Interactions of light with light mesons

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Light Meson Dynamics, Mainz, Feb. 2014

Collaborators

- Uppsala: Per Engström, Bruno Strandberg (now Glasgow), Hazhar Ghaderi, Carla Terschlüsen
- GSI: Igor Danilkin (now JLAB), Matthias Lutz
- Bonn: Franz Niecknig, Martin Hoferichter (now Bern), Sebastian Schneider, Bastian Kubis

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Challenges of hadron (+nuclear) physics

- structure of matter
  - understand masses of hadrons
    (also, e.g., mass ordering: $m_\sigma < m_\rho$, $1440 < 1520$)
  - life times, branching ratios of hadron resonances
  - form factors and intrinsic structure
  - nature of hadrons
    (how much quark-antiquark? how much hadron-hadron? ...)
  - (nuclei, neutron stars)
- new forms of matter
- high-precision frontier of standard model

Challenges of hadron (+nuclear) physics

- structure of matter
- new forms of matter
  - non-$q\bar{q}$ mesons
    (exotic quantum numbers, exotic decomposition,
    X/Y/Z states, glueballs, meson molecules, ...)
  - non-3q baryons, di-baryons ($\Delta - \Delta$ by WASA?), ...
  - (quark-gluon plasma, color superconductors,
    early universe, core of neutron stars)
- high-precision frontier of standard model

Challenges of hadron (+nuclear) physics

- structure of matter
- new forms of matter
- high-precision frontier of standard model
    - determine parameters of standard model (light quark masses, CKM matrix, ...)
    - traces of physics beyond standard model (rare decays, $g-2$ of muon, ...)

Challenges of hadron (+nuclear) theory

- structure of matter
- new forms of matter
- high-precision frontier of standard model

- from phenomenological models to real quantum field theories
  - physical form factors instead of ad-hoc cutoff form factors
  - do not neglect loops just because they are complicated
  - assign degrees of importance to processes, diagrams (e.g. power counting, separation of relevant from irrelevant degrees of freedom)
- reliable uncertainty estimates
- treat unitarity/rescattering, analyticity serious

We are not there yet!

Reactions of hadrons with (virtual) photons

Why is it interesting?

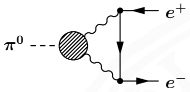
- explore intrinsic structure of hadrons
  - $\rightsquigarrow$ form factors
  - $\rightsquigarrow$ to which extent does vector meson dominance hold?

Reactions of hadrons with (virtual) photons

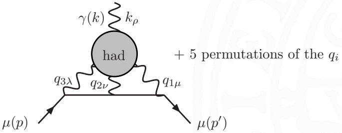
Why is it interesting?

- explore intrinsic structure of hadrons
  - ⇝ form factors
  - ⇝ to which extent does vector meson dominance hold?
- background for physics beyond standard model

⇝ rare pion decay $\pi^0 \to e^+e^-$

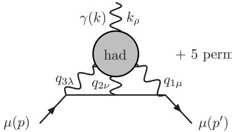


⇝ $g - 2$ of muon



Hadronic contribution to $g - 2$ of the muon

light-by-light scattering



+ 5 permutations of the q_i

- $\gamma^*\gamma^* \leftrightarrow$ hadron(s) is not directly accessible by experiment

$\hookrightarrow$ need good theory with reasonable estimate of uncertainty (ideally an effective field theory)

$\hookrightarrow$ need experiments to constrain such hadronic theories

true for all hadronic contributions:

- the lighter the hadronic system, the more important (though high-energy contributions not unimportant for light-by-light)

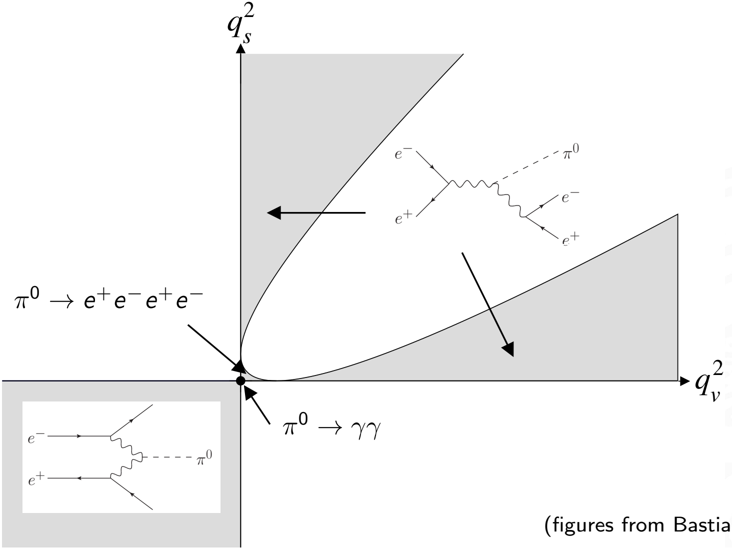
$\hookrightarrow$ $\gamma^{(*)}\gamma^{(*)} \leftrightarrow \pi^0$ (you've seen this before for rare pion decay), $\gamma^{(*)}\gamma^{(*)} \leftrightarrow 2\pi$, ...

Shopping list for hadron theory and experiment

- transition form factors of pseudoscalars $\gamma^{(*)}\gamma^{(*)} \leftrightarrow P$ with $P = \pi^0, \eta, \eta', \ldots$

$\hookrightarrow$ several interesting kinematical regions $\rightsquigarrow$ next slide (for pion)

$\pi^0 \to \gamma^*(q_v^2)\gamma^*(q_s^2)$ transition form factor



(figures from Bastian Kubis)

Shopping list for hadron theory and experiment

- transition form factors of pseudoscalars $\gamma^{(*)}\gamma^{(*)} \leftrightarrow P$ with $P = \pi^0, \eta, \eta', \dots$
- if invariant mass of dilepton around mass of a vector meson:

$\rightsquigarrow$ relation to
transition form factors of vector to pseudoscalar mesons
$V \leftrightarrow P\gamma^{(*)}$ with $V = \rho^0, \omega, \phi, \dots$

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- "two-gamma physics" $\gamma\gamma \to \pi^+\pi^-, \pi^0\pi^0, \pi^0\eta, K\bar{K}, \ldots$
  (cross relation to polarizability of the pion)

$\hookrightarrow$ has triggered a lot of experimental activity,
in particular MesonNet (WASA, KLOE, MAMI, HADES, ...)

Two complementary approaches

- Lagrangian approach
  - use only hadrons which are definitely needed (here: lowest nonets of pseudoscalar and vector mesons)
  - sort interaction terms concerning importance, essentially based on large-N_c
  - include causal rescattering/unitarization for reactions
    (I. Danilkin, L. Gil, M. Lutz, Phys.Lett. B703, 504 (2011))
  - long-term goal: obtain sensible estimates of uncertainties
- dispersive approach
  - include most important hadronic inelasticities
  - use measured (and dispersively improved) phase shifts (2-body)
  - use Breit-Wigner plus background for narrow resonances (n-body, $n > 2$)
  - error estimates from more vs. less subtracted dispersion relations

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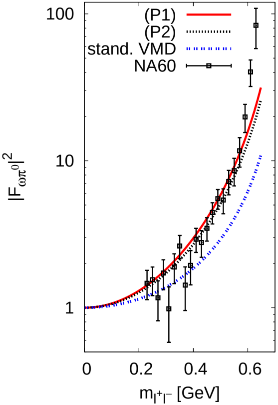
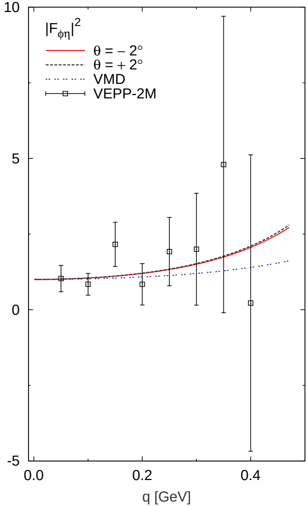
Transition form factor $\omega \to \pi^0 +$ dilepton



- data and our Lagrangian approach show strong deviations from vector-meson dominance (VMD)
- our approach describes data fairly well except for large invariant masses close to phase-space limit (log plot!)
- second experimental confirmation desirable

C. Terschlüsen, S.L., Phys. Lett. B691, 191 (2010)

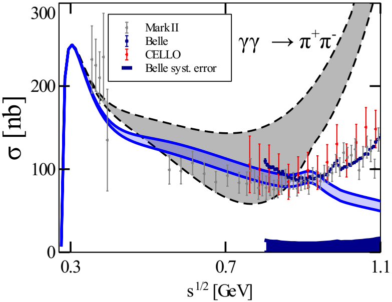
Transition form factor $\phi \to \eta +$ dilepton

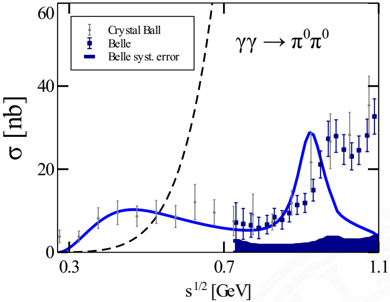


- our Lagrangian approach deviates from VMD
- new data from KLOE will come soon

C. Terschlüsen, S.L., M.F.M. Lutz, Eur.Phys.J. A48, 190 (2012)

$\gamma\gamma \to \pi^+\pi^-, \pi^0\pi^0$





- dashed black lines: tree level,
  blue lines: with coupled-channel rescattering of two pseudoscalar mesons
- overall good description, room for improvement concerning $f_0(980)$
- at high energies spin-2 mesons are missing

I.V. Danilkin, M.F.M. Lutz, S.L., C. Terschlüsen,

Eur.Phys.J. C73, 2358 (2013)

$\gamma\gamma$ to other meson pairs

$\hookrightarrow$ stay tuned for Matthias' talk

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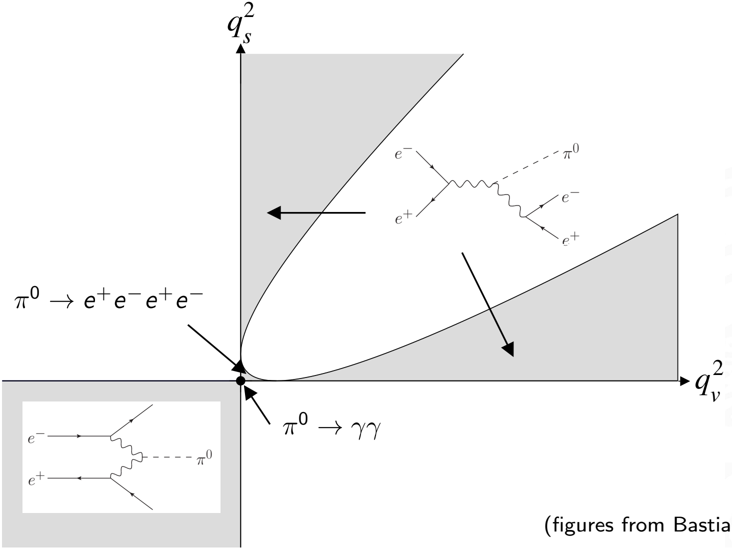
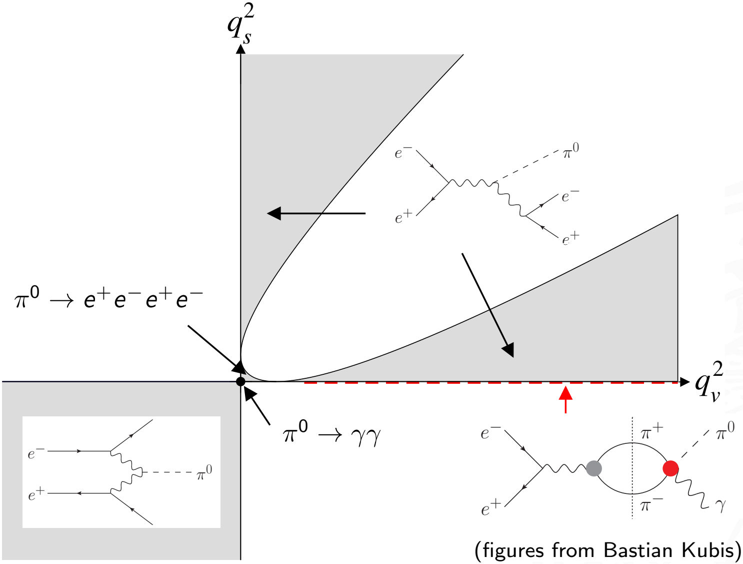
$\pi^0 \to \gamma^*(q_v^2)\gamma^*(q_s^2)$ transition form factor



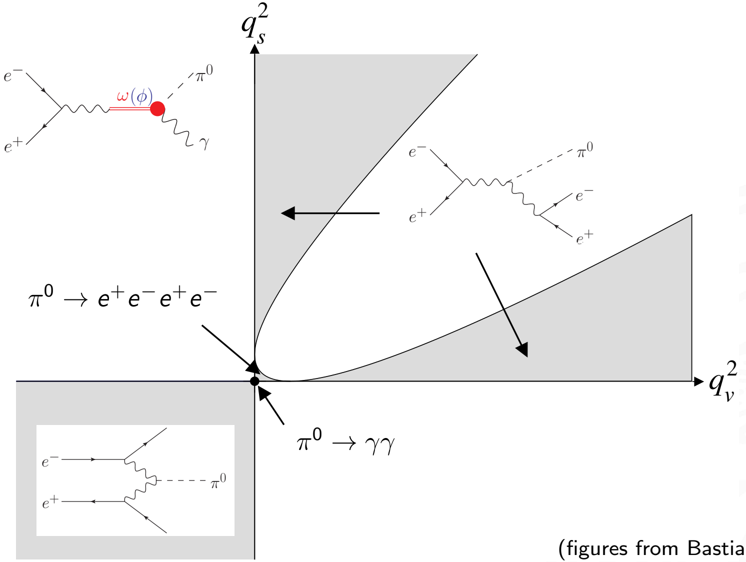
(figures from Bastian Kubis)

$\pi^0 \to \gamma^*(q_v^2)\gamma$ transition form factor



(figures from Bastian Kubis)

$\pi^0 \to \gamma\gamma^*(q_s^2)$ transition form factor



(figures from Bastian Kubis)

Pion transition form factor — dispersive approach

- want prediction for $e^+e^- \to \pi^0\gamma$ (up to $\approx 1\,\text{GeV}$)

$\hookrightarrow$ dominant inelasticities:

  - $I = 1$: $e^+e^- \to \pi^+\pi^- \to \pi^0\gamma$
  - $I = 0$: $e^+e^- \to \pi^0\pi^+\pi^- \to \pi^0\gamma$

- required input for $I = 1$:
  - pion phase shift and pion form factor $\rightsquigarrow$ measured
  - strength of amplitude $\pi^+\pi^- \to \pi^0\gamma \rightsquigarrow$ chiral anomaly

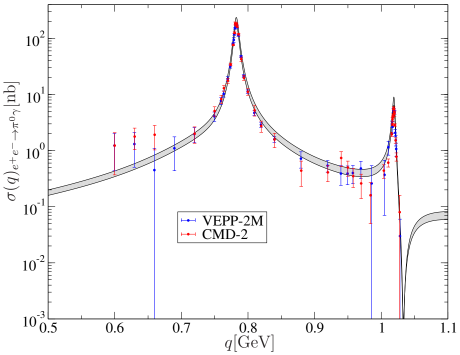
    (M. Hoferichter, B. Kubis, D. Sakkas, Phys.Rev. D86 (2012) 116009)

- input for $I = 0$ (three-body!):
  - dominated by narrow resonances ω, ϕ

  $\hookrightarrow$ use Breit-Wigners plus background for amplitude

  $\hookrightarrow$ fit to $e^+e^- \to \pi^+\pi^-\pi^0$ and decay widths $\omega/\phi \to \pi^0\gamma$

Pion transition form factor ($e^+e^- \to \pi^0\gamma$)



- height between peaks is not a fit!
- can be extended to decay region $\pi^0 \to \gamma\, e^+e^-$ and to spacelike region
- final aim: double virtual transition form factor

$\hookrightarrow$ relevant for $g-2$ and $\pi^0 \to e^+e^-$

M. Hoferichter, B. Kubis, S.L., F. Niecknig and S. P. Schneider, in preparation

Summary

- meson (transition) form factors and two-photon reactions allow access to intrinsic structure of hadrons

↪ quark structure, polarizabilities, ...

- in addition input for standard-model baseline calculations for rare decays (π^0) and high-precision determinations (muon's $g-2$)

↪ we are sharpening our theory tools to improve the accuracy of predictions

Instead of an outlook

From two- to three-gamma physics

- yet another contribution to light-by-light scattering:

$$\gamma^* \to \omega \to 3\gamma^{(*)}$$

$\hookrightarrow$ related to scattering amplitude (dispersion theory)

$$\gamma\,\omega \to \pi\,\pi \to \gamma\,\gamma$$

i.e. to decays

$$\omega \to \gamma\,\pi^+\,\pi^- \,, \qquad \omega \to \gamma\,\pi^0\,\pi^0$$

- more (differential) data needed
- and also ϕ instead of ω (better data situation)

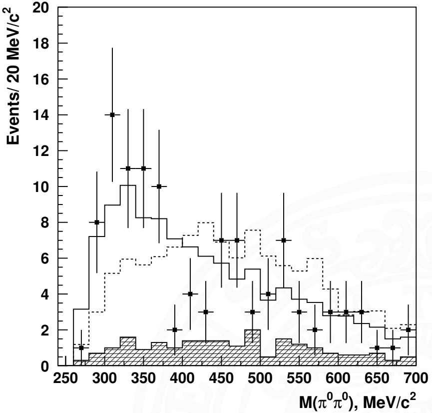
Rare ω decays into $2\pi\,\gamma$

- $\omega \to \pi^+\pi^-\gamma$:
  only upper limit

- $\omega \to \pi^0\pi^0\gamma$:

↪ branching ratio: $6.6 \cdot 10^{-5}$

↪ differential data from CMD2 (Akhmetshin et al., Phys.Lett.B580, 119 (2004))



histograms are simulations with an intermediate rho (full) or sigma meson (dotted)

backup slides

How we sort interactions/diagrams

- without assigning importance to anything:
  - infinitely many interaction terms (with more and more derivatives)
  - infinitely many loop diagrams
- large-N_c framework (N_c = number of colors)
  - ↪ loops are suppressed
  - note: we resum loops from rescattering, s-channel
  - ↪ sorting scheme applies to scattering kernel (potential), not to scattering amplitude
- for interaction terms:
  - ensure appropriate N_c scaling by dimensionful decay constant $f \sim \sqrt{N_c}$
  - to ensure pertinent dimension of interaction term in Lagrangian:
  - ↪ assume large scale $\Lambda_{\rm hard} \gg m_V$ in denominator
  - ↪ expansion in derivatives/momenta over $\Lambda_{\rm hard}$
  - depends on chosen representation

Examples for interaction terms

- relevant, e.g., for $\omega \to 3\pi$ and $\omega \to \pi\gamma^*$
- both can proceed directly or via $\pi\rho^*$
- some unsuppressed interaction terms

$$\varepsilon_{\mu\nu\alpha\beta}\,\mathrm{tr}\left(\{V^{\mu\nu}, \nabla_\lambda V^{\lambda\alpha}\}\, u^\beta\right)\,,$$

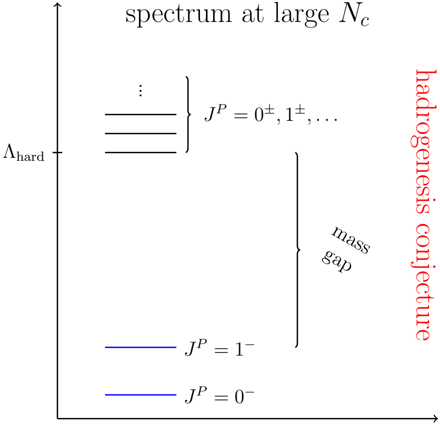
$$i\, f\, \mathrm{tr}(V_{\mu\nu}\,[u^\mu, u^\nu])\,, \qquad f\, \mathrm{tr}\left(V^{\mu\nu}\, f^+_{\mu\nu}\right)$$

- some suppressed interaction terms (the direct ones)

$$\frac{f}{\Lambda^2_{\mathrm{hard}}}\, \varepsilon^{\mu\nu\alpha\beta}\, \mathrm{tr}(\nabla^\lambda V_{\lambda\mu}\, u_\nu\, u_\alpha\, u_\beta)\,,$$
$$\frac{f}{\Lambda^2_{\mathrm{hard}}}\, \varepsilon^{\mu\nu\alpha\beta}\, \mathrm{tr}(\{\nabla^\lambda V_{\lambda\mu}, f^+_{\nu\alpha}\}\, u_\beta)\,.$$

- Λ_{hard}: hadrogenesis gap or (here also O.K.) mass of excited vector mesons

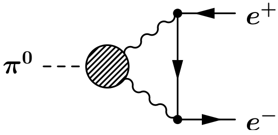
hadrogenesis conjecture



other observed mesons below Λ_{hard} are supposed to be dynamically generated, i.e. meson molecules

C. Terschlüsen, S.L., M.F.M. Lutz, Eur.Phys.J. A48, 190 (2012)

Rare pion decay — status

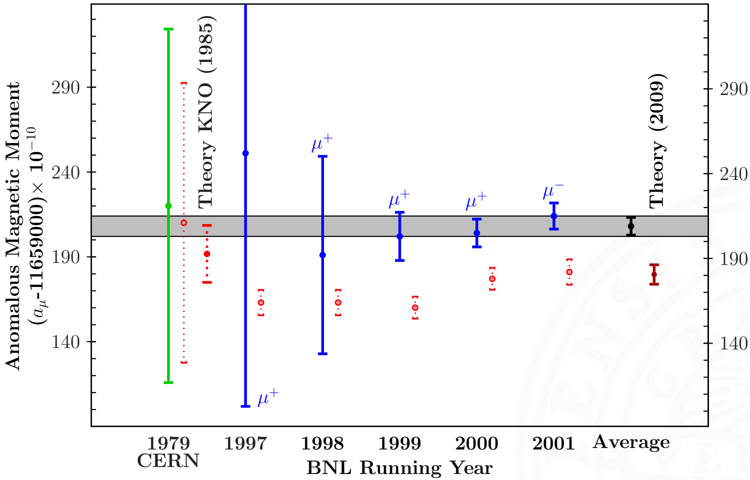


- $B(\pi^0 \to e^+e^-) = (6.46 \pm 0.33) \cdot 10^{-8}$ (KTeV, 2007)
- 3 σ deviation between experiment and standard model
  Dorokhov/Ivanov, Phys. Rev. D75, 114007 (2007)
  (but controversial among theorists!)

- for point-like pion QED loop is divergent

$\hookrightarrow$ process is sensitive to hadronic transition form factor of pion $\pi^0 \leftrightarrow \gamma^{(*)}\gamma^{(*)}$

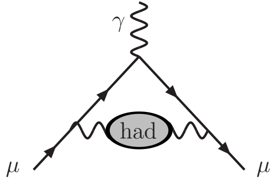
$g-2$ of the muon — status

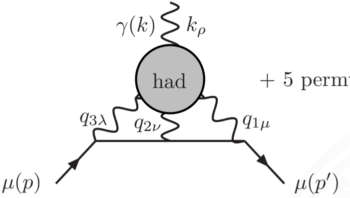


Jegerlehner/Nyffeler, Phys. Rept. 477, 1 (2009)

$g - 2$ of the muon — theory

Largest uncertainty of standard model: hadronic contributions



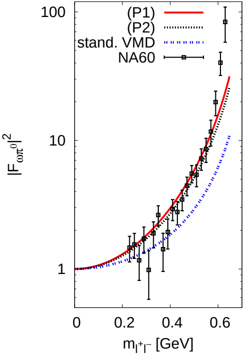


$+ 5$ permutations of the q_i

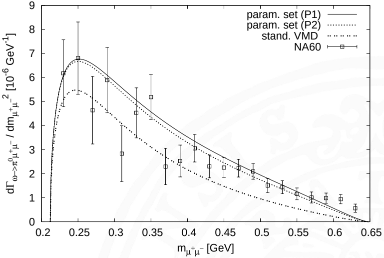
vacuum polarization
$\sim \alpha^2$

light-by-light scattering
$\sim \alpha^3$

Transition form factor $\omega \to \pi^0 + \mu^+\mu^-$



corresponding differential decay rate:



theory: C. Terschlüsen, S.L., Phys. Lett. B691, 191 (2010)

data: NA60, Phys. Lett. B 677, 260 (2009)