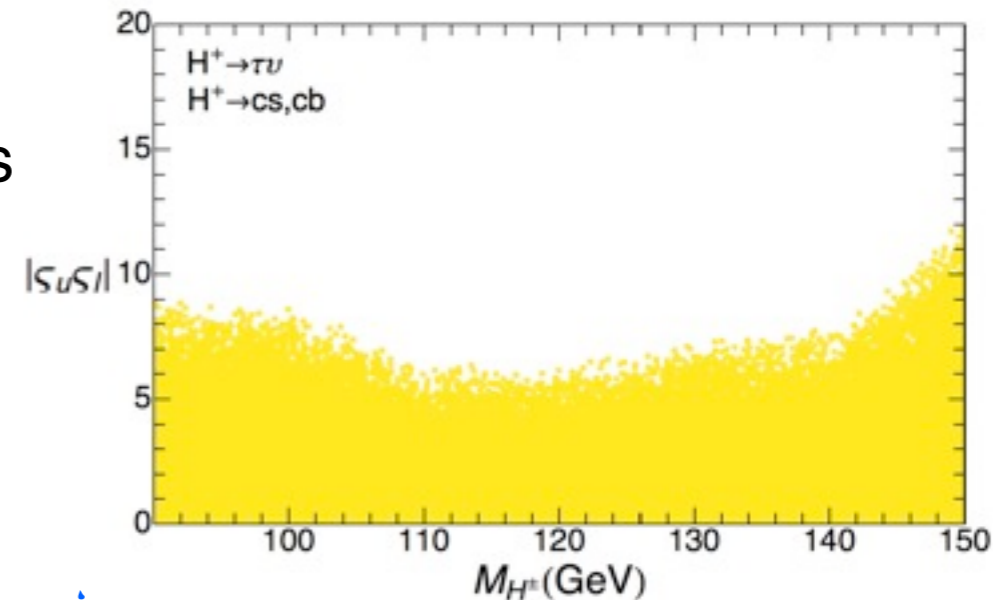
LEP limit:

$$M_{H^\pm} \gtrsim 80 \text{ GeV}$$

from current
ATLAS and CMS direct limits

[arXiv:1310.7941](https://arxiv.org/abs/1310.7941)

$$\Rightarrow |\varsigma_u \varsigma_l| / M_{H^\pm}^2 \lesssim 10^{-3} \text{ GeV}^{-2}$$



Rich interplay between collider and flavour physics

looking into the future

$$B \rightarrow D^{(*)} \tau \nu$$

Disentangling different new physics contributions

Look for observables that do not depend on the charged Higgs contribution

$$\frac{\text{Br}(B \rightarrow \tau \nu_\tau)}{\text{Br}(B \rightarrow \mu \nu_\mu)}$$

ratio independent of scalar contributions *(in the A2HDM)*

We want to test NP in $b \rightarrow c$ tau nu transitions, without assumptions on flavour structure

Look for observables that are particularly sensitive to the charged Higgs

$$\text{Br}(B_c \rightarrow \tau \nu_\tau) \quad \text{Large enhancement expected}$$

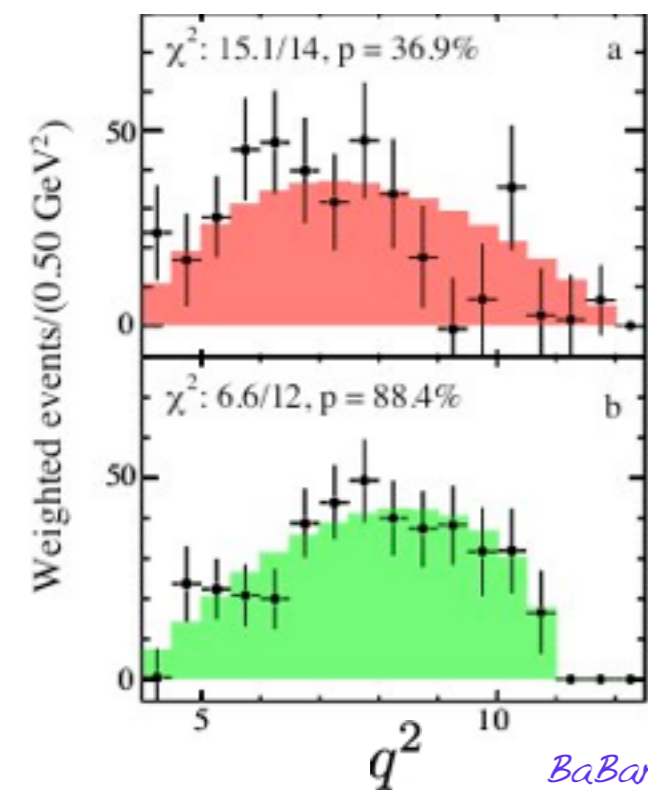
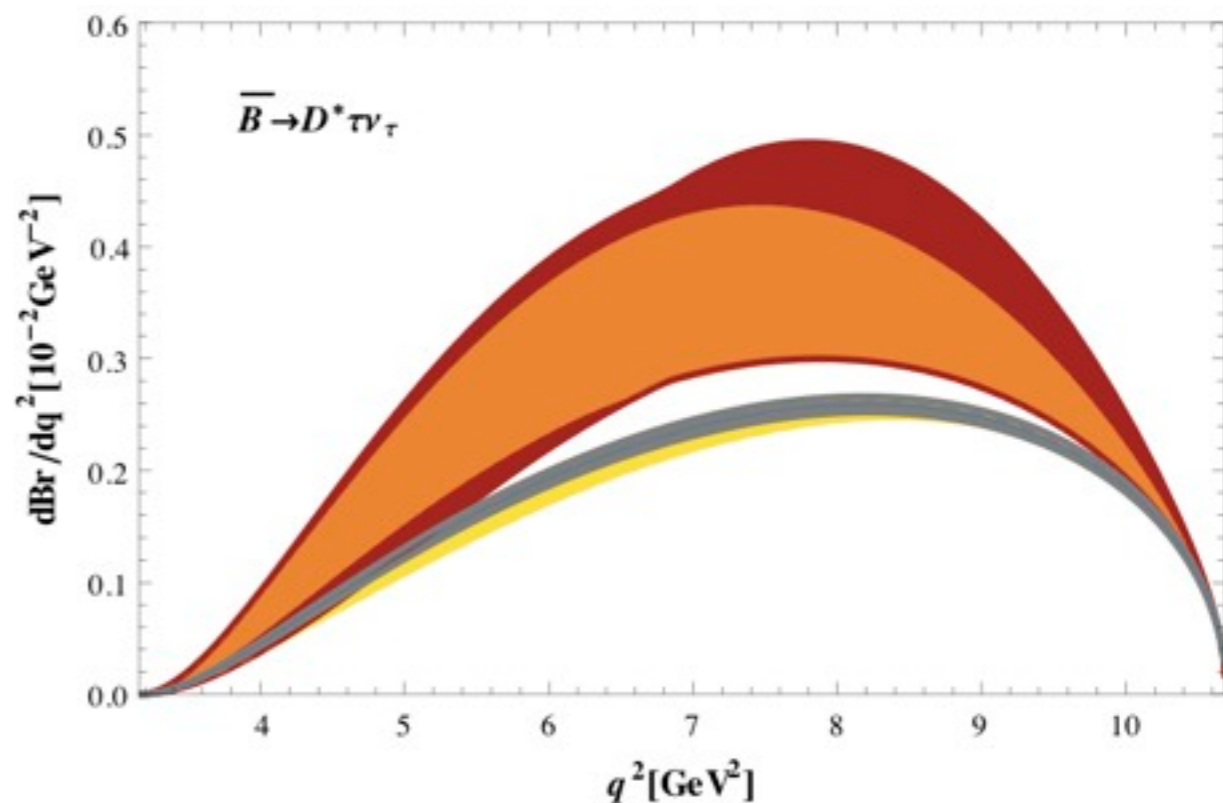
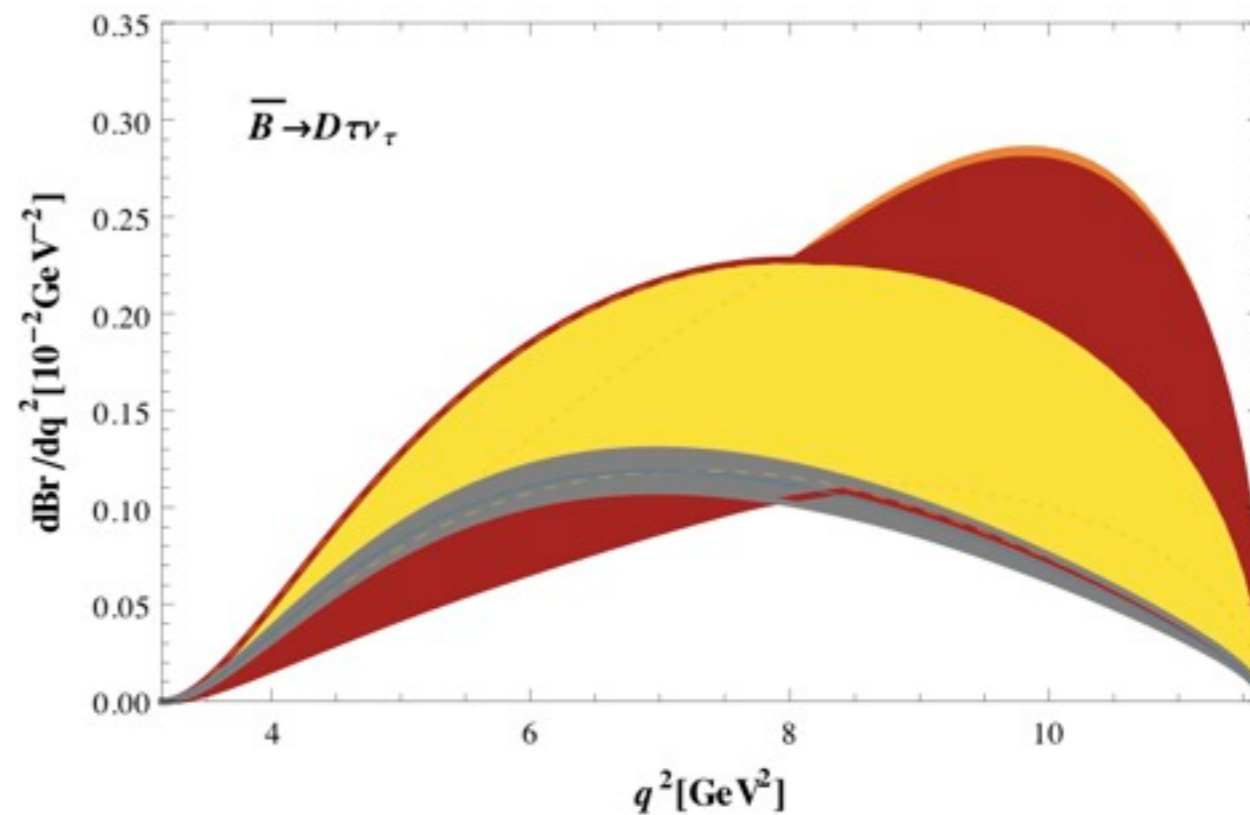
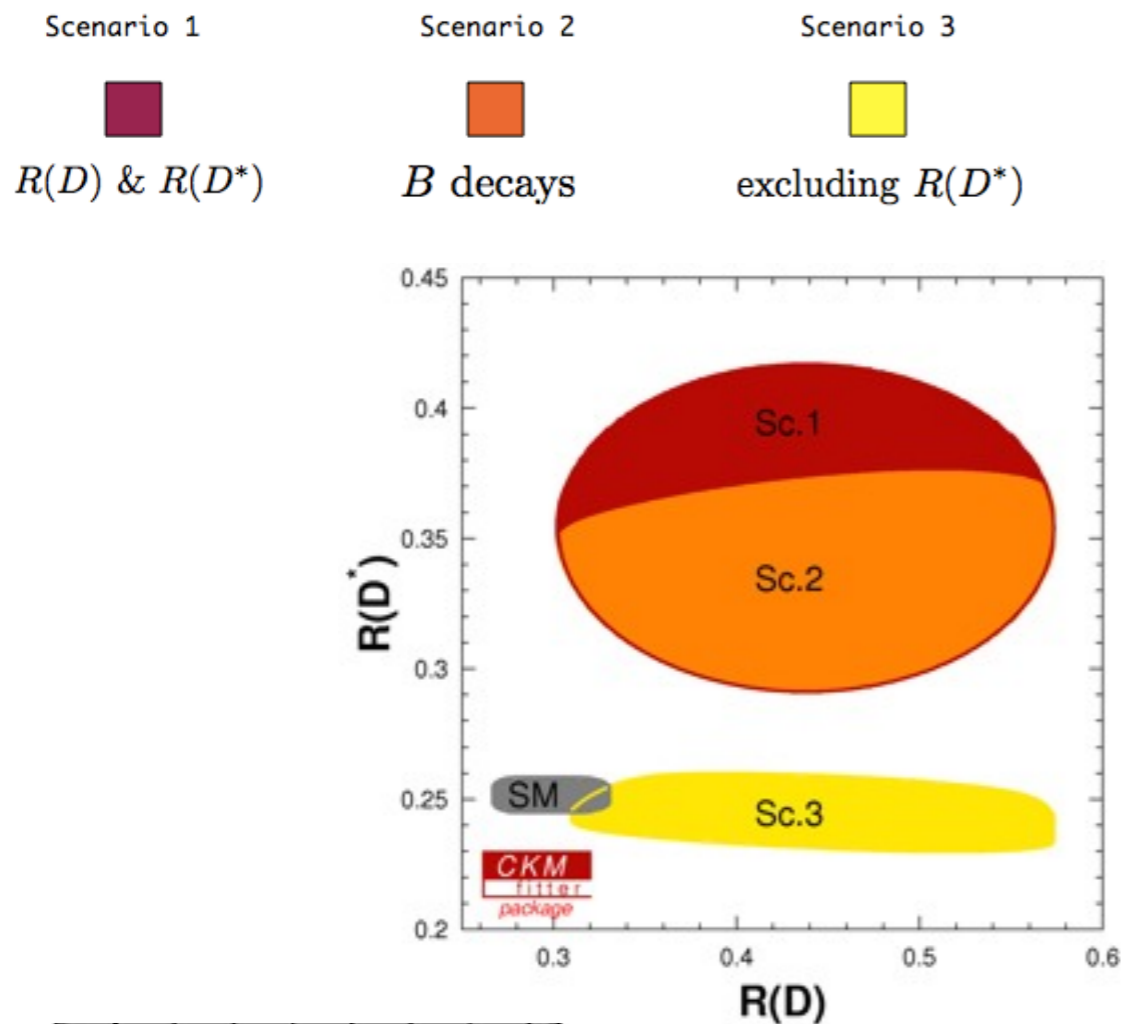
Look for differential distribution in momentum transfer, polarization of the tau and D^* , forward-backward asymmetry,...

interesting prospects for Belle-II. for details [AC, Jung, X-Q. Li, Pich \(2012\)](#) and [arXiv:1302.5992](#)

looking into the future

$$B \rightarrow D^{(*)} \tau \nu$$

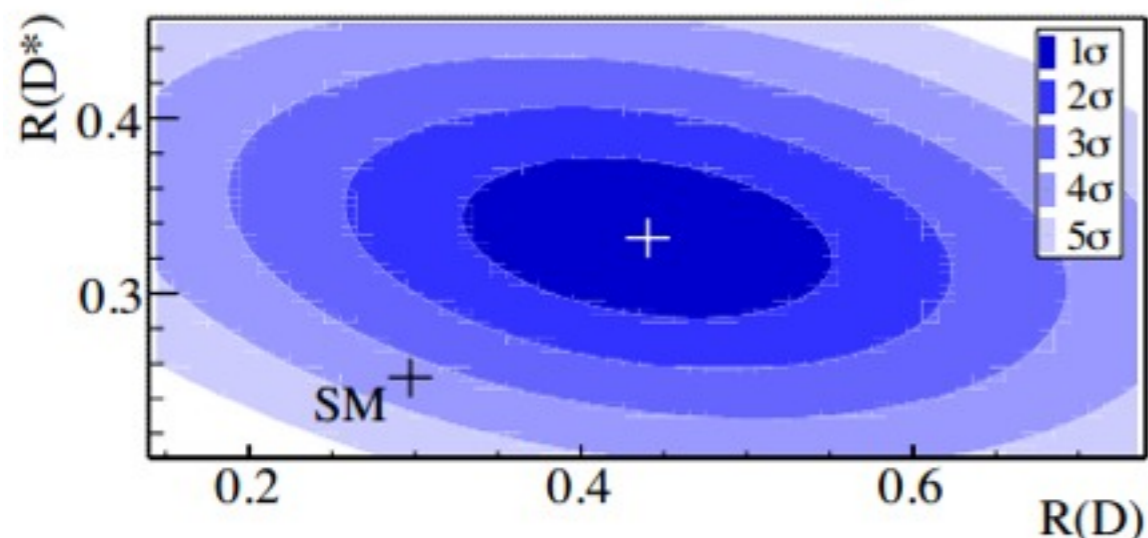
exploiting the rich kinematical structure



BaBar Collaboration, [arXiv:1303.0571]

The current situation

BaBar Collaboration, Phys.Rev.D88 (2013) > 100 citations in Inspire



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$$R(D^*) = \left\{ \begin{array}{l} 0.332 \pm 0.030 \quad \text{BABAR} \\ 0.252 \pm 0.003 \quad \text{SM} \end{array} \right\} \left. \begin{array}{l} 2.7\sigma \\ \\ \end{array} \right\}$$

many studies within different new physics scenarios

Fajfer, Kamenik, Nisandzic, Zupan (2012)

Fajfer, Kamenik, Nisandzic (2012)

Kamenik, Mescia (2008)

Crivellin, Greub, Kokulu (2012)

AC, Jung, X-Q. Li, Pich (2012)

Tanaka, Watanabe (2012)

apologies for those not included

- Lattice QCD results for $B \rightarrow D^*$ form factors would be helpful
- Can be measured at LHCb?, competitive with Belle/BaBar?
- Interesting prospects for Belle-II, exploit rich kinematics.

G. M. CIEZAREK Talk at Implications of LHCb measurements and future prospects