Academic genealogy and direct probes of flavor-changing neutral currents in e^+e^- collisions

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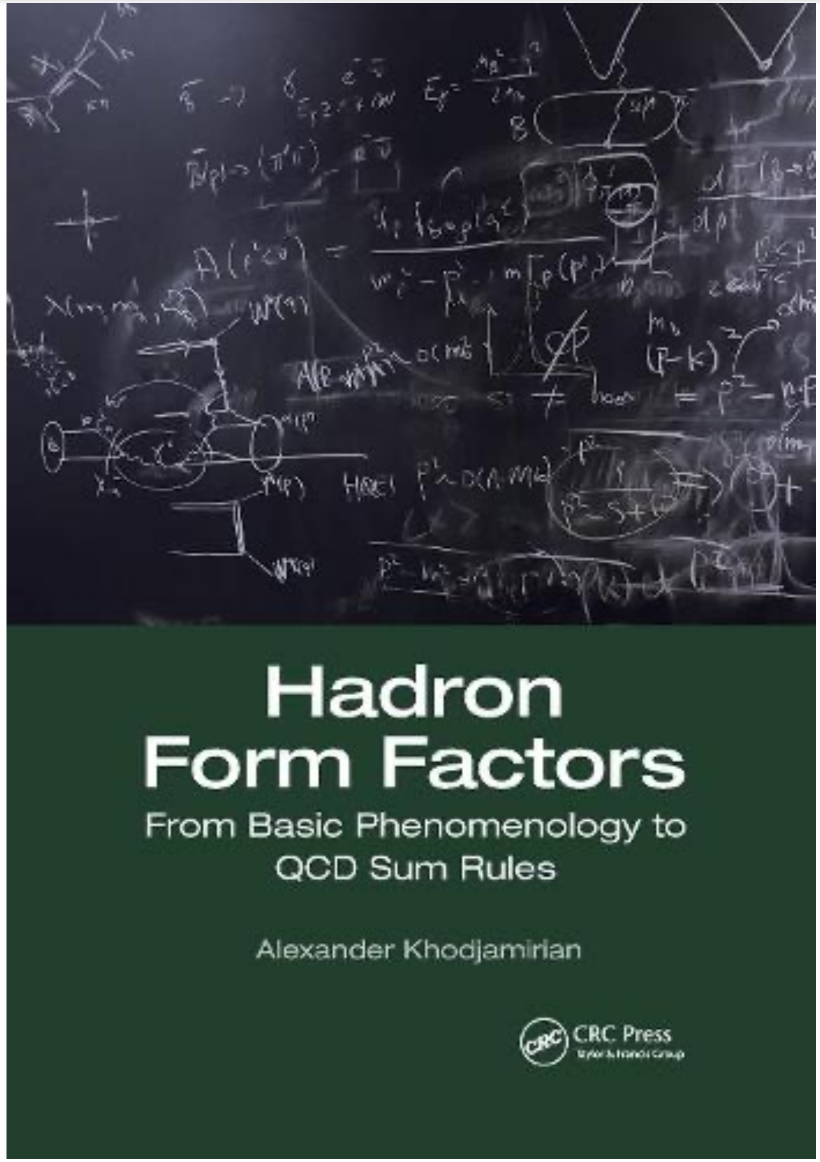
Wayne State University
Leinweber Center for Theoretical Physics

Table of Contents:

Happy Birthday, Alex!!!

Instead of introduction…



AK Academic Genealogy

★ Data up to 1500's

Sources: SPIRES, Wiki, MathGenealogy Project

★ Mostly German scientists

but clear tendency towards Italy is noted

★ Assumptions and cutoffs

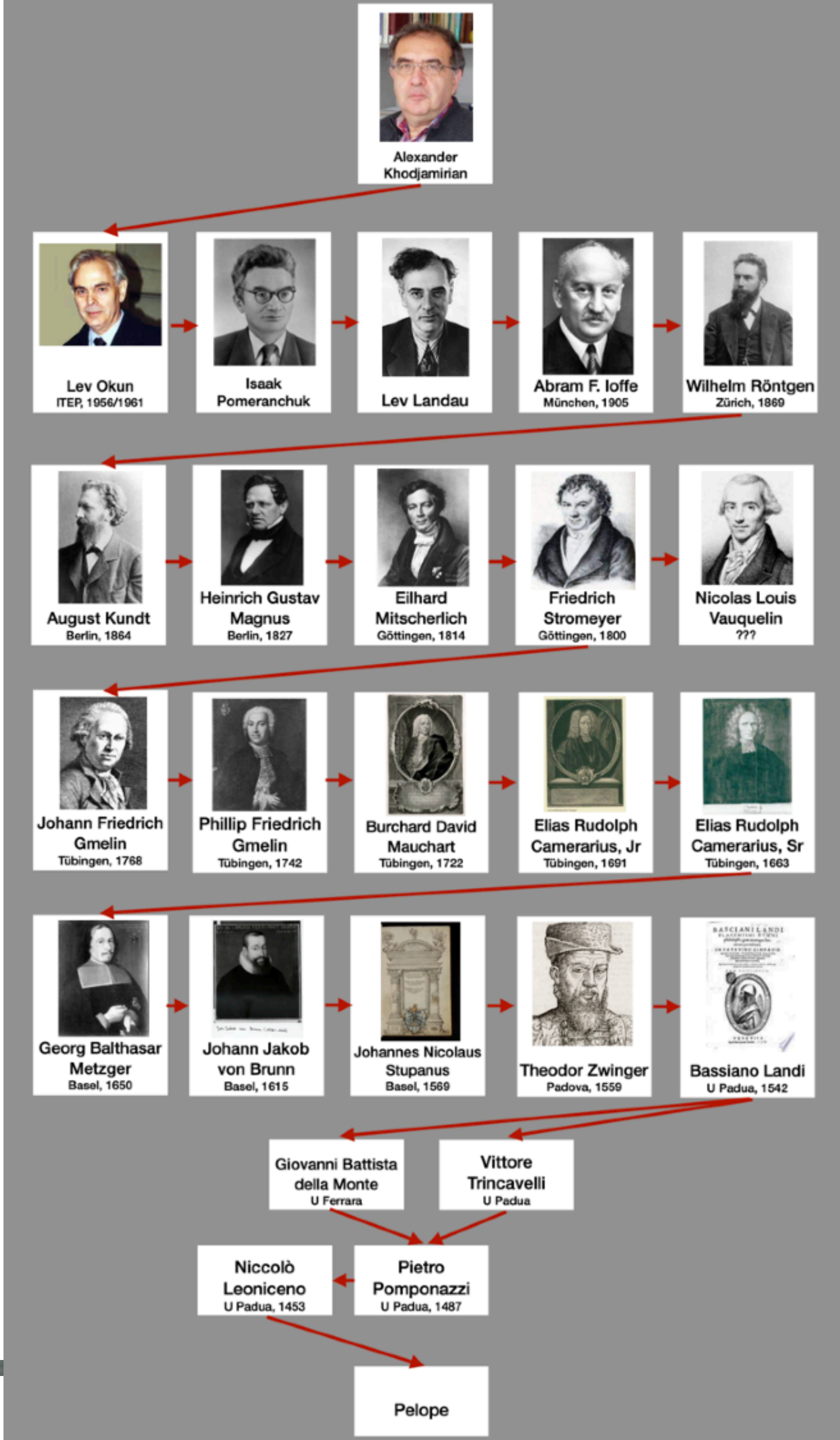
A: L. Landau's advisor

C: anything older than 1400

★ Non-linear: tendency to QCD and flavor physics encoded

nonlinearity and loops included

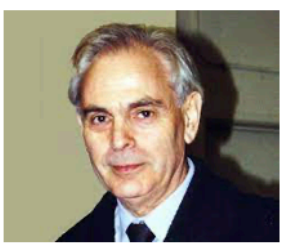
Note: AK and TM have the same "ancestors"!



AK's Academic Genealogy

Alexander Khodjamirian

Place: YerPhI/ITEP
Time: 1980
Advisor: Lev Okun
Opponent: Arkady Vainshein
External: Yakov Azimov



Lev Okun
ITEP, 1956/1961

→

Isaak Pomeranchuk

→

Lev Landau

?

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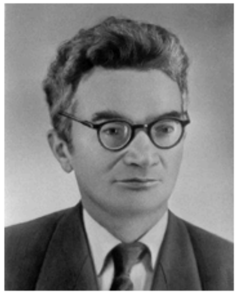
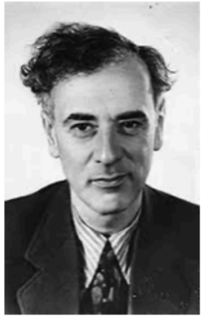
Lev Okun
ITEP, 1956/1961

→



Isaak Pomeranchuk

→



Lev Landau

→

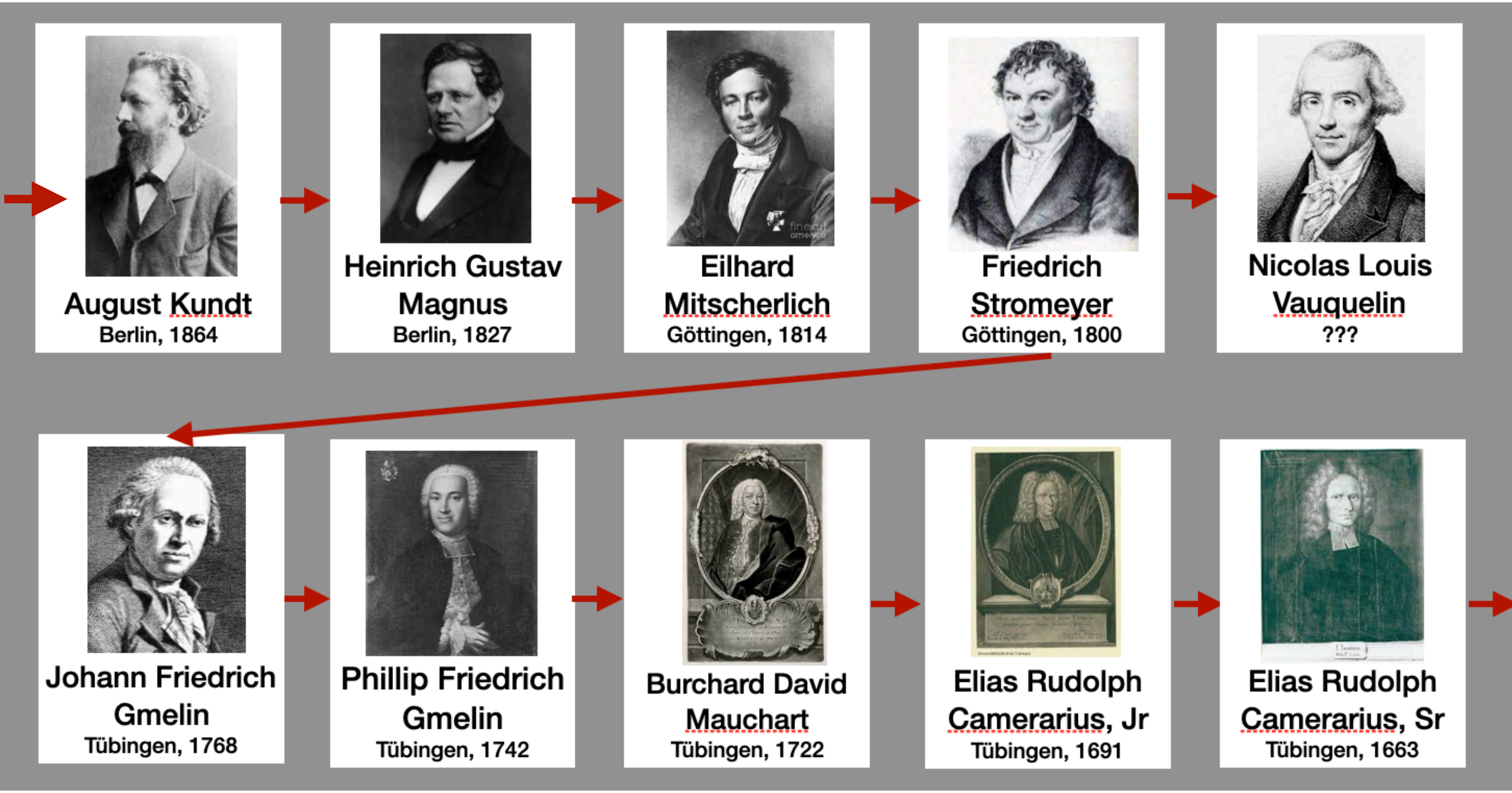
Abram F. Ioffe
München, 1905

→

Wilhelm Röntgen
Zürich, 1869

→

AK's Academic Genealogy



AK's Academic Genealogy

Georg Balthasar Metzger
Basel, 1650

Johann Jakob von Brunn
Basel, 1615

Johannes Nicolaus Stupanus
Basel, 1569

Theodor Zwinger
Padova, 1559

Bassiano Landi
U Padua, 1542

Giovanni Battista della Monte
U Ferrara

Vittore Trincavelli
U Padua

Pietro Pomponazzi
U Padua, 1487

Niccolò Leoniceno
U Padua, 1453

Pelope

... at which point AK's and TM's academic ancestors coincide!

I started collaborating with Alex when I came to Siegen as a Comenius Professor for my sabbatical leave in 2015-17

Comenius bringt Gastdozenten nach Siegen

Neues Programm trägt zur internationalen Vernetzung und Profilierung der Universität Siegen bei. Zwei Comenius-Gastprofessuren sind bereits vergeben.

Die Universität Siegen baut ihre internationale Vernetzung und Profilierung in den Bereichen Forschung und Lehre aus. Seit Oktober 2014 hat die Universität deshalb ein Comenius-Gastprofessuren-Programm etabliert, um den intensiven Austausch mit international profilierten Wissenschaftlerinnen und Wissenschaftlern zu stärken. Im Rahmen des Comenius-Programms werden Aufenthalte von einer Dauer von zwei bis zwölf Monaten gefördert. Stipendien können vergeben, Sachkostenzuschüsse gewährt oder zusätzliche Leistungen erbracht werden, beispielsweise für die An- und Abreise oder einen Familienzuschlag. Benannt ist das Gastprofessuren-Programm nach dem Philosophen, Theologen und Pädagogen Johann Amos Comenius (1592 – 1670), der 1611 an der Hohen Schule in Herborn Theologie studierte. „Die Gäste leisten mit ihrer Persönlichkeit und ihrer Forschung enorme Beiträge zur Stärkung der Forschung und Lehre an der Uni Siegen. Das Comenius-Gastprofessuren-Programm ist deshalb ein wichtiger Baustein für die internationale Ausrichtung unserer Universität", sagt Prof. Dr. Peter Haring Bolívar, Prorektor für Forschung und wissenschaftlichen Nachwuchs.

2. Flavor violation in quarks: rare decays

★ Studies of the beauty FCNC transitions did not reveal large NP effects
- analyses now must rely on theoretical calculations to “sort out” NP
- flavor anomalies?

★ Can New Physics be “hiding” in the up-type quark transitions
- explicit models can be constructed where it can be done
- long-distance effects complicate interpretation
- must use exp and theo tricks to sort out

$$\mathcal{H}_{eff}^{SM} = -\frac{G_F}{\sqrt{2}} V_{cb}^* V_{ub} \sum_{i=7,9,10} \left(C_i \mathcal{O}_i + C_i' \mathcal{O}'_i \right)$$

$$\begin{aligned}
\mathcal{O}_7 &= \frac{e}{8\pi^2} m_c F_{\mu\nu} \bar{u} \sigma^{\mu\nu} (1+\gamma_5) c, \\
\mathcal{O}_9 &= \frac{e^2}{16\pi^2} \bar{u}_L \gamma_\mu c_L \bar{\ell} \gamma^\mu \ell, \\
\mathcal{O}_{10} &= \frac{e^2}{16\pi^2} \bar{u}_L \gamma_\mu c_L \bar{\ell} \gamma^\mu \gamma_5 \ell, \\
\mathcal{O}_7' &= \frac{e}{8\pi^2} m_c F_{\mu\nu} \bar{u} \sigma^{\mu\nu} (1-\gamma_5) c, \\
\mathcal{O}_9' &= \frac{e^2}{16\pi^2} \bar{u}_R \gamma_\mu c_R \bar{\ell} \gamma^\mu \ell, \\
\mathcal{O}_{10}' &= \frac{e^2}{16\pi^2} \bar{u}_R \gamma_\mu c_R \bar{\ell} \gamma^\mu \gamma_5 \ell,
\end{aligned}$$

Maybe correlations between different measurements can help sorting out NP in charm?

Any new ideas?

★ Two-body decays of D or B [a.k.a. B(D) → l^+l^-]

$$B^{(\mathrm{s.d.})}_{D^0\ell^+\ell^-} \simeq \frac{G_F^2 M_W^2 f_D m_\ell}{\pi^2} F\,,$$

- only one hadron to deal with: decay constant?
- but: probes limited number of operators, helicity suppression
    - e.g. not sensitive to vector-like New Physics (such as vector Z')
- soft photon effects preclude studies of electron decay modes:

$$\frac{\mathcal{B}(B_s \to \gamma \ell^+\ell^-)}{\mathcal{B}(B_s \to \ell^+\ell^-)} \propto \alpha \frac{m_B^2}{m_\ell^2}$$

★ Three-body decays of D or B [a.k.a. B(D) → M l^+l^-]
- probes several operators, many different observables
- but: two hadrons: four form-factors, hard to calculate non-perturbatively
- recent "issues" with lepton universality in B-decays ("flavor anomalies" $R_{K(*)}$)

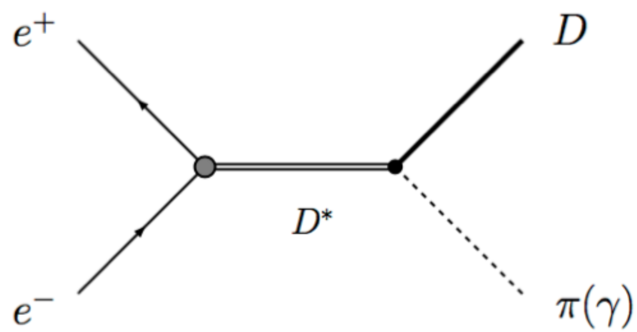
Can one remove helicity suppression AND enlarge the set of probed operators by studying electroweak decays of excited states of D or B (like D* or B*)?

Studies of D*(B*) → e^+e^- in resonance production

★ Instead of searching for a decay of D*/B*, let's produce it!

- resonant enhancement possible if e+e- energy is tuned to m_{D^*}(m_{B^*})
- single heavy flavor + photon in the final state is a nice tag

Khodjamirian, Mannel, AAP
JHEP 11 (2015) 142



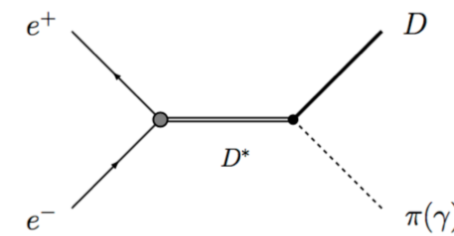
- contrary to a usual way of studying FCNC, production cross section is small

★ This way, the FCNC branching ratio for D*(2007) → e+e- is probed

$$\sigma(e^+e^- \to D\pi)_{\sqrt{s}\simeq m_{D^*}} \equiv \sigma_{D^*}(s) = \frac{12\pi}{m_{D^*}^2} \mathcal{B}_{D^*\to e^+e^-} \mathcal{B}_{D^*\to D\pi} \frac{m_{D^*}^2 \Gamma_0^2}{(s-m_{D^*}^2)^2 + m_{D^*}^2\Gamma_0^2},$$

Studies of D*(B*) → e⁺e⁻ in resonance production

- Is it at all possible and feasible experimentally???



★ D* has a small width defined by strong and radiative decays

$$\Gamma_0 = \Gamma(D^{*0} \to D^0\pi^0) + \Gamma(D^{*0} \to D^0\gamma)$$
$$\simeq \frac{\Gamma_+ \mathcal{B}_{D^{*+}\to D^0\pi^+}}{2} \left(\frac{\lambda(m^2_{D^{*0}}, m^2_{D^0}, m^2_{\pi^0})}{\lambda(m^2_{D^{*+}}, m^2_{D^0}, m^2_{\pi^+})} \right)^{3/2} \left(1 + \frac{\mathcal{B}_{D^{*0}\to D^0\gamma}}{\mathcal{B}_{D^{*0}\to D^0\pi^0}}\right) \simeq 60 \text{ keV}$$

★ … with contributions from higher excitations being highly suppressed

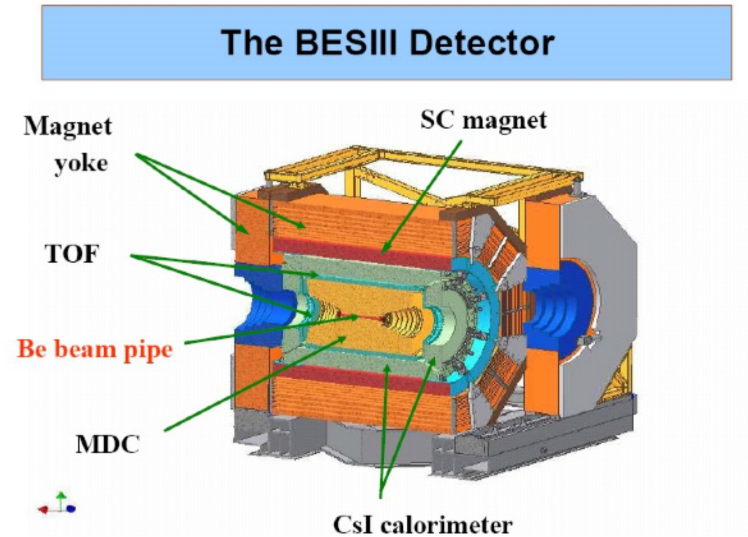
$$\left| \frac{f_{D^{0*\prime}}\, g_{D^{*\prime 0} D^0 \pi^0}\, m_{D^{*0\prime}}}{f_{D^{0*}}\, g_{D^{*0} D^0 \pi^0}\, m_{D^{*0}}} \right| \times \left| \frac{i\Gamma_0}{2\Delta - i\Gamma_{D^{*\prime}}} \right| \sim 5.0 \cdot 10^{-5}$$

★ … thus running for a "Snowmass year" (~10^7 s) with $L \approx 1.0 \times 10^{32}\ cm^{-2} s^{-1}$

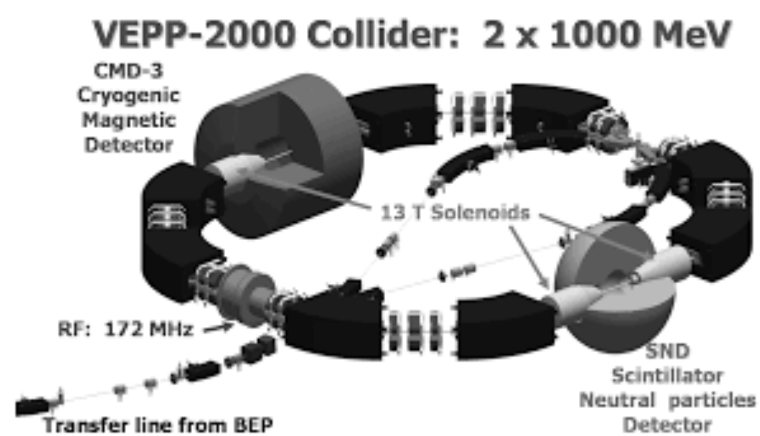
$$\mathcal{B}_{D^*\to e^+e^-} \geq \left(\frac{1}{\epsilon \int L dt}\right) \times \frac{m^2_{D^*}}{12\pi\ \mathcal{B}_{D^*\to D\pi}}. \quad \text{probes} \quad \mathcal{B}_{D^*\to e^+e^-} > 4 \times 10^{-13}$$

Studies of $D^*(B^*) \to e^+e^-$ in resonance production

★ BEPCII machine with BESIII detector (China)
- optimized for Psi(3770)
- already made scans $\sqrt{s} = 2.0 - 4.2$ GeV.
- luminosity is about 5×10^{31} $cm^{-2}s^{-1}$



★ VEPP-2000 machine (Novosibirsk, Russia)
- optimized for $E_{CM} < 2000$ MeV
- possible upgrade to $E_{CM} > 2000$ MeV
- luminosity is about 1×10^{32} $cm^{-2}s^{-1}$



★ HIEPA: new tau-charm factory in Hefei (if approved)
- luminosity is about 5×10^{34} $cm^{-2}s^{-1}$

Calculation of D*(B*) → e⁺e⁻ in EFT

★ Most general effective Hamiltonian: $\langle e^+e^-|\mathcal{H}_{\rm eff}|D^*\rangle = G\sum_i c_i(\mu)\langle e^+e^-|\widetilde{Q}_i|D^*\rangle|_\mu$

$$\begin{aligned}
\widetilde{Q}_1 &= (\overline{\ell}_L\gamma_\mu\ell_L)\ (\overline{u}_L\gamma^\mu c_L), \quad \widetilde{Q}_4 = (\overline{\ell}_R\ell_L)\ (\overline{u}_R c_L),\\
\widetilde{Q}_2 &= (\overline{\ell}_L\gamma_\mu\ell_L)\ (\overline{u}_R\gamma^\mu c_R), \quad \widetilde{Q}_5 = (\overline{\ell}_R\sigma_{\mu\nu}\ell_L)\ (\overline{u}_R\sigma^{\mu\nu} c_L),\\
\widetilde{Q}_3 &= (\overline{\ell}_L\ell_R)\ (\overline{u}_R c_L), \qquad \text{plus } L \leftrightarrow R
\end{aligned}$$

★ ... thus, the amplitude for $D^* \to e^+e^-/\mu^+\mu^-$ decay is

$$\begin{aligned}
A(D^*\to e^+e^-) = \overline{u}(p_-,s_-)\Big[&A\gamma_\mu + B\gamma_\mu\gamma_5 + \frac{C}{m_{D^*}}(p_+-p_-)_\mu\\
&+\frac{D}{m_{D^*}}(p_+-p_-)_\mu i\gamma_5\Big]\, v(p_+,s_+)\ \epsilon^\mu(p),
\end{aligned}$$

$$\mathcal{B}_{D^*\to e^+e^-} = \frac{m_{D^*}}{12\pi\Gamma_0}\left[\left(|A|^2+|B|^2\right)+\frac{1}{2}\left(|C|^2+|D|^2\right)\right]$$

$$\begin{aligned}
A &= \frac{G}{4}f_{D^*}m_{D^*}\left(c_1+c_2+c_6+c_7\right),\\
B &= -\frac{G}{4}f_{D^*}m_{D^*}\left(c_1+c_2-c_6-c_7\right)
\end{aligned}$$

Studies of D*(B*) → e+e- in the Standard Model

★ Standard Model, short distance:

- local O_9 and O_{10} operators

$$O_9 = \frac{e^2}{16\pi^2}\left(\widetilde{Q}_1 + \widetilde{Q}_7\right), \quad O_{10} = \frac{e^2}{16\pi^2}\left(\widetilde{Q}_7 - \widetilde{Q}_1\right)$$

- additional dipole contribution

$$H_{\rm eff}^{(7\gamma)} = \frac{4G_F}{\sqrt{2}} C_7^{\rm c,eff}\left(\frac{e}{16\pi^2} m_c\, \overline{u}_L \sigma^{\mu\nu} c_R F_{\mu\nu}\right)$$

★ Decay amplitude depends on additional non-perturbative parameter

$$\langle 0|\overline{u}\sigma^{\mu\nu}c|D^*(p)\rangle = i f_{D^*}^T \left(\epsilon^\mu p^\nu - p^\mu \epsilon^\nu\right)$$

★ Short-distance result is well-defined

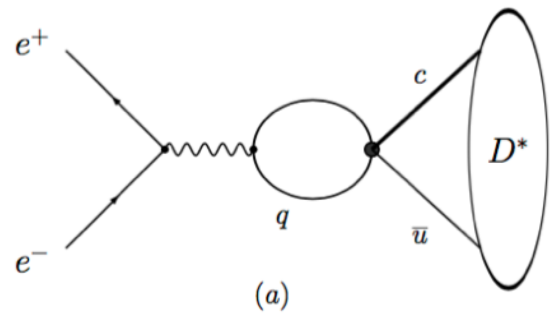
$$\mathcal{B}_{D^*\to e^+e^-} = \frac{\alpha^2 G_F^2}{96\pi^3 \Gamma_0} m_{D^*}^3 f_{D^*}^2 \left(\left|C_9^{\rm c,eff} + 2\frac{m_c}{m_{D^*}}\frac{f_{D^*}^T}{f_{D^*}} C_7^{\rm c,eff}\right|^2 + |C_{10}^{\rm c}|^2\right)$$

★ … but the Br is small (the width is not though): $\mathcal{B}_{D^*\to e^+e^-}^{SD} = \dfrac{\Gamma(D^* \to e^+e^-)}{\Gamma_0} \approx 2.0 \times 10^{-19}$

No helicity suppression: no issues with testing lepton universality!

Studies of D*(B*) → e⁺e⁻ in the Standard Model

★ Standard Model, long distance:
- local O_1 and O_2 operators
- additional penguin-like contribution



★ Decay amplitude:

$$\langle e^+e^-|\mathcal{H}_w|D^*(p)\rangle = -e^2\bar{u}(p_-,s_-)\gamma^\mu v(p_+,s_+)\left(\frac{\Sigma_\mu(p^2)}{p^2}\right)\Bigg|_{p^2=m_{D^*}^2}$$

with $\Sigma_\mu(p^2) = i\int d^4x e^{ip\cdot x}\langle 0|T\left\{j_\mu^{em}(x)\mathcal{H}_w(0)\right\}|D^*(p)\rangle$

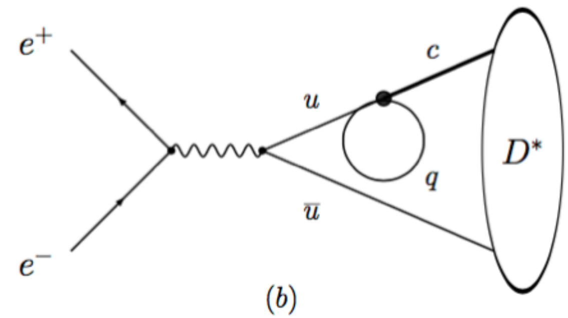
$$\Sigma_\mu^{(a)}(p^2) = \frac{G_F}{\sqrt{2}}\sum_{q=d,s} Q_q\left(C_1^{c(q)} + \frac{C_2^{c(q)}}{N_c}\right)\left\{i\int d^4x e^{ip\cdot x}\langle 0|T\left\{\bar{q}\gamma_\mu q(x)\ \bar{q}\gamma_\nu q(0)\right\}|0\rangle\right\} \times \langle 0|\bar{u}\gamma^\nu c|D^*(p)\rangle\,,$$

$$\Pi_{\mu\nu}^{(q)}(p) = \left(-g_{\mu\nu}p^2 + p_\mu p_\nu\right)\Pi^{(q)}(p^2)$$

$$\Pi^{(q)}(p^2) = \frac{p^2}{12\pi^2 Q_q^2}\int_0^\infty ds\frac{R^{(q)}(s)}{s(s-p^2-i\epsilon)}$$ with $$R(s) \equiv \frac{\sigma(e^+e^-\to hadrons)}{\sigma(e^+e^-\to\mu^+\mu^-)} = \sum_{q=u,d,s} R^{(q)}(s)$$

Studies of D*(B*) → e^+e^- in the Standard Model

★ Standard Model, long distance:
- local O_1 and O_2 operators
- additional penguin-like contribution



★ As a result:

$$\mathcal{B}^{LD,A}_{D^*\to e^+e^-} \simeq \begin{cases} 4.7\times 10^{-20} & \text{(NLO)} \\ 5.7\times 10^{-18} & \text{(LO)} \end{cases}$$

$$\mathcal{B}^{(LD,b)}_{D^*\to e^+e^-} \geq (0.1-5.0)\times 10^{-19}$$

… and recall that the short distance $\mathcal{B}^{SD}_{D^*\to e^+e^-} \approx 2.0\times 10^{-19}$

★ Overall, the Standard Model contribution to D* → e+e- is rather small, but
- -its smallness is NOT due to helicity suppression
- -it is four orders of magnitude higher than the Br(D → e+e-)!
- the long-distance contribution is moderate
- there is a large window to probe New Physics, as e.g. with BES-III

$$\mathcal{B}_{D^*\to e^+e^-} > 4\times 10^{-13}$$

Khodjamirian, Mannel, AAP (2015)

Any interesting New Physics scenarios?

D*(B*) → e⁺e⁻: example of NP contribution

★ A plethora of NP models that realize charm (beauty) FCNC interactions can be probed
- consider a model with a Z' coupling to a left-handed FCNC quark currents

$$\mathcal{L}_{Z'} = -g'_{Z'1}\bar{\ell}_L\gamma_\mu\ell_L Z'^\mu - g'_{Z'2}\bar{\ell}_R\gamma_\mu\ell_R Z'^\mu$$
$$- g^{cu}_{Z'1}\bar{u}_L\gamma_\mu c_L Z'^\mu - g^{cu}_{Z'2}\bar{u}_R\gamma_\mu c_R Z'^\mu.$$

★ At low energies integrate out Z':

$$\mathcal{L}^{Z'}_{\text{eff}} = -\frac{1}{M^2_{Z'}}\left[g'_{Z'1}g^{cu}_{Z'1}\widetilde{Q}_1 + g'_{Z'1}g^{cu}_{Z'2}\widetilde{Q}_2 + g'_{Z'2}g^{cu}_{Z'2}\widetilde{Q}_6 + g'_{Z'2}g^{cu}_{Z'1}\widetilde{Q}_7\right]$$

★ ...which leads to a branching ratio (for $g'_{Z'1} = \frac{g}{\cos\theta_W}\left(-\frac{1}{2}+\sin^2\theta_W\right), \quad g'_{Z'2} = \frac{g\sin^2\theta_W}{\cos\theta_W}$,)

$$\mathcal{B}^{Z'}_{D^*\to e^+e^-} = \frac{\sqrt{2}G_F}{3\pi\Gamma_0}m^3_{D^*}f^2_{D^*}\frac{|g^{cu}_{Z'1}|^2}{M^2_{Z'}}\frac{M^2_Z}{M^2_{Z'}}\left(\frac{1}{4}-\sin^2\theta_W+2\sin^4\theta_W\right)$$

★ ... and current constraint of $\mathcal{B}^{Z'}_{D^*\to e^+e^-} < 2.5\times 10^{-11}$

Plenty of room in the parameter space to constrain

Experimental studies of $D^* \to e^+e^-$

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ELEMENTARY PARTICLES AND FIELDS
Experiment

Search for the Process $e^+e^- \to D^*(2007)^0$ with the CMD-3 Detector

D. N. Shemyakin[1,2*]
(on behalf of the CMD-3 Collaboration)

Received May 13, 2020; revised May 13, 2020; accepted May 13, 2020

Abstract—Searches for the process of electron–positron (e^+e^-) annihilation to the $D^*(2007)^0$ meson were performed by means of the CMD-3 detector at the VEPP-2000 e^+e^- collider. In the data analysis, use was made of two dominant modes of D^{*0}-meson decay to $D^0\pi^0$ and $D^0\gamma$, where D^0 was reconstructed in the $K^\pm\pi^\mp\pi^+\pi^-$ channel. By employing a 3.7 pb^{-1} data sample accumulated at the c.m. energy of $E_{\text{c.m.}} = 2006.62$ MeV, an upper bound of $\mathcal{B}(D^{*0} \to e^+e^-) < 1.7 \times 10^{-6}$ on the decay branching ratio was obtained at a 90% confidence level.

DOI: 10.1134/S1063778820060277

We selected two events that could be candidates for the $D^0\gamma$ intermediate state, estimating the respective background at 1.2 ± 0.5, and one event for the $D^0\pi^0$ channel, estimating the background at 1.5 ± 0.7. As a result, we measured an upper limit for the first time and, within the Bayesian approach, found that $\mathcal{B}(D^* \to e^+e^-) < 1.7 \times 10^{-6}$ at a confidence level of 90%.

Anything different about $B^*_s \to e^+e^-$?

★ Experimentally:

- m(B^*_s) = 5415.4 MeV, so need Belle II
- no phase space for $B^* \to B\pi$ decay
- considerably smaller total width

$$\Gamma^{tot}_{B_s^*} \simeq \Gamma(B_s^* \to B_s \gamma) = \frac{\alpha}{24} |g_{B_s^* B_s \gamma}|^2 \left(\frac{m^2_{B_s^*} - m^2_{B_s}}{m_{B_s^*}} \right)^3 \simeq 0.07 \text{ keV}$$

★ Standard Model contribution is rather large and unambiguous

- long-distance contribution is small

$$\mathcal{B}(B_s^* \to e^+e^-) = \frac{\alpha^2 G_F^2}{96\pi^3 \Gamma^{tot}_{B_s^*}} m^3_{B_s^*} f^2_{B_s^*} |V_{tb}V^*_{ts}|^2 \left(\left| C_9 + 2\frac{m_b}{m_{B_s^*}} \frac{f^T_{B_s^*}}{f_{B_s^*}} C_7^{\text{eff}} \right|^2 + |C_{10}|^2 \right)$$

$$\mathcal{B}_{B_s^* \to e^+e^-} = 0.98 \times 10^{-11}$$

★ Standard Model-type rate can be probed for similar luminosity 1x10^{32} $cm^{-2}s^{-1}$

$$\mathcal{B}(B_s^* \to e^+e^-) > 2.0 \times 10^{-12}$$

Khodjamirian, Mannel, AAP (2015)
B. Grinstein, J. Martin Calamach (2015)

- Academic genealogy studies are fun!
- … but physics is important!
- Indirect effects of New Physics at flavor factories help to distinguish among models possibly observed at the LHC in the future
  - a combination of bottom/charm sector studies
  - one should not be afraid of looking for NP in the unconventional places
- New reach: $D^*(B^*) \to e^+e^-$ can be studied with resonance production
  - plenty of parameter space for New Physics reach
  - probes New Physics models that $D(B) \to e^+e^-/\mu^+\mu^-$ decays are not sensitive to!
  - reasonably simple hadronic physics: no dominance of LD physics for the D*
  - first experimental bound: Br($D^* \to e^+e^-$)=1.7×10^{-6}

Happy Birthday, Alex!!!