On the $h \to V \ell^+ \ell^-$ decays

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and
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QCD@Work 2016
Martina Franca 27−30 June 2016

Higgs

Higgs particle has been observed by ATLAS and CMS on July 2012

Phys Lett B716 (2012) 1
Phys Lett B716 (2012) 30

The "Big Five" channels

Brandstetter Talk at FPCP 2016

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2. $h \to \gamma\gamma$ (M_h)

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1. $h \to ZZ \to 4\ell$ (M_h, Γ_h, Spin-Parity)
2. $h \to \gamma\gamma$ (M_h)
3. $h \to WW \to 2\ell 2\nu$ (Spin-Parity)

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4. $h \to \tau\tau$ (Yukawa coupling)

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4. $h \to \tau\tau$ (Yukawa coupling)
5. $h \to bb$ (Yukawa coupling)

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4. $h \to \tau\,\tau$ (Yukawa coupling)
5. $h \to b\,b$ (Yukawa coupling)

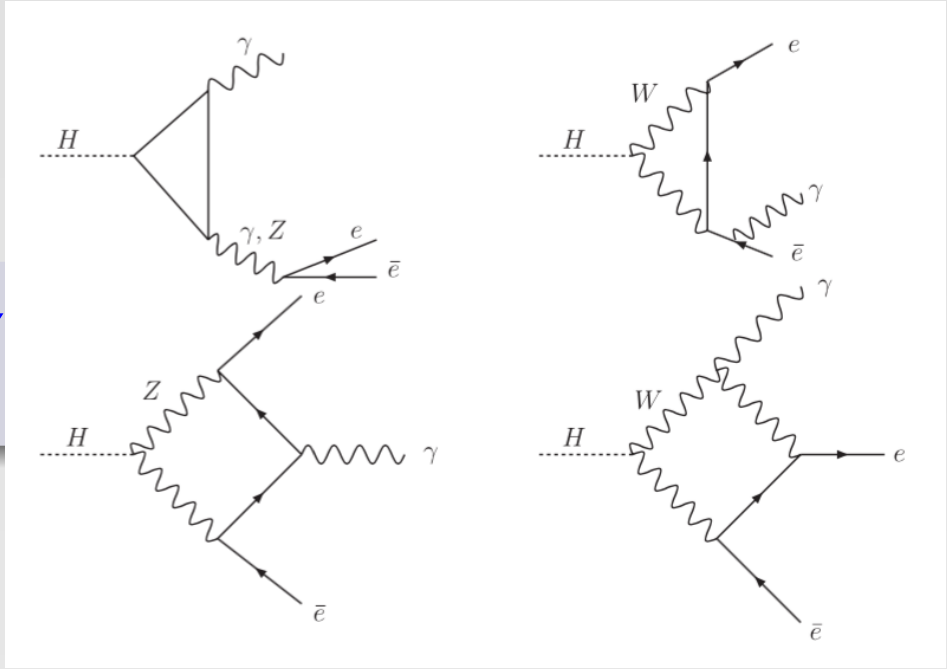
What about the couplings to the first two generations of fermions?

Higgs Couplings to the Light Fermions

Light Leptons

$h \to \ell\bar{\ell}\gamma$

$\ell \equiv \{e, \mu\}$



*PRD*55 (1997) 5647, *PLB*726 (2013) 306
JHEP 5 (2013) 61, *PRD*87 (2013) 077301
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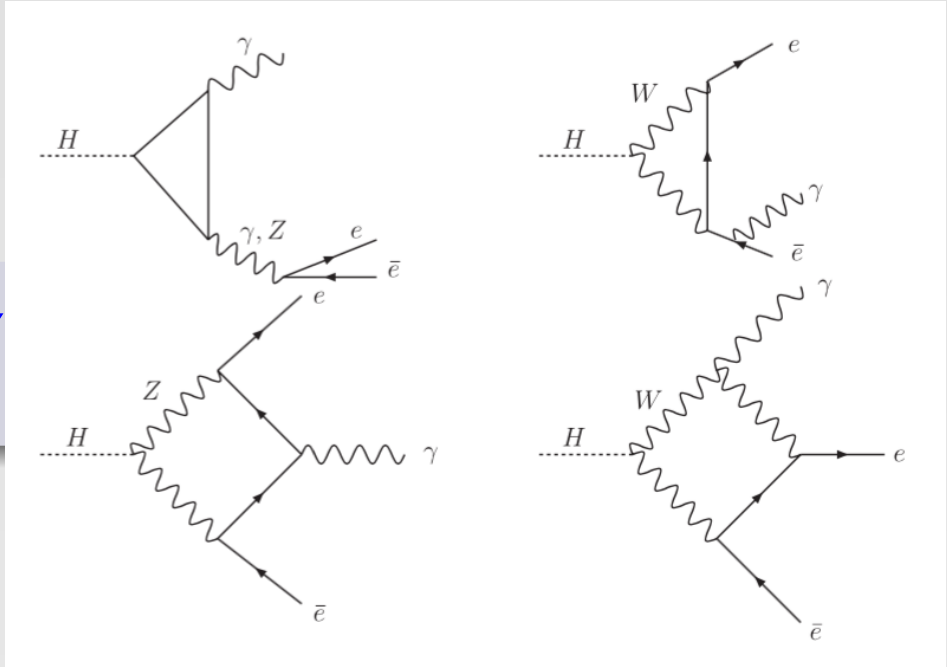

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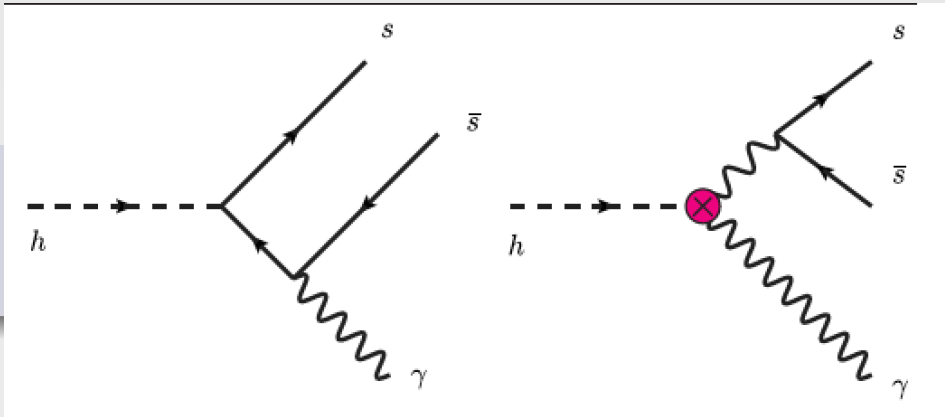
Light Quarks

$h \to V\gamma$

$V \equiv \{\phi, \rho, J/\psi, \Upsilon(1S)\}$



G. T. Bodwin et al, *PRD* 88, (2013) 053003,
A. L. Kagan et al, *PRL* 114, 101802 (2015)
M. Koenig and M. Neubert, *JHEP* 08 (2015) 012

Higgs Couplings to the Light Fermions (2)

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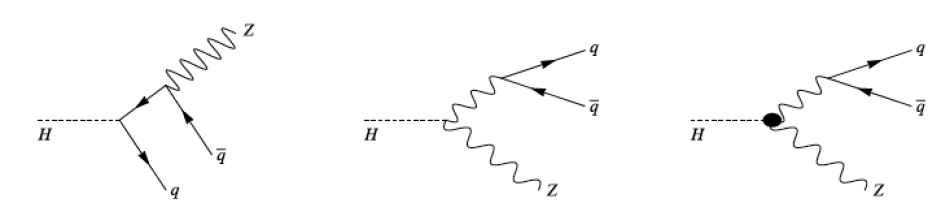

B. Bhattacharya et al, *PLB* 736 (2014) 421
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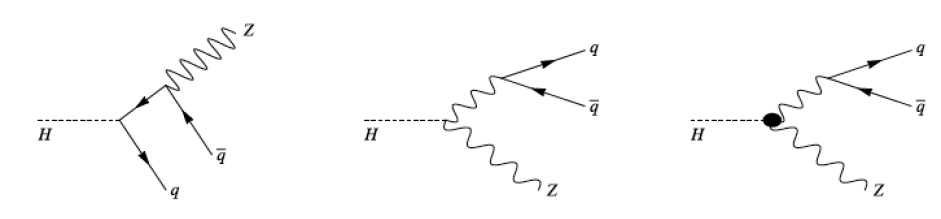

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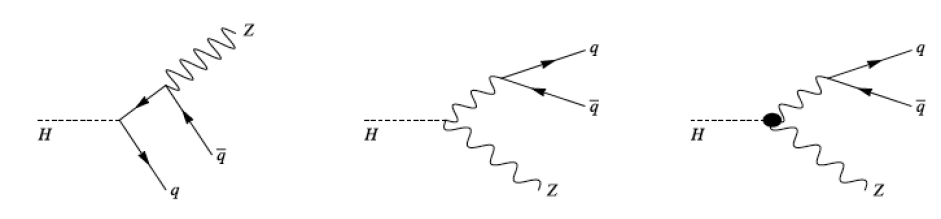

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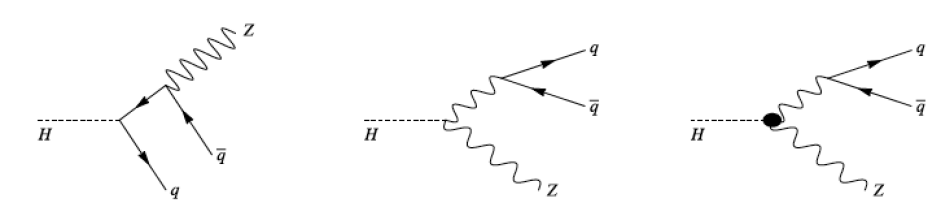

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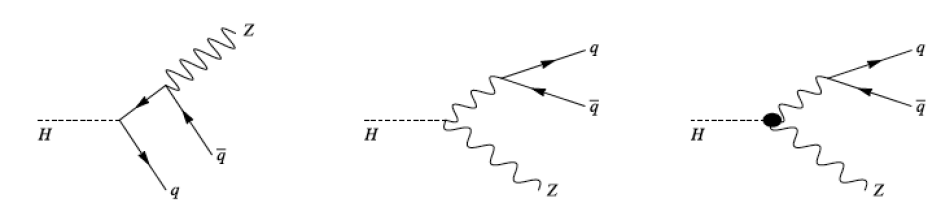

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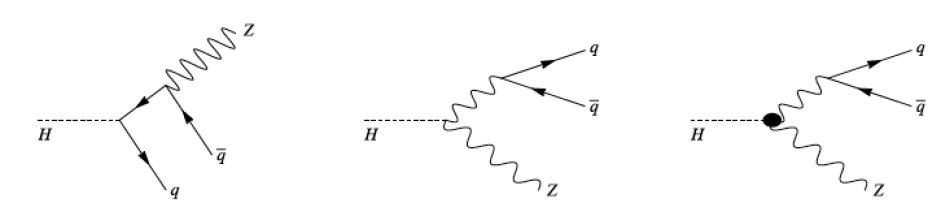

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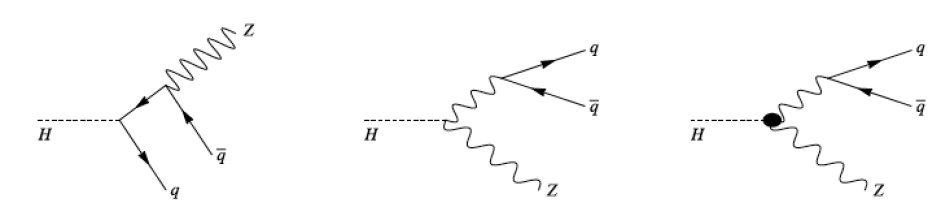

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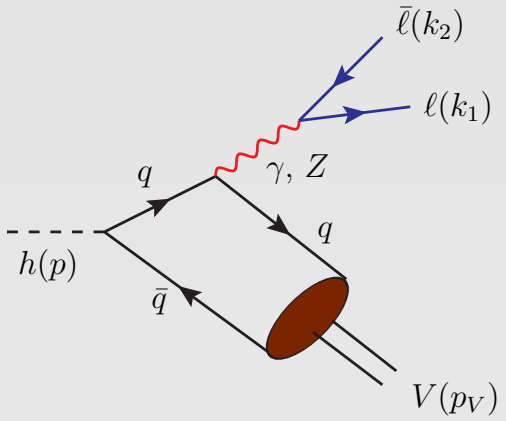
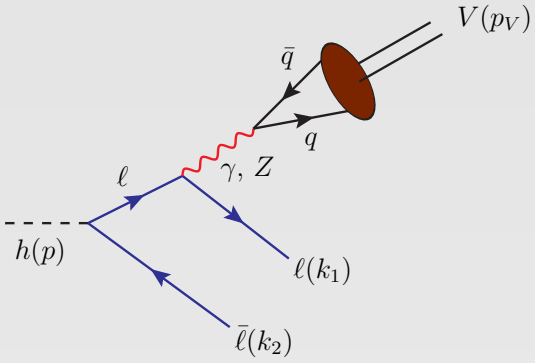
- Rates but also distributions in the dilepton mass squared
- Interferences between many amplitudes $\to$ look at various Higgs couplings
- Small Branching Ratios but clear experimental signature
- Lepton flavour violating signals

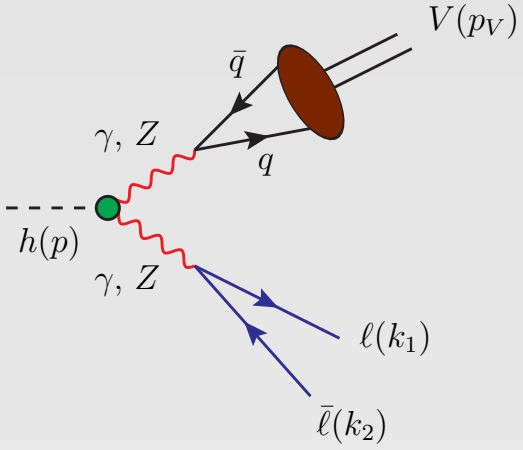
Paper in collaboration with P. Colangelo and F. De Fazio, arXiv:1602.01372 [hep-ph]

$h \to V\ell^+\ell^-$: the Diagrams

The diagrams contributing to $h \to V\ell^+\ell^-$ are the following







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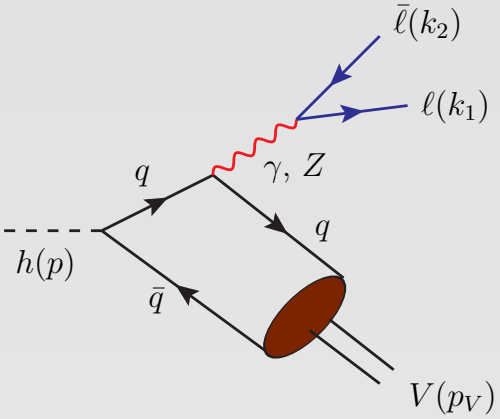

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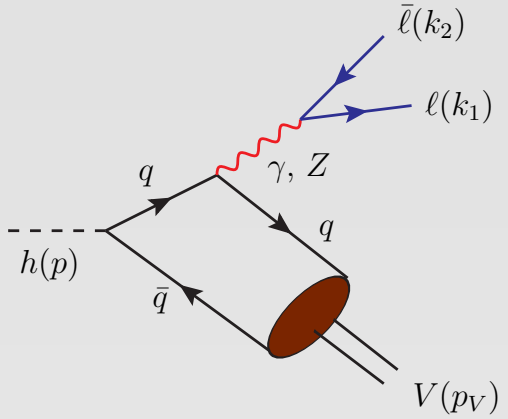

QCD hard exclusive processes approach to study quark pair hadronization

Lepage, Brodsky, Chernyak and Zhitnitsky

$$\langle\, V(p_V, \varepsilon_V)|\bar{q}(y)\sigma_{\mu\nu}q(x)|0\rangle$$

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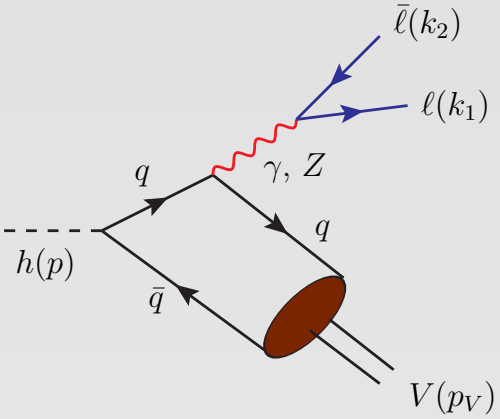

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$$-f_V^{\perp}(\varepsilon^*_{V\mu}p_{V\nu} - \varepsilon^*_{V\nu}p_{V\mu})\int_0^1 du\, e^{i u p_V\cdot x + i\bar{u} p_V\cdot y}\phi_\perp^V(u)$$

$\phi_\perp^V(u)$ leading twist of Light Cone Distribution Amplitude (LCDA)
$f_V^{\perp}$ from Lattice or QCD Sum Rules

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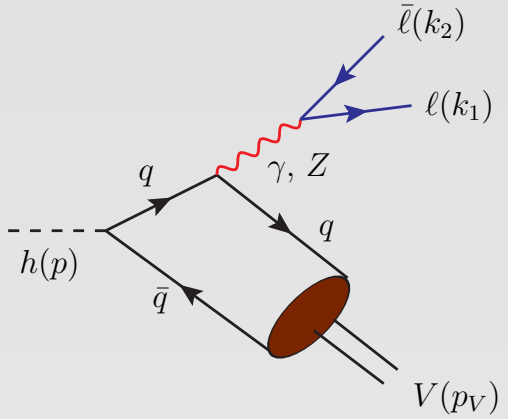

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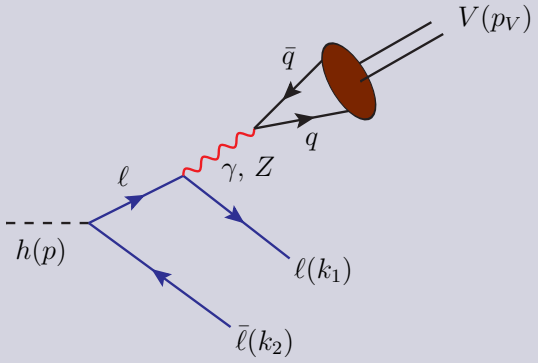
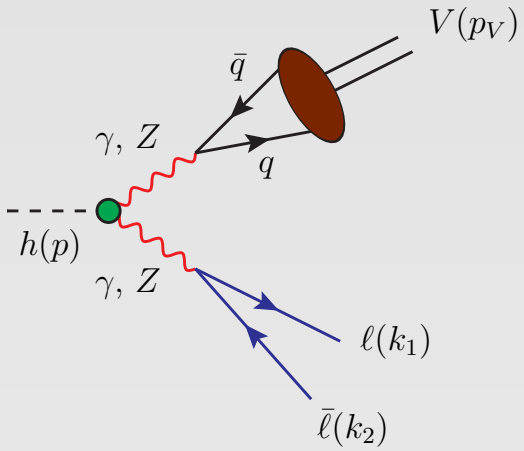


$$\langle V(p_V, \varepsilon_V)|\bar{q}\gamma_\mu q|0\rangle = -\imath\, f_V\, m_V\, \varepsilon^*_{V\mu}$$

$h \to V\ell^+\ell^-$: the Diagrams (3)



Couplings

- hZZ tree level in the SM
- $h\gamma\gamma$ and $h\gamma Z$ effective- by loop diagrams

$$A(h \to G_1 G_2) = i\frac{\alpha}{\pi v} C_{G_1 G_2} \left[g_{\mu\nu}(p_V \cdot q) - p_{V\mu} q_\nu \right] \varepsilon^{*\mu}_{G_1} \varepsilon^{*\nu}_{G_2}$$

Bergstrom, Hulth, Konig, Neubert

Branching Ratios

$$Br(h \to V\ell^+\ell^-) = \frac{\Gamma(h \to V\ell^+\ell^-)}{\Gamma(h \to \gamma\gamma)} Br(h \to \gamma\gamma)_{exp}$$

	$Br(h \to V\mu^+\mu^-)$	$Br(h \to V\tau^+\tau^-)$	$Br(h \to V\gamma)$ König & Neubert	$Br(h \to VZ)$ Isidori et al.
$V \equiv \phi$	$(7.93 \pm 0.39) \times 10^{-8}$	$(2.35 \pm 0.12) \times 10^{-6}$	$(2.31 \pm 0.11) \times 10^{-6}$	2.2×10^{-6}
$V \equiv J/\psi$	$(9.10 \pm 0.50) \times 10^{-8}$	$(1.82 \pm 0.10) \times 10^{-6}$	$(2.95 \pm 0.17) \times 10^{-6}$	2.2×10^{-6}
$V \equiv \Upsilon$	$(5.60 \pm 0.37) \times 10^{-7}$	$(5.66 \pm 0.29) \times 10^{-7}$	$\mathcal{O}(10^{-9})$	

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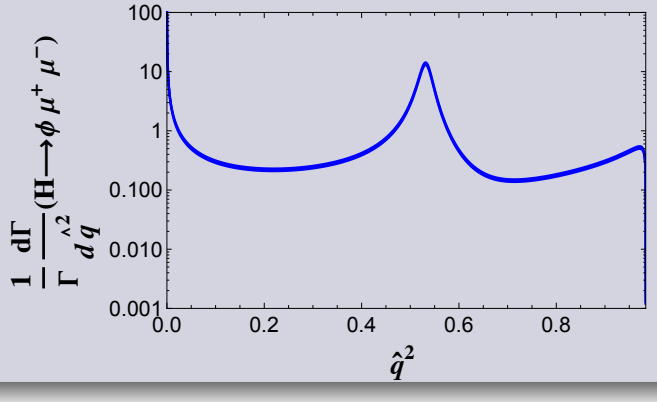
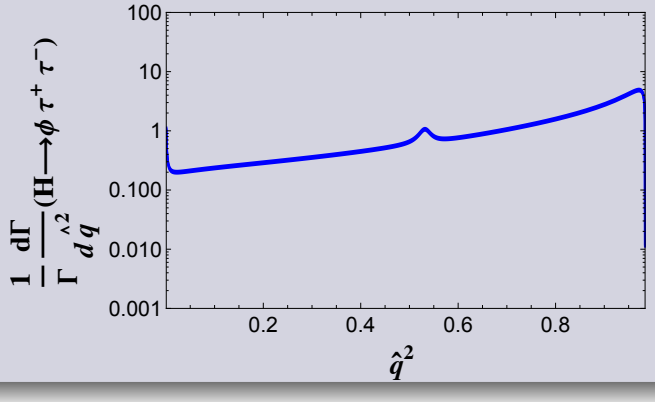
The errors

- The parameters of the LCDA
- f_V
- $f_V^\perp$
- $Br(h \to \gamma\gamma)_{exp}$ $\quad Br(h \to \gamma\gamma)_{exp} = (2.28 \pm 0.11) \times 10^{-3}$

Normalized Decay Distributions: $\frac{1}{\Gamma}\frac{d\Gamma(h\to V\ell^+\ell^-)}{d\hat{q}^2}$, $\hat{q}^2=\frac{q^2}{m_h^2}$

$V\equiv\phi$





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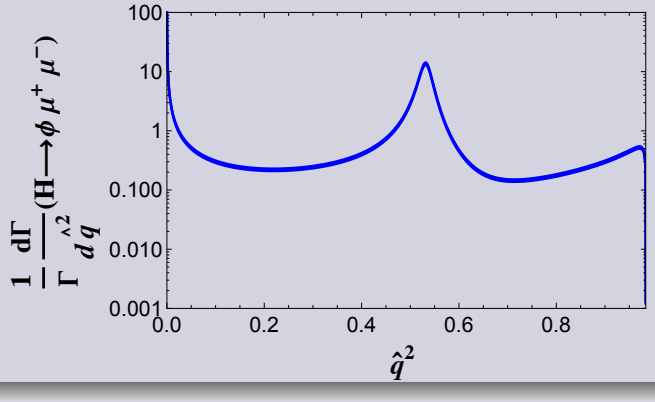

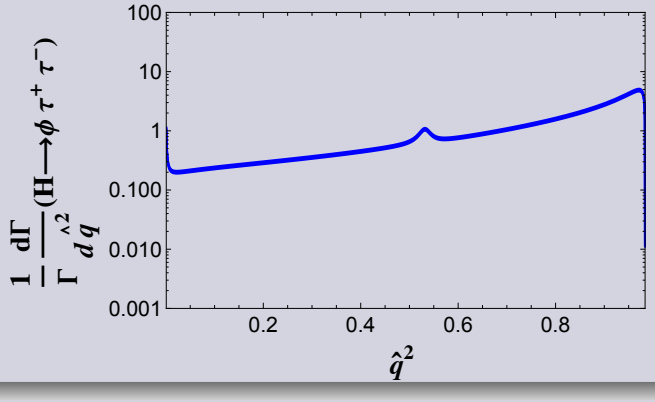

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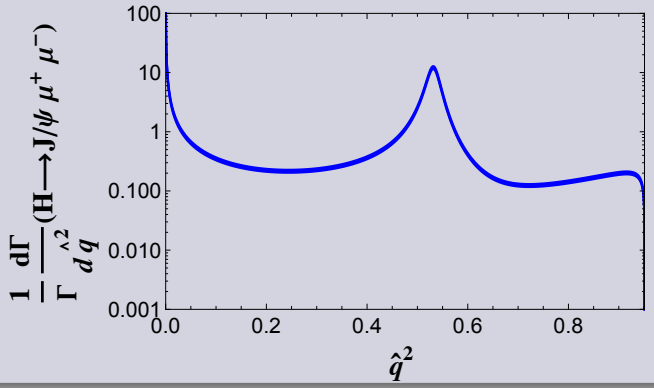

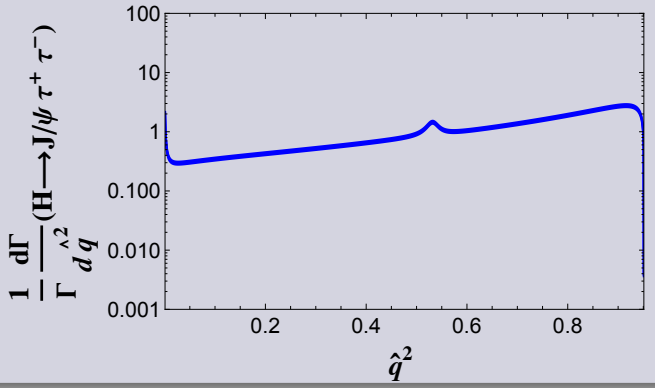

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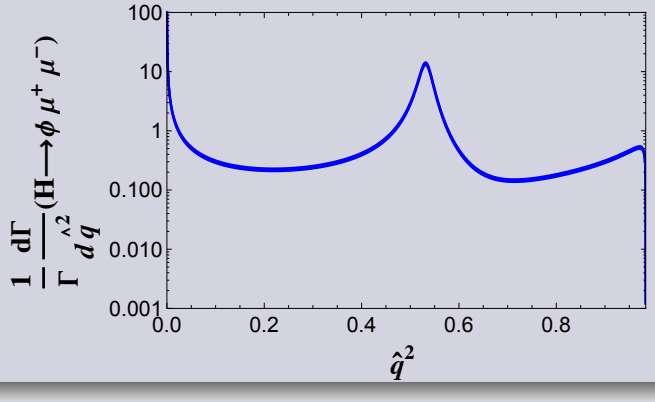

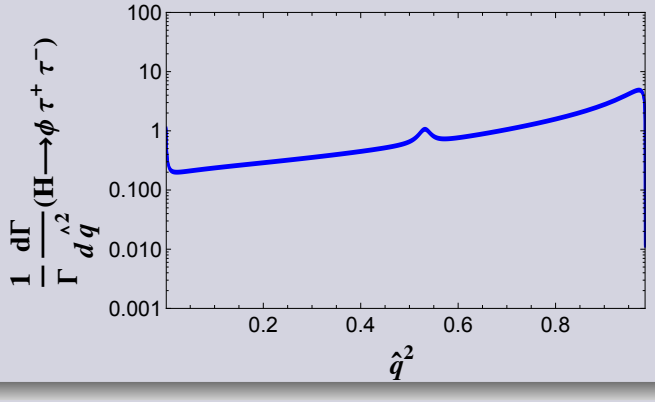

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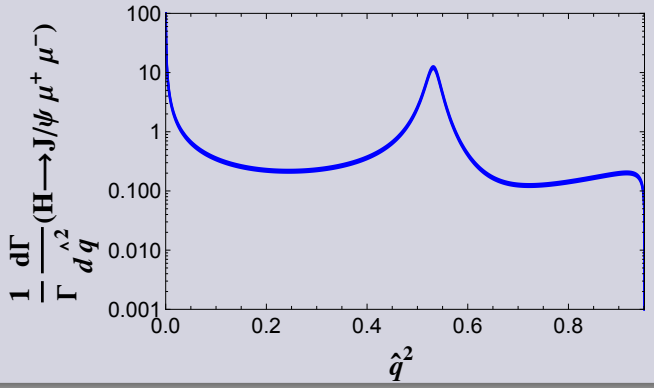

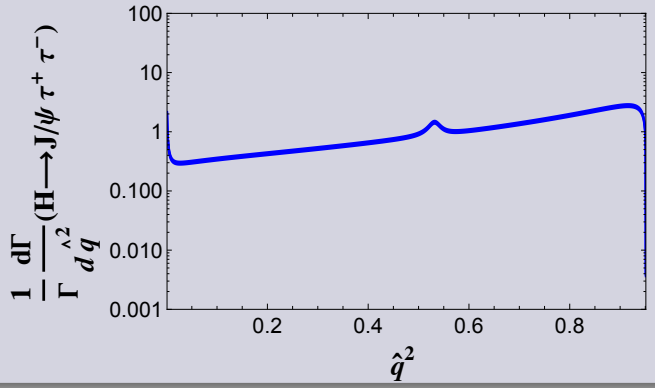

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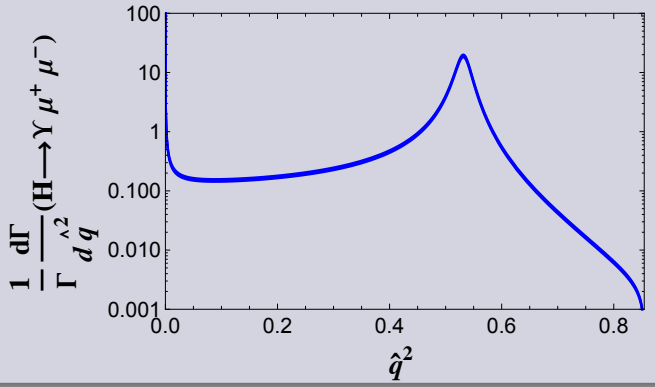
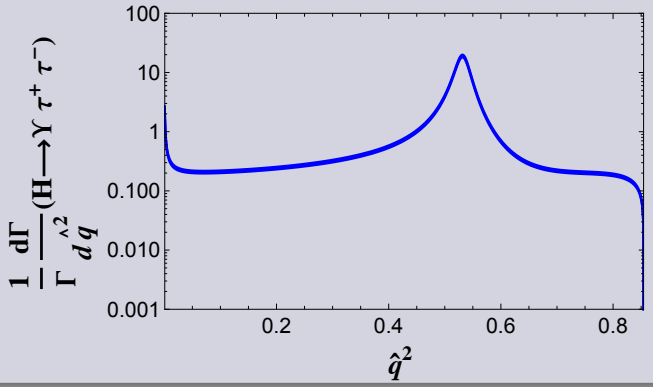
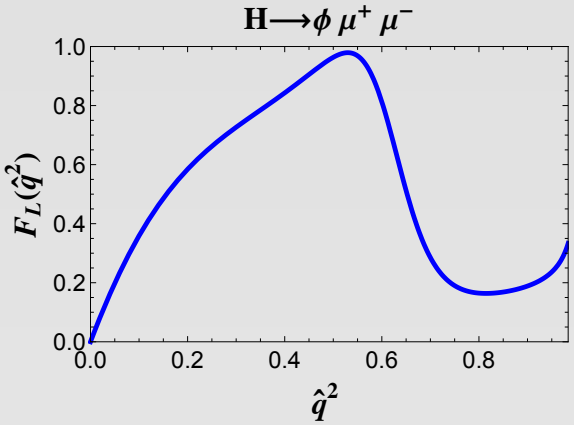
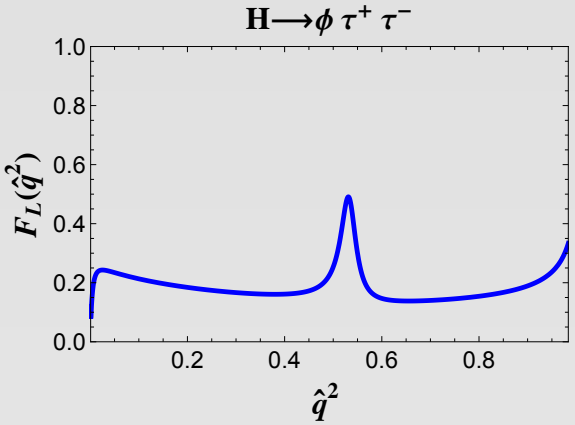




Fraction $F_L(\hat{q}^2)$ of Longitudinally Polarized Meson: $F_L(\hat{q}^2) = \frac{d\Gamma_L(h \to V\ell^+\ell^-)/d\hat{q}^2}{d\Gamma(h \to V\ell^+\ell^-)/d\hat{q}^2}$





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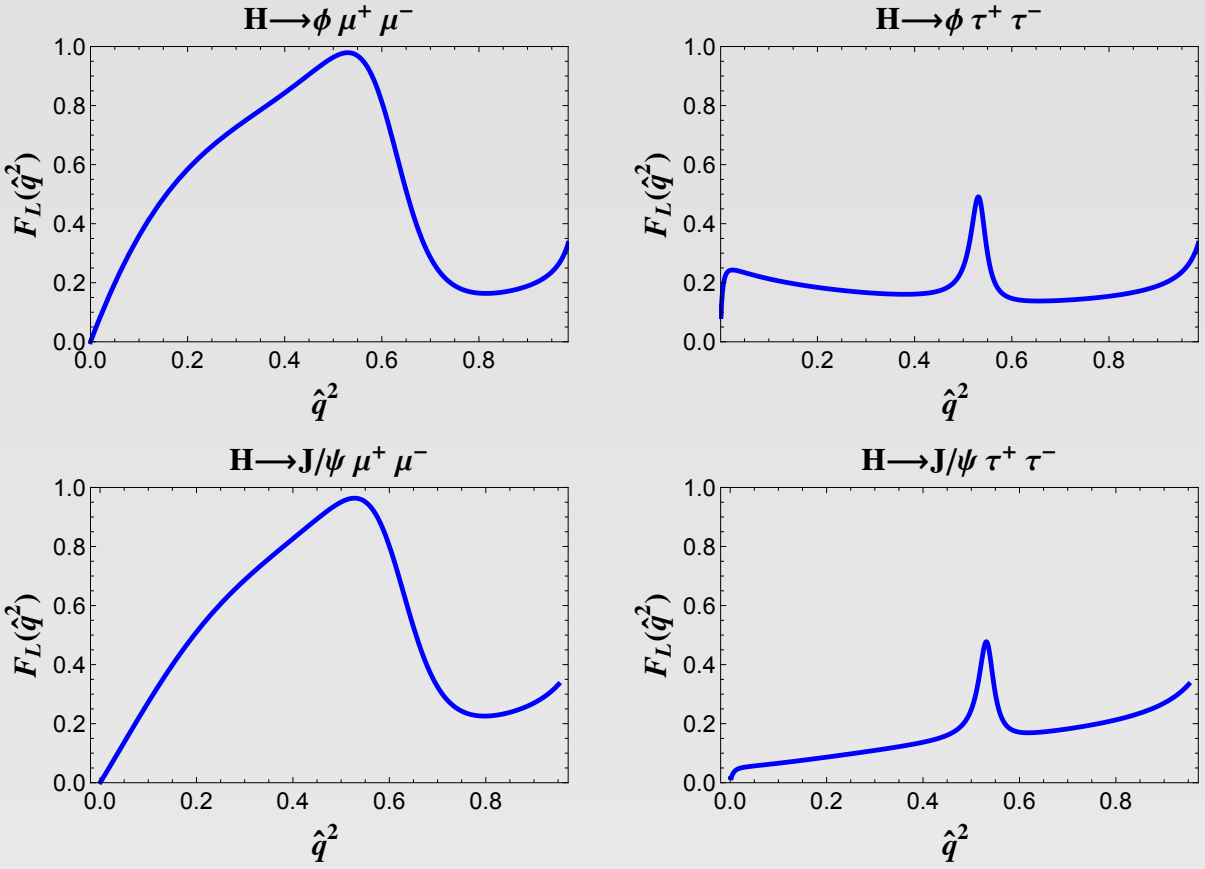

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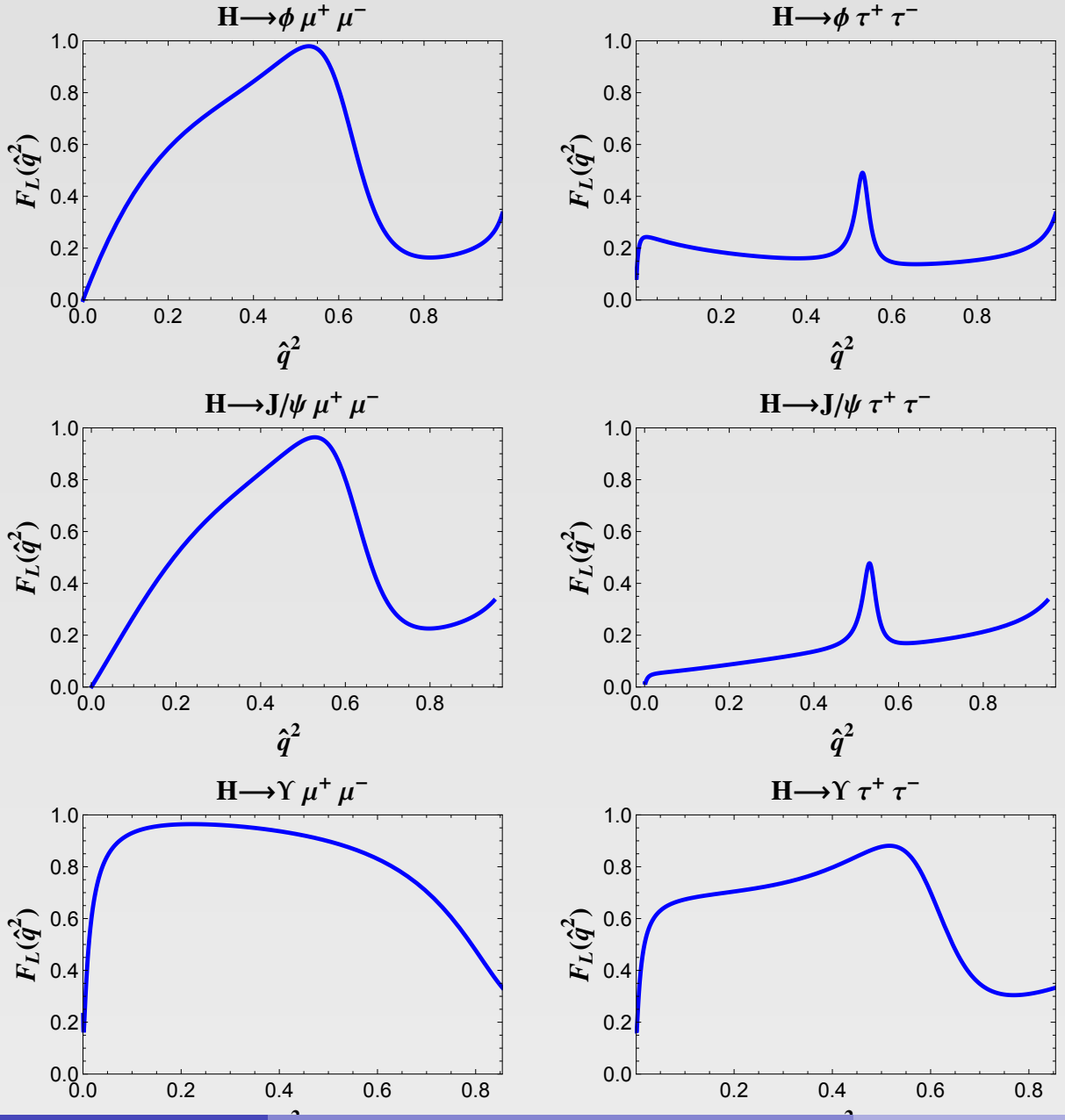

Lepton Flavour Violation in h Decay

$Br(h \to \tau\mu) = (0.84^{+0.39}_{-0.37})\%$	$\kappa_{h\tau\mu} = (2.6 \pm 0.8) \times 10^{-3}$	CMS, PLB 749 (2015) 337
$Br(h \to \tau\mu) < 1.51\%$ at 95% CL	$\kappa_{h\tau\mu} < 3.9 \times 10^{-3}$	ATLAS, JHEP 11 (2015) 211

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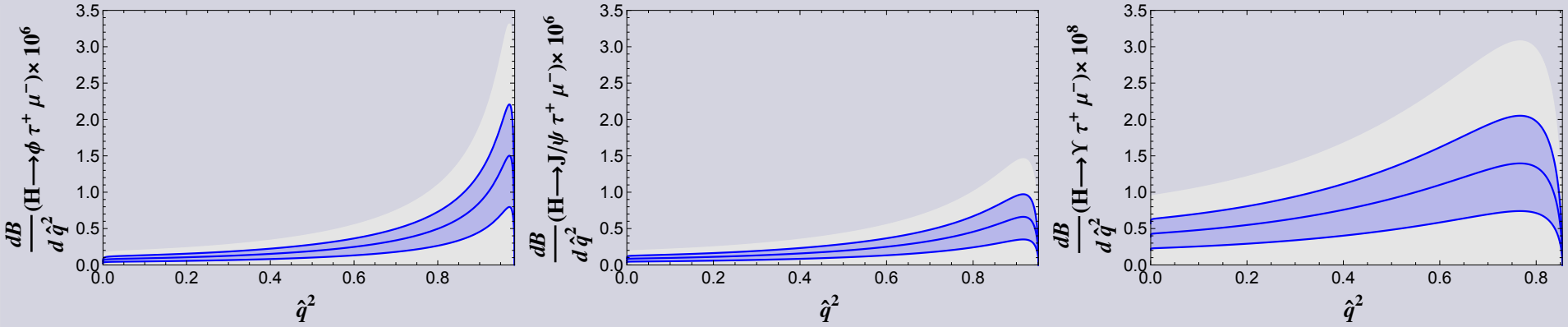

Summary

- We have studied the set of exclusive $h \to \{\phi, J/\psi, \Upsilon\}\ell^+\ell^-$ modes, Brs are in the range $10^{-8} \div 10^{-6}$ in SM
- The q^2 distributions have been studied: the resonant structures at low q^2 and at $q^2 = m_Z^2$ are recognized
- The consequences of the Lepton flavor-changing processes in these decays have been studied

Backup Slides

LCDA and Decay Constants

$$\langle V(p_V,\varepsilon_V)|\bar{q}(y)\sigma_{\mu\nu}q(x)|0\rangle = -f_V^{\perp}(\varepsilon^*_{V\mu}p_{V\nu}-\varepsilon^*_{V\nu}p_{V\mu})\int_0^1 du\, e^{iup_V\cdot x+i\bar{u}p_V\cdot y}\phi_\perp^V(u)$$

$\phi_\perp^V$ in terms of the Gegenbauer polynomials $C_n^{3/2}$

$$\phi_\perp^V(u,\mu) = 6u\bar{u}\left[1+\sum_{n=1}^{\infty} a_n^{V_\perp}(\mu)C_n^{3/2}(2u-1)\right]$$

$$a_n^{V_\perp}(\mu) = \left[\frac{\alpha_s(\mu)}{\alpha_s(\mu_0)}\right]^{\gamma_n^\perp/(2\beta_0)} a_n^{V_\perp}(\mu_0)$$

$V \equiv \phi$

$$a_2^{\phi_\perp}(\mu_0) = 0.14 \pm 0.07$$

$$a_4^{\phi_\perp}(\mu_0) = 0.00 \pm 0.15$$

$V \equiv \{J/\psi, \Upsilon\}$

$$\phi_V^\perp(u,\mu_0) = N_\sigma \frac{4u\bar{u}}{\sqrt{2\pi}\sigma_V}\exp\left[-\frac{u-\frac{1}{2}}{2\sigma_V^2}\right]$$

$$\sigma_{J/\psi} = 0.228 \pm 0.057$$

$$\sigma_\Upsilon = 0.112 \pm 0.028$$

$$f_\phi = 0.223 \pm 0.0014 \text{ MeV}$$

$$f_{J/\psi} = 0.4033 \pm 0.0051 \text{ MeV}$$

$$f_\Upsilon = 0.6844 \pm 0.0046 \text{ MeV}$$

$$f_\phi^\perp/f_\phi = R_{f_\phi} = 0.76 \pm 0.04$$

$$f_{J/\psi}^\perp/f_{J/\psi} = R_{f_{J/\psi}} = 0.91 \pm 0.14$$

$$f_\Upsilon^\perp/f_\Upsilon = R_{f_\Upsilon} = 1.09 \pm 0.04$$

The $h \to V\,\nu\,\bar{\nu}$ decay

$$
\begin{aligned}
Br(h \to \phi\,\nu\,\bar{\nu}) &= (1.50 \pm 0.08) \times 10^{-7} \\
Br(h \to J/\psi\,\nu\,\bar{\nu}) &= (1.54 \pm 0.09) \times 10^{-7} \\
Br(h \to \Upsilon\,\nu\,\bar{\nu}) &= (1.52 \pm 0.08) \times 10^{-6}
\end{aligned}
$$