Measurement of the $D^0 \to \pi^- e^+ \nu$ BR, form factor and implications for V_{ub}

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On behalf of the BaBar Collaboration

Outline

[PRD 91, 052022 (2015)]

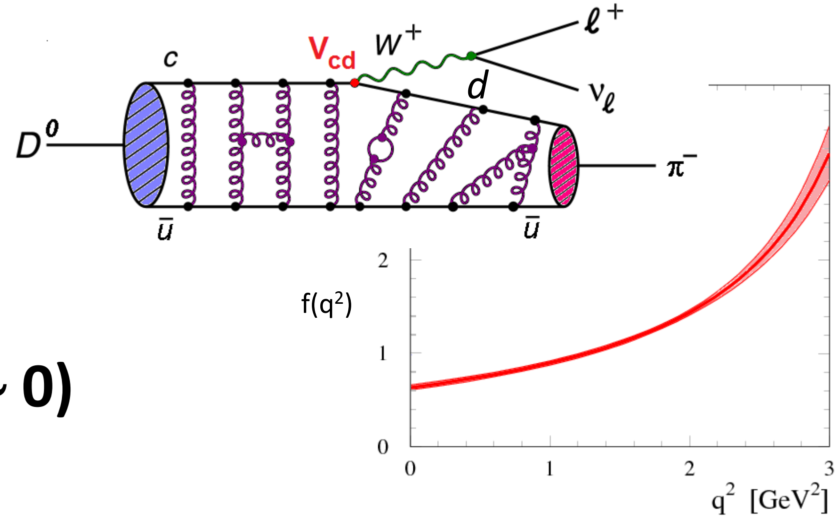
- Motivation
- Analysis of $D^0 \to \pi^- e^+ \nu$ events at BaBar
- Measurement of the branching fraction
- Form factor interpretation
- Application: V_{ub} extraction
- Conclusions

Motivation

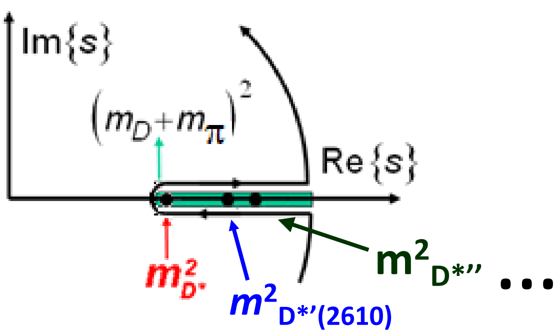
$$q^2 = (p_e + p_{\nu_e})^2 = (p_D - p_\pi)^2$$

- The $D^0 \to \pi^- e^+ \nu$ decay channel:

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{cd}|^2 p_\pi^3 (q^2) \left| f_+(q^2) \right|^2$$



- Only one form factor: $f_+(q^2)$ ($m_e \sim 0$)



$$f^\pi_{+,D}(q^2) \simeq \sum_i^\infty \frac{Res(f^\pi_{+,D})_{D_i^*}}{m^2_{D_i^*} - q^2}$$

D^*_i are $J^P = 1^-$ states ($\to D\pi$)

- Partially known: contributions from the D* and D*' poles
- Can be related to the $B \to \pi$ form factor at the same $E_\pi \to V_{ub}$

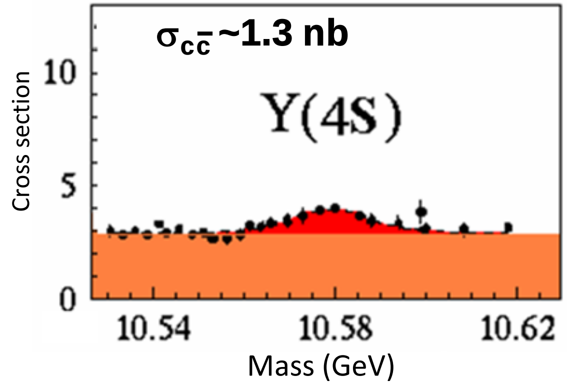
Analysis method

- **Based on similar techniques as in other BaBar analyses**

  $D^0 \to K^- e^+ \nu$ (PRD 76 (07) 052005), $D_s \to K^+ K^- e^+ \nu$ (PRD78 (08) 051101 (RC)) , $D^+ \to K^- \pi^+ e^+ \nu$ (PRD 83 (11) 072001)

- **$D^0 \to \pi^- e^+ \nu$: Cabibbo suppressed (BR~0.3%); large backgrounds from π's**

- **From 347.2 fb^{-1} of $e^+e^- \to c\bar{c}$ events at the Υ(4S) recontruct $D^{*+} \to D^0 \pi^+$, $D^0 \to \pi^- e^+ \nu$:**

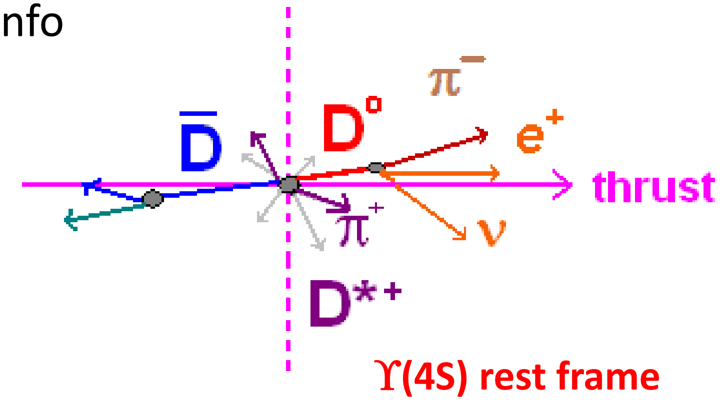


  → Partially reconstructed: π^+, π^- and e^+ in the same hemisphere

  → Require tight PID signal pions and veto against kaons

  → Reconstruct $p_{D^0} = p_{\pi^-} + p_{e^+} + p_\nu$ using E_{miss} and info of the rest of the event

  → Constraints using m_{D^0} and $m_{D^{*+}}$



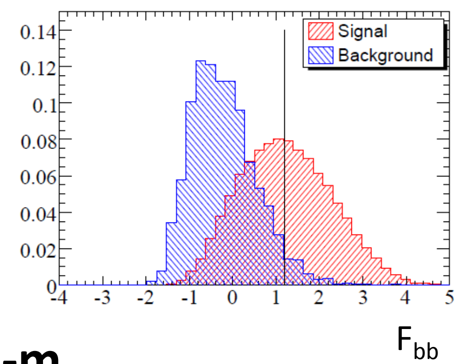
- **Control channel from data: $D^0 \to K^- \pi^+$**

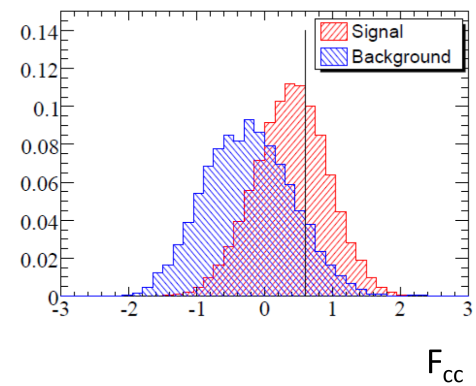
Analysis method

- **The background is reduced using Fisher discriminant variables**

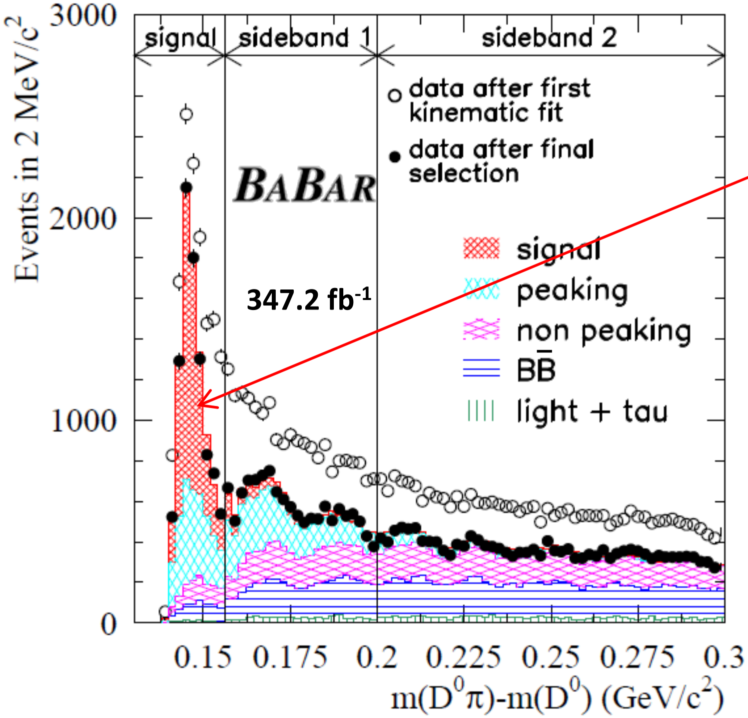
  - F_{bb}: against $B\bar{B}$ events (event shape)
  - F_{cc}: against non-signal $c\bar{c}$ events (additional tracks topology)

  ε: 1.8%, S/B ~ 1.2





- **Signal events selected in $\delta m = m_{D^{*+}} - m_{D^0}$**



~ 10000 candidates
50 % background

Background sources:

- **$B\bar{B}$ background**
- **Charm non-peaking (π not from D*)**
- **Charm peaking (13 subcategories)**
- **Light quarks**

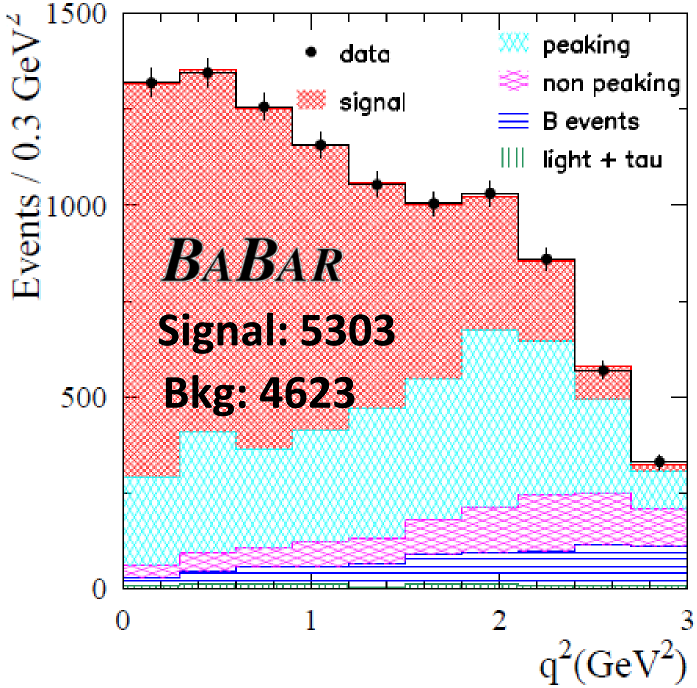
- **Use $\delta m = m_{D^{*+}} - m_{D^0}$ sidebands from on-peak ($B\bar{B}$ + $c\bar{c}$+light) and off-peak (37fb^{-1}; $c\bar{c}$+light) data samples to determine the different backgrounds (fit E_{miss} vs p_π)**

  → Main systematic uncertainty in the analysis assessed using data

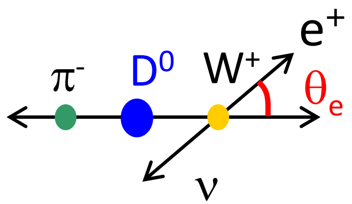
Analysis method

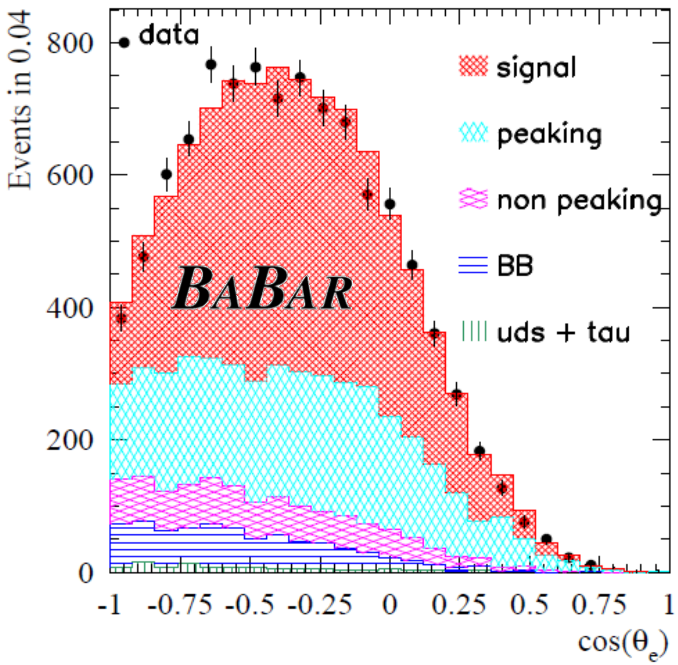
- **The $q^2 = (p_{D^0} - p_{\pi^-})^2 = (p_{e^+} + p_\nu)^2$ distribution is measured in 10 bins:**

$\delta m = m(D^0\pi) - m(D^0) < 0.150$ GeV



Cross-check: Pseudoscalar, known angular distribution



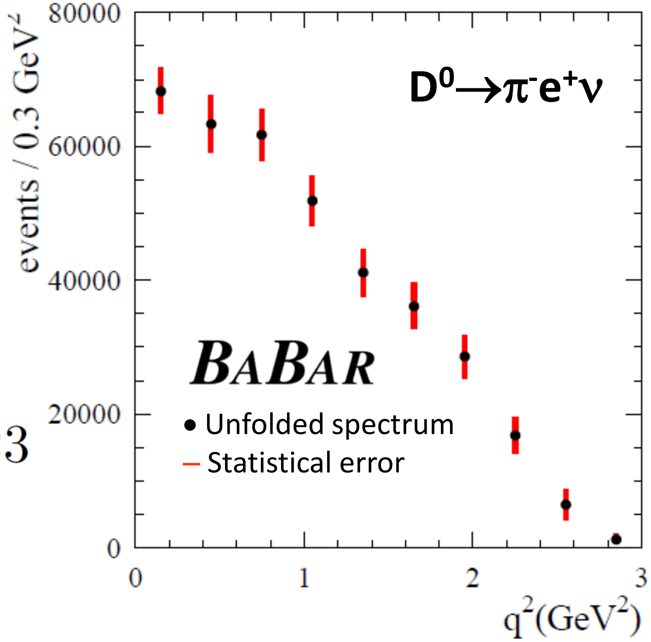


→ **Resolution $\sigma(q^2) \sim 0.085$ GeV² (50%) and 0.311 GeV² (50%)**

Measurement of the Branching Fraction

- **Normalization: relative to the $D^0 \to K^- \pi^+$ decay channel**

  - Try to have a selection as similar as possible for the $D^0 \to \pi^- e^+ \nu$ and $D^0 \to K^- \pi^+$ channels
  - Measure $B(D^0 \to \pi^- e^+ \nu)/B(D^0 \to K^- \pi^+)$ in data and in MC
  - From the unfolded number of signal events:



$$R_D = \frac{\mathcal{B}(D^0 \to \pi^- e^+ \nu_e)_{data}}{\mathcal{B}(D^0 \to K^- \pi^+)_{data}} = 0.0702 \pm 0.0017 \pm 0.0023$$

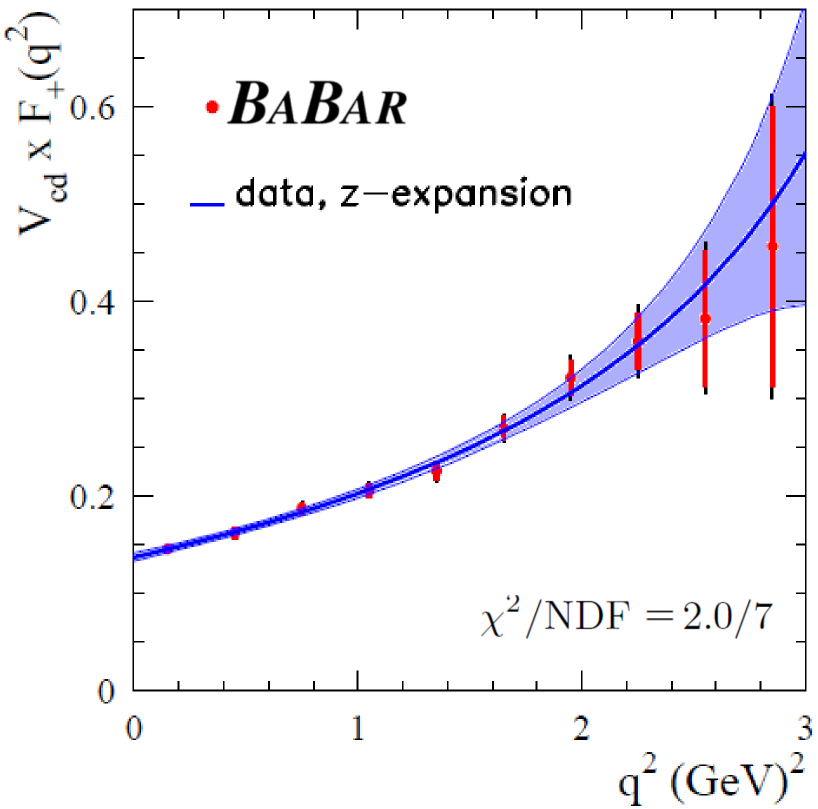
Using the world average for $BR(D^0 \to K^- \pi^+)$:

$$\mathcal{B}(D^0 \to \pi^- e^+ \nu_e) = (2.770 \pm 0.068 \pm 0.092 \pm 0.037) \times 10^{-3}$$

PDG 2014 : $BR(D^0 \to \pi^- e^+ \nu) = (2.89 \pm 0.08) \times 10^{-3}$

Form factor interpretation

- **Form factor fit in the z-expansion formalism:**



z-expansion

$$F(t) = \frac{1}{P(t)\phi(t,t_0)} \sum_{k=0}^{\infty} a_k(t_0) z(t,t_0)^k$$

$|z| << 1$

$t \equiv q^2$

$$z(t,t_0) = \frac{\sqrt{t_+ - t} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - t} + \sqrt{t_+ - t_0}} \qquad t_0 = t_+(1 - \sqrt{1 - t_-/t_+}) \qquad t_\pm = (m_{D^0} \pm m_{\pi^+})^2$$

$$\sum_{k=0}^{\infty} a_k^2(t_0) \leq 1$$

$P(t)=1$ for $D \to \pi e \nu$

→ Model independent, based on QCD properties

→ a_K parameters (fitted) have no physics interpretation

Fitted parameters:

$r_k = a_k/a_0$

$$r_1 = -1.31 \pm 0.70 \pm 0.43$$
$$r_2 = -4.2 \pm 4.0 \pm 1.9$$

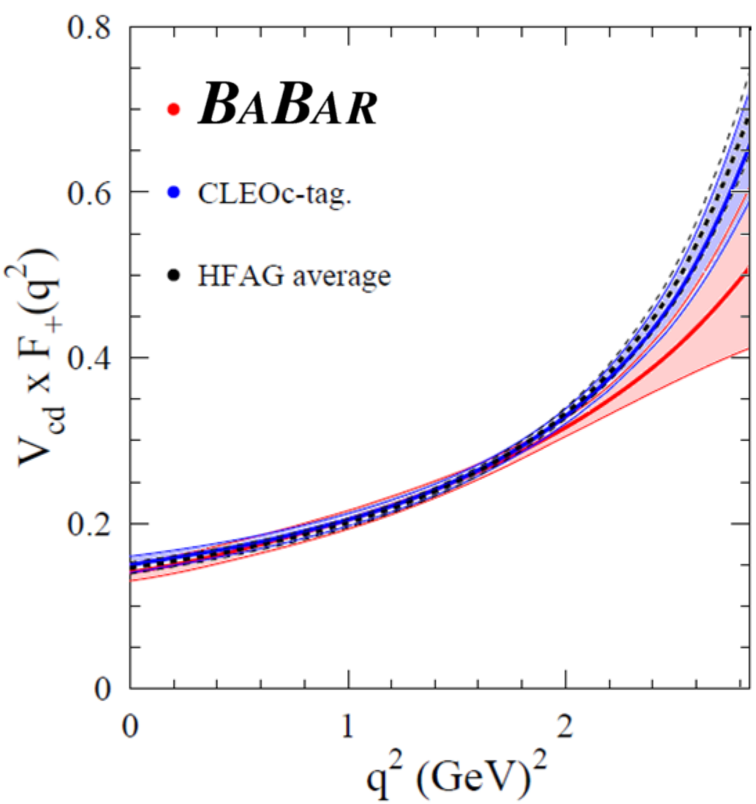
- **Normalization:**

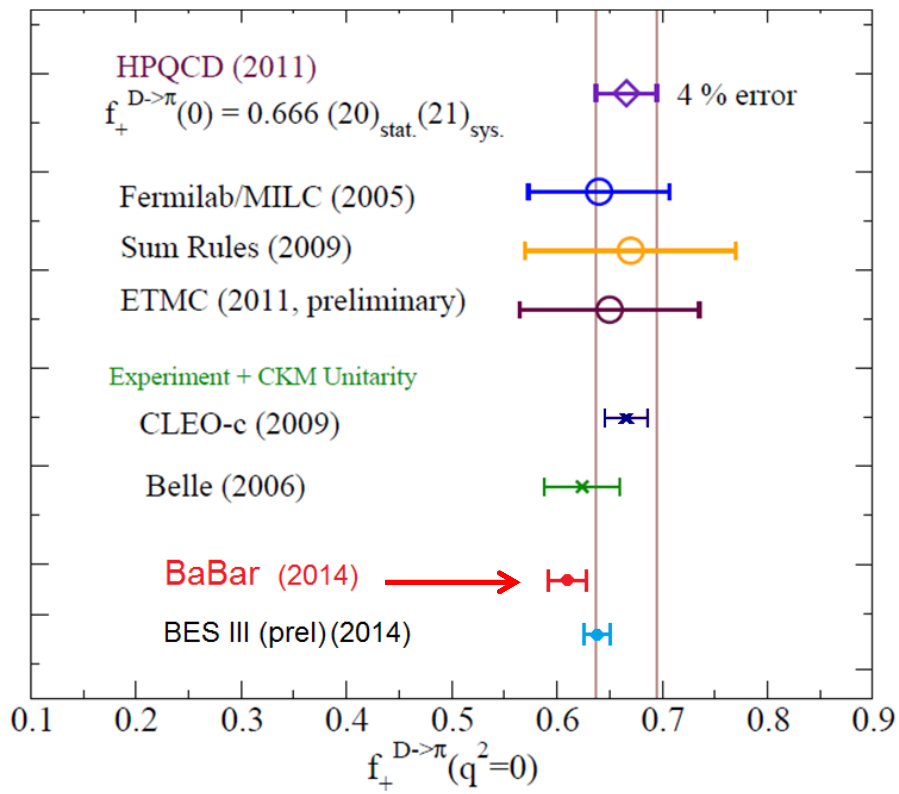
$$|V_{cd}| f_{+,D}^{\pi}(0) = 0.1374 \pm 0.0038_{\mathrm{stat.}} \pm 0.0022_{\mathrm{syst.}} \pm 0.0009_{\mathrm{ext.}}$$

Form factor interpretation

- **Comparison with other results:**

NEW Lattice 2015 (ETMC) $f_+(0)=0.610(23)(?)$
(N. Carrasco *et al.*)





$$|V_{cd}| = |V_{us}| = 0.2252 \pm 0.0009 \rightarrow f^{\pi}_{+,D}(0) = 0.610 \pm 0.017 \pm 0.010 \pm 0.005$$

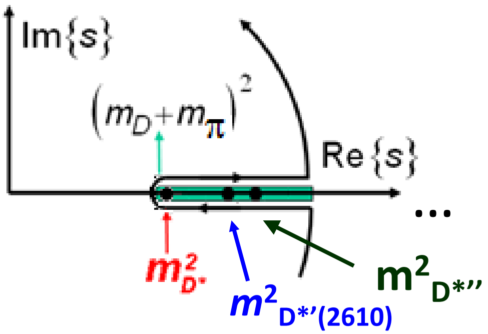
$$f^{\pi}_{+,D}(0) = 0.666 \pm 0.029 \rightarrow |V_{cd}| = 0.206 \pm 0.007_{\rm exp.} \pm 0.009_{\rm LQCD}$$

Lattice average (arXiv:1310.8555)

Form factor interpretation

- **Going further in the understanding of the form factor:**

Burdman and Kambor [PRD55 (1997) 2817] (and before)
Becirevic and Kaidalov [PLB(2000) 417]



$$f^{\pi}_{+,H}(q^2) \simeq \sum_{i}^{\infty} \frac{Res(f^{\pi}_{+,H})_{H^*_i}}{m^2_{H^*_i} - q^2}$$

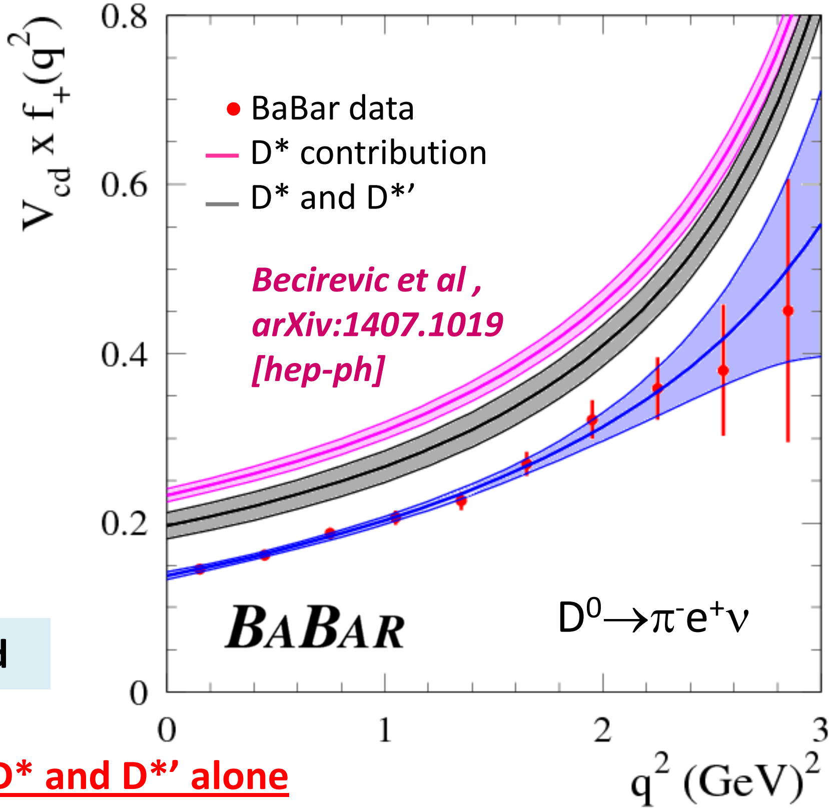
being H* = D*,D*', D*'',... (or B*, B*', B*'', ...) ($J^P=1^-$)

$$Res(f^{\pi}_{+,H})_{H^*} = \frac{1}{2} m_{H^*} f_{H^*} g_{H^*H\pi}$$

f_{H^*}, $g_{H^*H\pi}$ are the decay constant and coupling

- **For $D^0 \to \pi^- e^+ \nu$: - f_{D^*}, $f_{D^{*\prime}}$ determined by Lattice**
  - $g_{H^*H\pi}$, $g_{H^{*\prime}H\pi}$ from D*, D*' widths measured at BaBar

→ **D* and D*' contributions constrained**



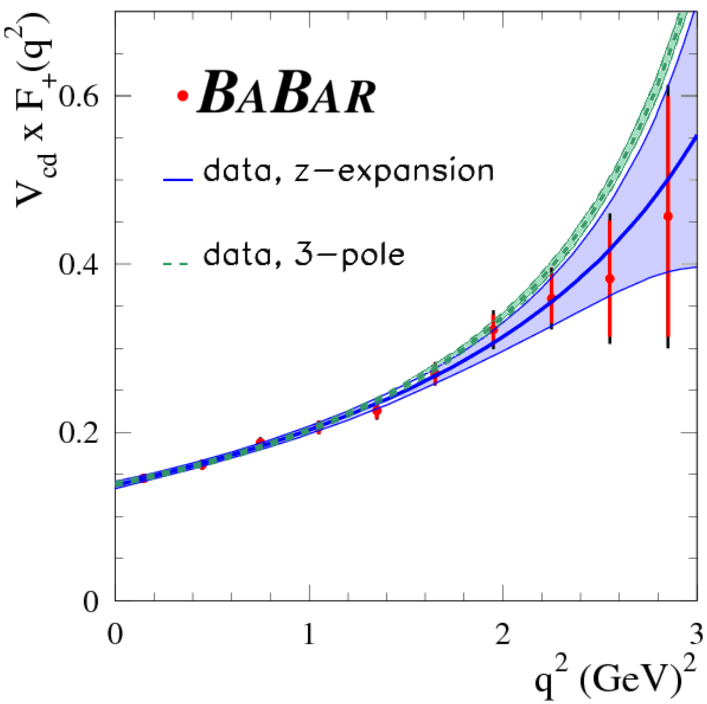
→ **The form factor cannot be explained by the D* and D*' alone**

Form factor interpretation

"Three" poles ansatz (multipole) *Becirevic et al (arXiv:1407.1019 [hep-ph])*

$$f^{\pi}_{+,D}(q^2) = \frac{f^{\pi}_{+,D}(0)}{1 - c_2 - c_3}\left(\frac{1}{1-\frac{q^2}{m^2_{D^*}}} - \sum_{i=2}^{3}\frac{c_i}{1-\frac{q^2}{m^2_{D_i^{*\prime}}}}\right)$$

c_i given by the residues of the poles (relative to D*) in terms of decay constants and couplings



Data is well described by this ansatz

if one fits a 3rd pole effective mass with the condition (*superconvergence*):

$$\sum_i Res(f^{\pi}_{+,D})_{D_i^{*(\prime)}} \simeq 0$$

$$m_{pole3} = (3.6 \pm 0.3)\, GeV/c^2$$

→ larger than the predicted third $J^P=1^-$ state by quark models ~3.1GeV,
(as expected since it is effective)

→ a unique 3rd contribution from $m_{D^{*\prime\prime}}$=3.1 GeV is excluded by data

Application: V_{ub} extraction

- **Having measured $d\Gamma_{D\to\pi e\nu}/dq^2$ we can extract V_{ub} from the relation between the $D\to\pi\ell\nu$ and $B\to\pi\ell\nu$ channels:**

Using $w_{B,D} = v_{B,D} \cdot v_\pi = E^*_\pi/m_\pi$ instead of q^2

$$w_{B,D} = \frac{M_{B,D}{}^2 + m_\pi^2 - q^2}{2M_{B,D}m_\pi}$$

At w_B=w_D :

$$\frac{d\Gamma(B\to\pi\ell\nu)/dw_B}{d\Gamma(D\to\pi\ell\nu)/dw_D} = \left|\frac{V_{ub}}{V_{cd}}\right|^2 \left(\frac{M_B}{M_D}\right) \left|\frac{f_+^{B\to\pi}}{f_+^{D\to\pi}}\right|^2$$

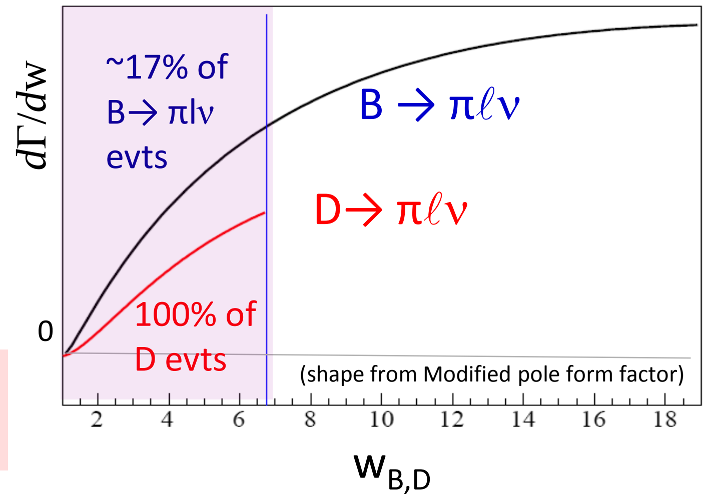
1) From Lattice

2) From a phenomenological model

→ ***Kinematic factors cancel*** **(same E_π)**

Experimentally, the common range in $w_{B,D}$

$w_{B,D} \in [1,6.7]$:
$q^2_D \in [0; 2.975]GeV^2$
$q^2_B \in [18; 26.4]$ GeV^2

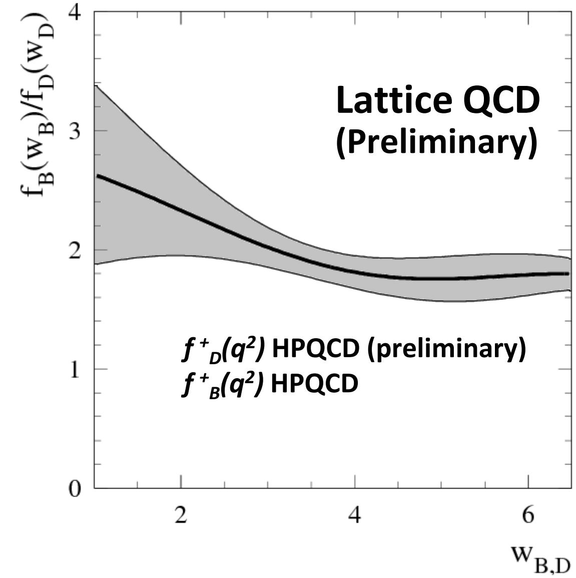


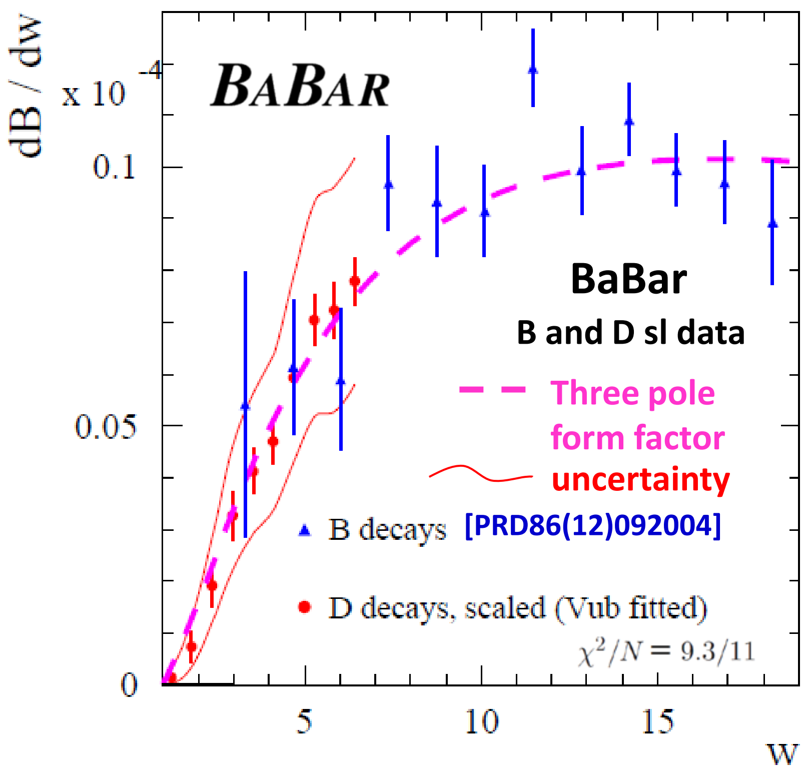
A physics interpretation of the charm form factor may allow to use it outside the D physical region

→Aim to extract V_{ub} with a different approach, different uncertainties

Application: V_{ub} extraction

- **1) <u>V_{ub} extraction</u> (from Lattice):**
  - → Using BaBar $D^0 \to \pi^- e^+ \nu$ and $B^0 \to \pi^- e^+ \nu$ data
  - → the **"three" poles** form factor fitted on $D^0 \to \pi^- e^+ \nu$
  - → extrapolated to the unphysical region
  - → **assuming a constant ratio of $f^+_B(w_B)/f^+_D(w_D)$**





→ good fit for several considered ranges in w:
data are compatible with a constant $f_B(w_B)/f_D(w_D)$

$$|V_{ub}| = (3.65 \pm 0.18 \pm 0.40) \times 10^{-3}$$

Experimental

Form factor ratio = 1.8 ± 0.2

It can be improved by LQCD, providing values for this ratio with better accuracy and for several values of q^2.

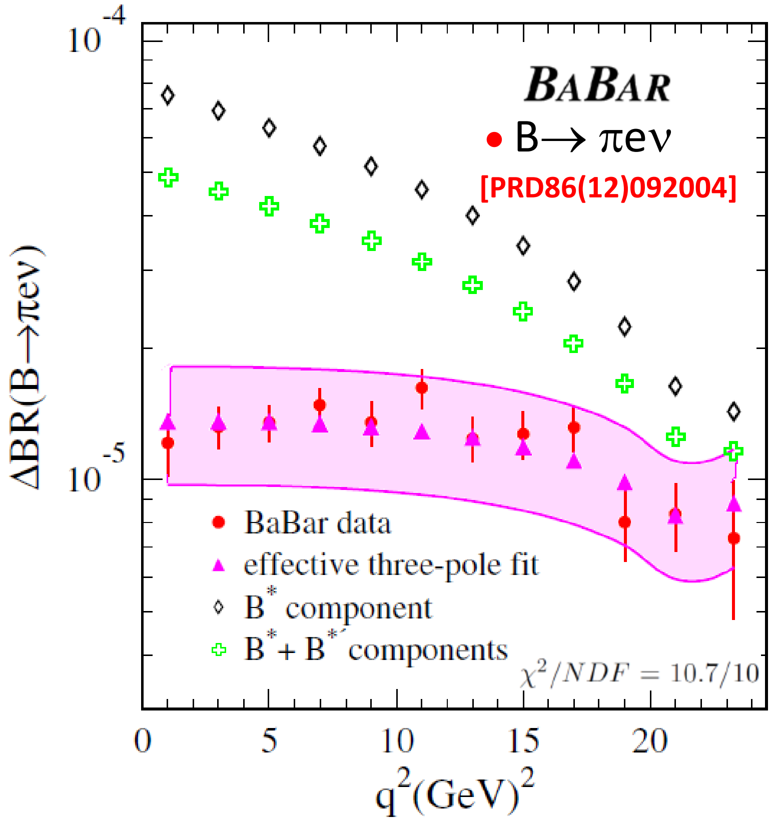
Application: V_{ub} extraction

- 2) **V_{ub} extraction** (**from the "three" poles model**): *[Becirevic et al , arXiv:1407.1019]*

→ Having tested the "three" poles model in $D^0 \to \pi^- e^+ \nu$

→ We can use it for fitting only **$B^0 \to \pi^- e^+ \nu$** data

→ Constraints from the residues of the first two poles (B*, B*') and fitting the **third pole with an effective mass**



$$f^{\pi}_{+,B}(q^2) \simeq \sum_i \frac{Res(f^{\pi}_{+,B})_{B^*_i}}{m^2_{B^*_i} - q^2}$$

Result on the third pole (effective):

$$m_{B^{*\prime\prime}} = (7.4 \pm 0.4)\, GeV/c^2$$

$$|V_{ub}| = (2.6 \pm 0.2 \pm 0.4) \times 10^{-3}$$

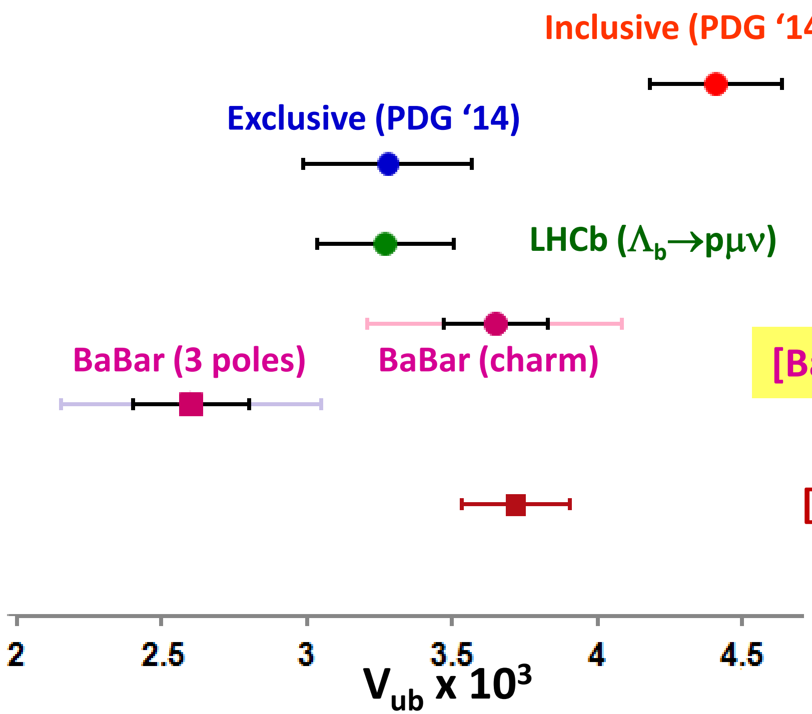
Experimental

$g_{H^*H\pi}$ couplings entering in the residues

It can can be improved by Lattice QCD

Application: V_{ub} extraction

- Comparison with other V_{ub} determinations:



[LHCb; arXiv:1504.01568]

[BaBar; PRD 91, 052022 (2015)]

[Lattice (FNAL, MILC) + BaBar,Belle; arXiv:1503.07839]

- BaBar systematics of different origin, expected to be reduced by Lattice calculations:

→ ● $f_B(q^2)/f_D(q^2)$ form factor ratio as function of E_π (or w)

→ ■ $g_{H^*H\pi}$ couplings

Conclusions

- **Measurement of the $D^0 \to \pi^- e^+ \nu$ form factor and branching fraction at BaBar, in agreement with CLEO-c, BELLE, and preliminary results from BES III.**

  [Phys. Rev. D 91, 052022 (2015)]

$$|V_{cd}| f^{\pi}_{+,D}(0) = 0.1374 \pm 0.0038_{\rm stat.} \pm 0.0022_{\rm syst.} \pm 0.0009_{\rm ext.}$$

$$\mathcal{B}(D^0 \to \pi^- e^+ \nu_e) = (2.770 \pm 0.068 \pm 0.092 \pm 0.037) \times 10^{-3}$$

  → Experimental results more accurate than Lattice calculations

- **Physics interpretation of the form factor:** **[Becirevic *et al*, arXiv:1407.1019 [hep-ph]]**
  - The form factor cannot be explained by the D* and D*' contributions alone.
  - The description in terms of an effective third-pole ansatz agrees well with data.

- **V_{ub} can be extracted using charm semileptonic data, using alternative approaches:**

  → Using the constant form factor ratio from Lattice (assumed to be constant at present).
  → Using the "three" poles model

  competitive when new lattice QCD calculations become available

Thank you!

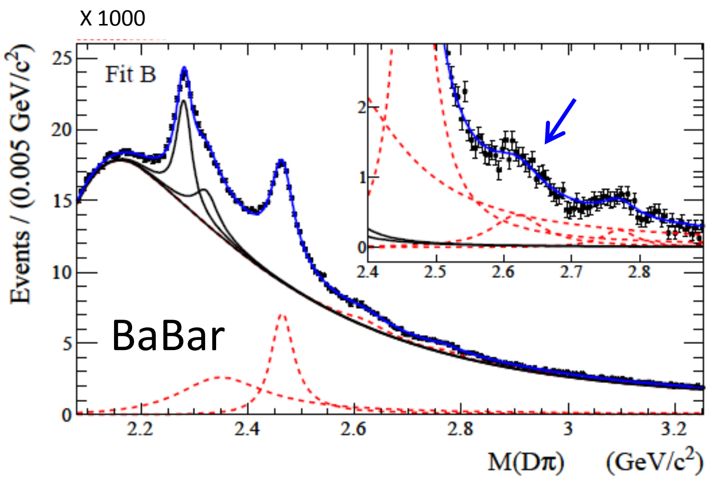
B and D spectroscopy

- From Godfrey and Isgur [PRD32 (85)189]

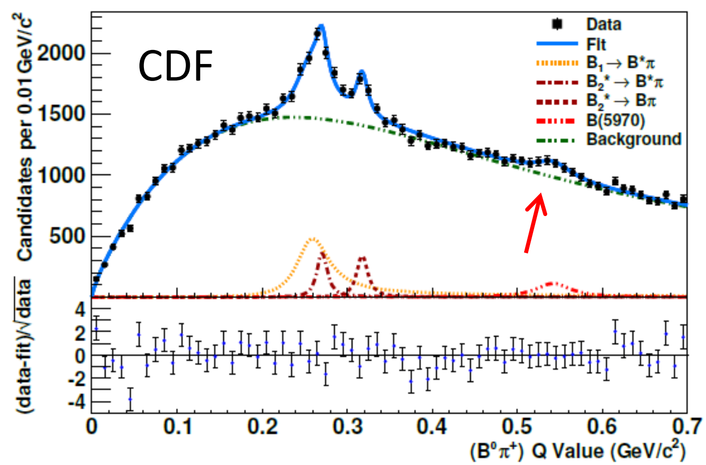
Measurement (GeV)		$J^P = 1^-$ states — Prediction: D mesons	$J^P = 1^-$ states — Prediction: B mesons		Measurement (GeV)
(PDG)	**2.0103(1)** →	$m_0 = 2.037$ GeV (L=0)	$m_0 = 5.37$ GeV (L=0)	←	**5.325(1)** (PDG)
(BaBar)	**2.609(4)** ? →	$m_1 = 2.645$ GeV (L=0)	$m_1 = 5.93$ GeV (L=0)	←	**5.970(13)** (CDF)
(LHCb)	**2.649(5)**	$m_2 = 2.816$ GeV (L=2)	$m_2 = 6.11$ GeV (L=2)		
		$m_3 = 3.11$ GeV (L=0)	$m_3 = 6.355$ GeV (L=0)		(A. Le Yaouanc)

$\rightarrow$ Lowing lying state: D*, B*

$\rightarrow$ Radially excited states: observed by BaBar and LHCb (D*'), and CDF (B*')



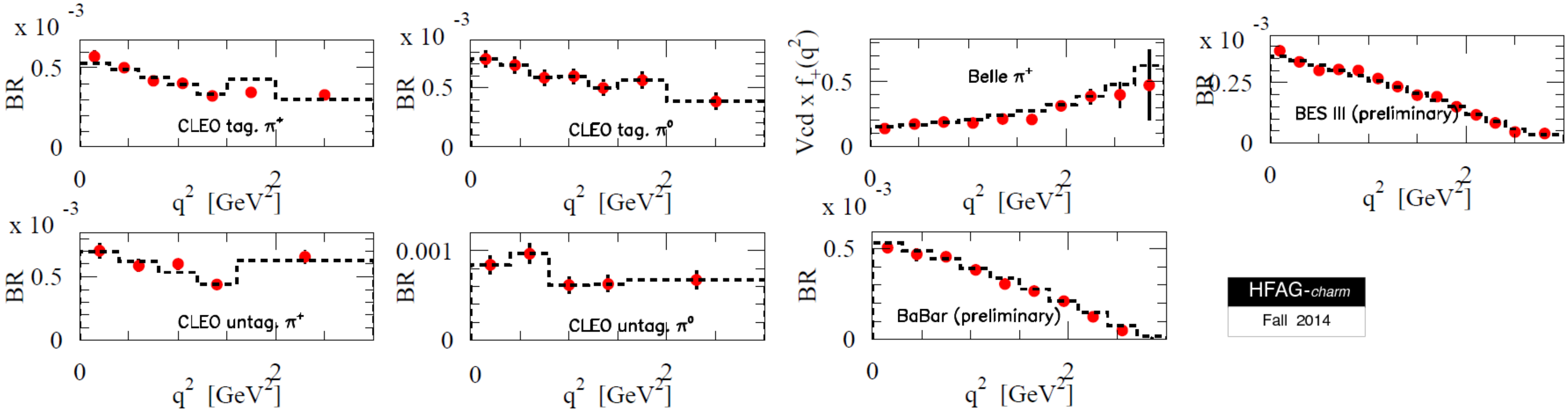
[PRD82(10)111101]



[arXiv:1309.5961 [hep-ex]]

Form factor interpretation

"Three" poles ansatz (multipole) *Becirevic et al (arXiv:1407.1019 [hep-ph])*



It works well for all experimental data.