Exclusive decays of heavy baryons

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Flavour physics in the LHC era

- *"If it looks like a Higgs, swims like a Higgs and quacks like a Higgs, then it is probably a Higgs"* M. Klute
    - Higgs discovery an early triumph for the LHC
- What next?
    - LHC(b) is also a phenomenal machine for flavour physics
    - Look for deviations from the Standard Model
        - Exciting opportunities in bottom baryon sector

FCNC decays: $\Lambda_b \to \Lambda \gamma$, $\Lambda_b \to \Lambda \mu^+ \mu^-$

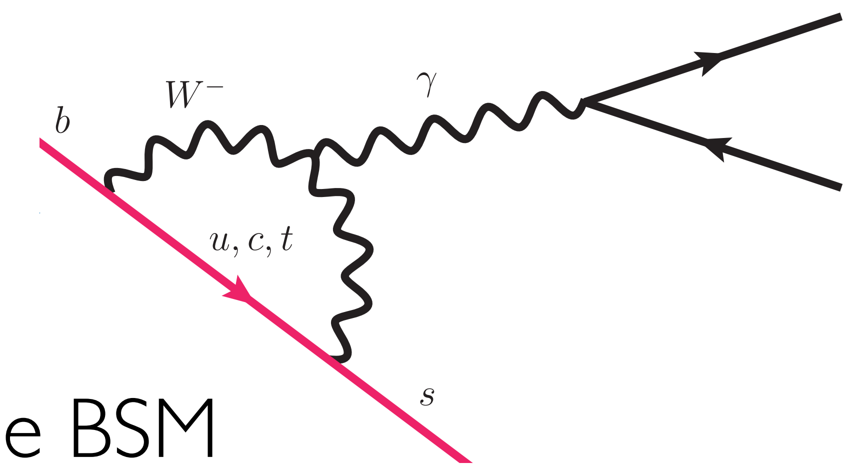
[Detmold, Lin, Meinel, & Wingate Phys. Rev. D 87, 074502 (2013)]

Rare decay: $\Lambda_b \to p \mu^- \bar{\nu}$ and $|V_{ub}|^2$

[Detmold, Lin, Meinel, & Wingate arXiv:1306.0446]

Flavour-changing neutral currents

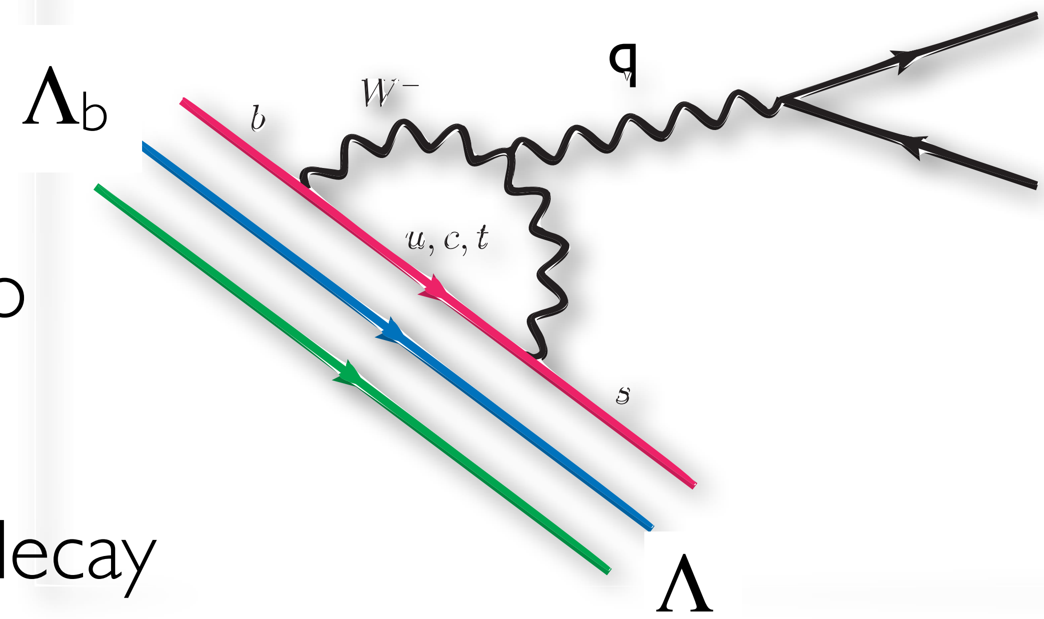
- Flavour changing neutral currents are absent in the SM at tree level
  - First occur at loop level and are generally GIM suppressed
  - Small size allows sensitivity to possible BSM contributions which may be of similar size



- Well studied in B ➞ K decays and also more recently in studies of B ➞ K*
  - No significant evidence for deviations from SM

Flavour-changing neutral currents

- Baryon decay modes $\Lambda_b \to \Lambda\gamma$, $\Lambda_b \to \Lambda l^+ l^-$ depend on polarisation of Λ_b and Λ so many angular observables possible
  - In principle different sensitivities to BSM physics [Mannel & Recksiegel 1997]



- Final state undergoes further weak decay $\Lambda \to$ p which is self-analysing

$$\frac{dN}{d\Omega}[\Lambda \to p\pi] \sim (1 + a\vec{s}_\Lambda \cdot \vec{p}_p), \qquad a = 0.64(1)$$

- At LHC, Λ_b is produced almost unpolarised [Aaij 1302.5578]
- First observation of baryonic decay at CDF [2012]
- LHCb preliminary results shown recently [FPCP 2013]

Effective Hamiltonian

- At hadronic scales the relevant interactions are described by the effective Hamiltonian

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{i=1,\ldots,10,S,P} (C_i O_i + C_i' O_i'),$$

where the relevant b → s operators are

$$\begin{aligned}
O_7 &= \frac{e}{16\pi^2} m_b \, \bar{s}\sigma^{\mu\nu} P_R b \, F_{\mu\nu}^{(\text{e.m.})}, & O_7' &= \frac{e}{16\pi^2} m_b \, \bar{s}\sigma^{\mu\nu} P_L b \, F_{\mu\nu}^{(\text{e.m.})}, \\
O_9 &= \frac{e^2}{16\pi^2} \bar{s}\gamma^\mu P_L b \, \bar{l}\gamma_\mu l, & O_9' &= \frac{e^2}{16\pi^2} \bar{s}\gamma^\mu P_R b \, \bar{l}\gamma_\mu l, \\
O_{10} &= \frac{e^2}{16\pi^2} \bar{s}\gamma^\mu P_L b \, \bar{l}\gamma_\mu \gamma_5 l, & O_{10}' &= \frac{e^2}{16\pi^2} \bar{s}\gamma^\mu P_R b \, \bar{l}\gamma_\mu \gamma_5 l, \\
O_S &= \frac{e^2}{16\pi^2} m_b \, \bar{s} P_R b \, \bar{l} l, & O_S' &= \frac{e^2}{16\pi^2} m_b \, \bar{s} P_L b \, \bar{l} l, \\
O_P &= \frac{e^2}{16\pi^2} m_b \, \bar{s} P_R b \, \bar{l}\gamma_5 l, & O_P' &= \frac{e^2}{16\pi^2} m_b \, \bar{s} P_L b \, \bar{l}\gamma_5 l,
\end{aligned}$$

C_i are Wilson coefficients containing short distance physics

$\Lambda_b \to \Lambda\, \mu^+ \mu^-$

- Decay amplitude determined by matrix elements of H_{eff}

$$\mathcal{M} = -\langle \Lambda(p', s')\, \ell^+(p_+, s_+)\, \ell^-(p_-, s_-)|\mathcal{H}_{\rm eff}|\Lambda_b(p, s)\rangle$$

- Hadronic part determined by $\Lambda_b \to \Lambda$ form factors
  - In general, 10 form factors contribute
  - In static limit ($m_b \to \infty$), only two FFs ($F_{1,2}$) survive

$$\langle \Lambda(p', s')|\, \bar{s}\Gamma Q\, |\Lambda_Q(v, 0, s)\rangle = \overline{u}(p', s')\, [F_1(p' \cdot v) + v\, F_2(p' \cdot v)]\, \Gamma\, \mathcal{U}(v, s)$$

where v=4-velocity of Λ_b and the FFs are independent of the choice of Dirac matrix Γ and we will use the basis $F_\pm = F_1 \pm F_2$

- Calculating FFs requires lattice QCD

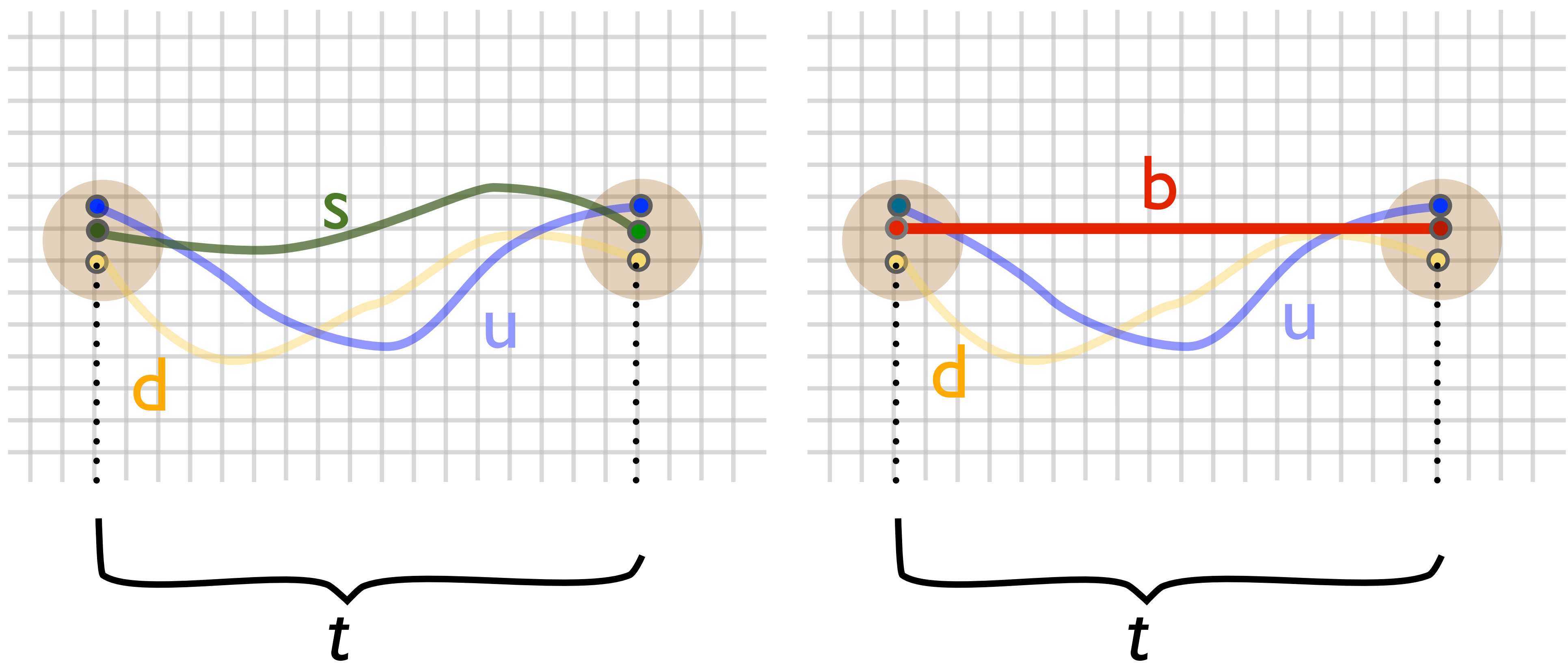
Anatomy of the QCD calculation

- Gluon configurations from RBC/UKQCD collaborations [Aoki et al. 2011]
  - Two lattice spacings with a single large volume
- Light and strange quarks: domain wall fermions with multiple quark masses (some partially quenched)
- b quarks: HQET static action [Eichten-Hill] with HYP-smearing

Set	$N_s^3 \times N_t \times N_5$	am_5	$am_s^{(\mathrm{sea})}$	$am_{u,d}^{(\mathrm{sea})}$	a (fm)	$am_s^{(\mathrm{val})}$	$am_{u,d}^{(\mathrm{val})}$	$m_\pi^{(\mathrm{vv})}$ (MeV)	$m_{\eta_s}^{(\mathrm{vv})}$ (MeV)	N_{meas}
C14	$24^3 \times 64 \times 16$	1.8	0.04	0.005	0.1119(17)	0.04	0.001	245(4)	761(12)	2705
C24	$24^3 \times 64 \times 16$	1.8	0.04	0.005	0.1119(17)	0.04	0.002	270(4)	761(12)	2683
C54	$24^3 \times 64 \times 16$	1.8	0.04	0.005	0.1119(17)	0.04	0.005	336(5)	761(12)	2780
C53	$24^3 \times 64 \times 16$	1.8	0.04	0.005	0.1119(17)	0.03	0.005	336(5)	665(10)	1192
F23	$32^3 \times 64 \times 16$	1.8	0.03	0.004	0.0849(12)	0.03	0.002	227(3)	747(10)	1918
F43	$32^3 \times 64 \times 16$	1.8	0.03	0.004	0.0849(12)	0.03	0.004	295(4)	747(10)	1919
F63	$32^3 \times 64 \times 16$	1.8	0.03	0.006	0.0848(17)	0.03	0.006	352(7)	749(14)	2785

Correlation functions

- Matrix elements extracted from ratios of two and three-point correlation functions
  - Two-point functions for Λ_b and Λ are standard



Correlation functions

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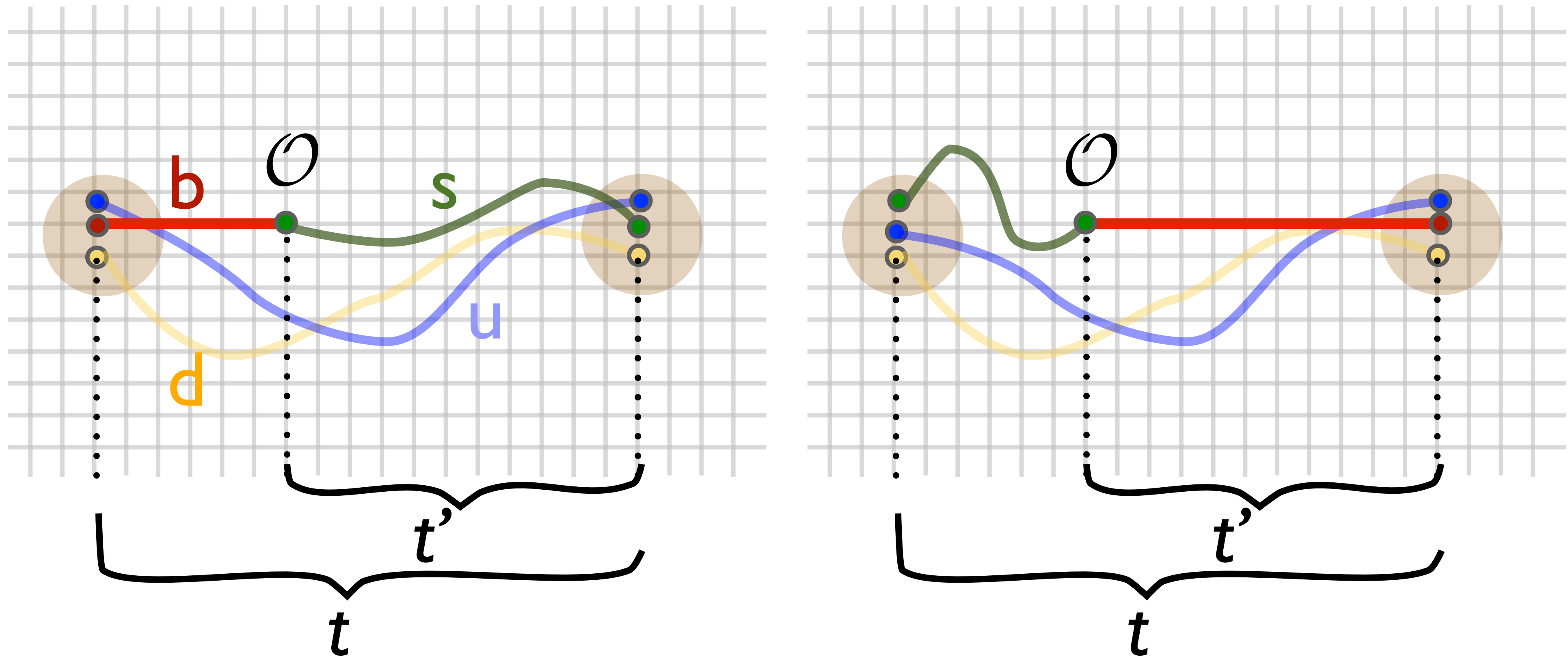

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$$C^{(3)}_{\delta\alpha}(\Gamma,\,\mathbf{p}',t,t') = \sum_{\mathbf{y}} e^{-i\mathbf{p}'\cdot(\mathbf{x}-\mathbf{y})} \Big\langle \Lambda_\delta(x_0,\mathbf{x})\;\; J_\Gamma^{(\mathrm{HQET})\dagger}(x_0-t+t',\mathbf{y})\;\; \overline{\Lambda}_{Q\alpha}(x_0-t,\mathbf{y})\Big\rangle$$

$$C^{(3,\mathrm{bw})}_{\alpha\delta}(\Gamma,\,\mathbf{p}',t,t-t') = \sum_{\mathbf{y}} e^{-i\mathbf{p}'\cdot(\mathbf{y}-\mathbf{x})} \Big\langle \Lambda_{Q\alpha}(x_0+t,\mathbf{y})\;\; J_\Gamma^{(\mathrm{HQET})}(x_0+t',\mathbf{y})\;\; \overline{\Lambda}_\delta(x_0,\mathbf{x})\Big\rangle$$

- NB: some technicalities in matching QCD current to HQET
- Spectral decomposition (ellipsis ~ excited states):

$$C^{(3)}_{\delta\alpha}(\Gamma,\,\mathbf{p}',t,t') = Z_{\Lambda_Q}\,\frac{1}{2E_\Lambda}\,\frac{1}{2}\,e^{-E_\Lambda(t-t')}\,e^{-E_{\Lambda_Q}t'}\,\Big[(Z^{(1)}_\Lambda+Z^{(2)}_\Lambda\gamma^0)(m_\Lambda+\not{p}')\big(F_1+\gamma^0F_2\big)\,\Gamma\,(1+\gamma^0)\Big]_{\delta\alpha}+\ldots$$

Correlator ratios

- Form ratios of correlators to cancel energy and time dependence for ground-state contribution

$$\mathcal{R}(\Gamma, \mathbf{p}', t, t') = \frac{4\,\mathrm{Tr}\left[C^{(3)}(\Gamma,\ \mathbf{p}', t, t')\ \ C^{(3,\mathrm{bw})}(\Gamma,\ \mathbf{p}', t, t-t')\right]}{\mathrm{Tr}[C^{(2,\Lambda,\mathrm{av})}(\mathbf{p}', t)]\ \mathrm{Tr}[C^{(2,\Lambda_Q,\mathrm{av})}(t)]}$$

- Combine for different Dirac structures

$$\mathcal{R}_+(\mathbf{p}', t, t') = \frac{1}{4}\left[\mathcal{R}(1, \mathbf{p}', t, t') + \mathcal{R}(\gamma^2\gamma^3, \mathbf{p}', t, t') + \mathcal{R}(\gamma^3\gamma^1, \mathbf{p}', t, t') + \mathcal{R}(\gamma^1\gamma^2, \mathbf{p}', t, t')\right]$$

$$\mathcal{R}_-(\mathbf{p}', t, t') = \frac{1}{4}\left[\mathcal{R}(\gamma^1, \mathbf{p}', t, t') + \mathcal{R}(\gamma^2, \mathbf{p}', t, t') + \mathcal{R}(\gamma^3, \mathbf{p}', t, t') + \mathcal{R}(\gamma_5, \mathbf{p}', t, t')\right]$$

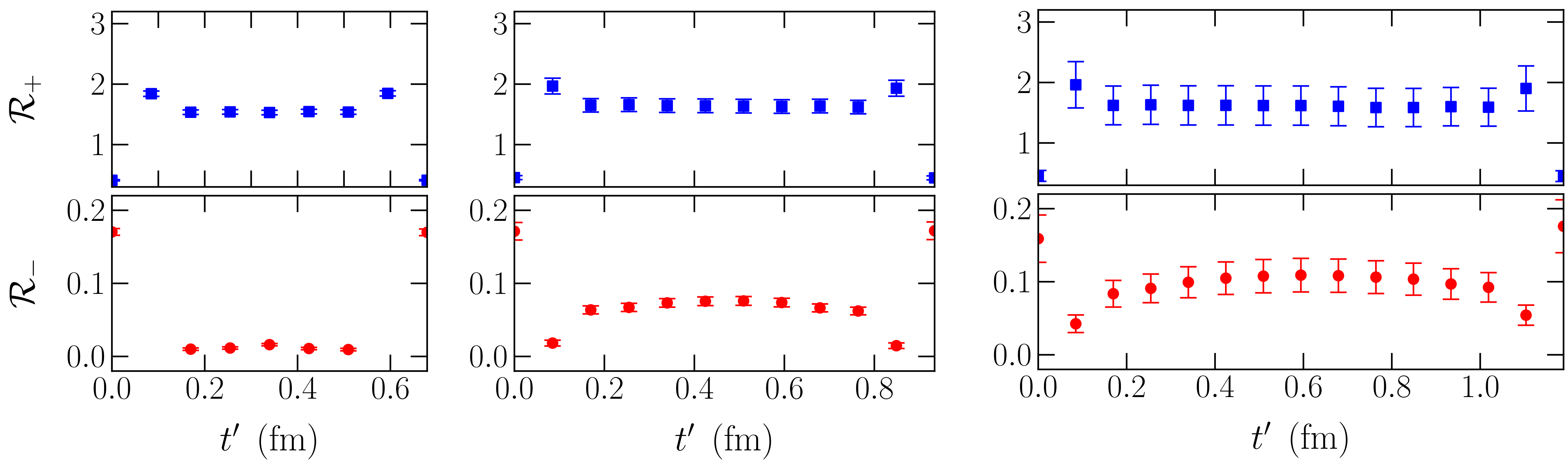
- Determine form factors (up to exponential contamination)

$$R_+(|\mathbf{p}'|^2, t) = \sqrt{\frac{E_\Lambda}{E_\Lambda + m_\Lambda}\mathcal{R}_+(|\mathbf{p}'|^2,\ t,\ t/2)} \ \ \stackrel{t\to\infty}{\longrightarrow}\ F_+(v\cdot p) + \ldots$$

$$R_-(|\mathbf{p}'|^2, t) = \sqrt{\frac{E_\Lambda}{E_\Lambda - m_\Lambda}\mathcal{R}_-(|\mathbf{p}'|^2,\ t,\ t/2)} \ \ \stackrel{t\to\infty}{\longrightarrow}\ F_-(v\cdot p) + \ldots$$

Form factor extractions

- Ratios are relatively insensitive to operator insertion time
  - Take midpoint to reduce excited state



- Strongly dependent on source-sink separation

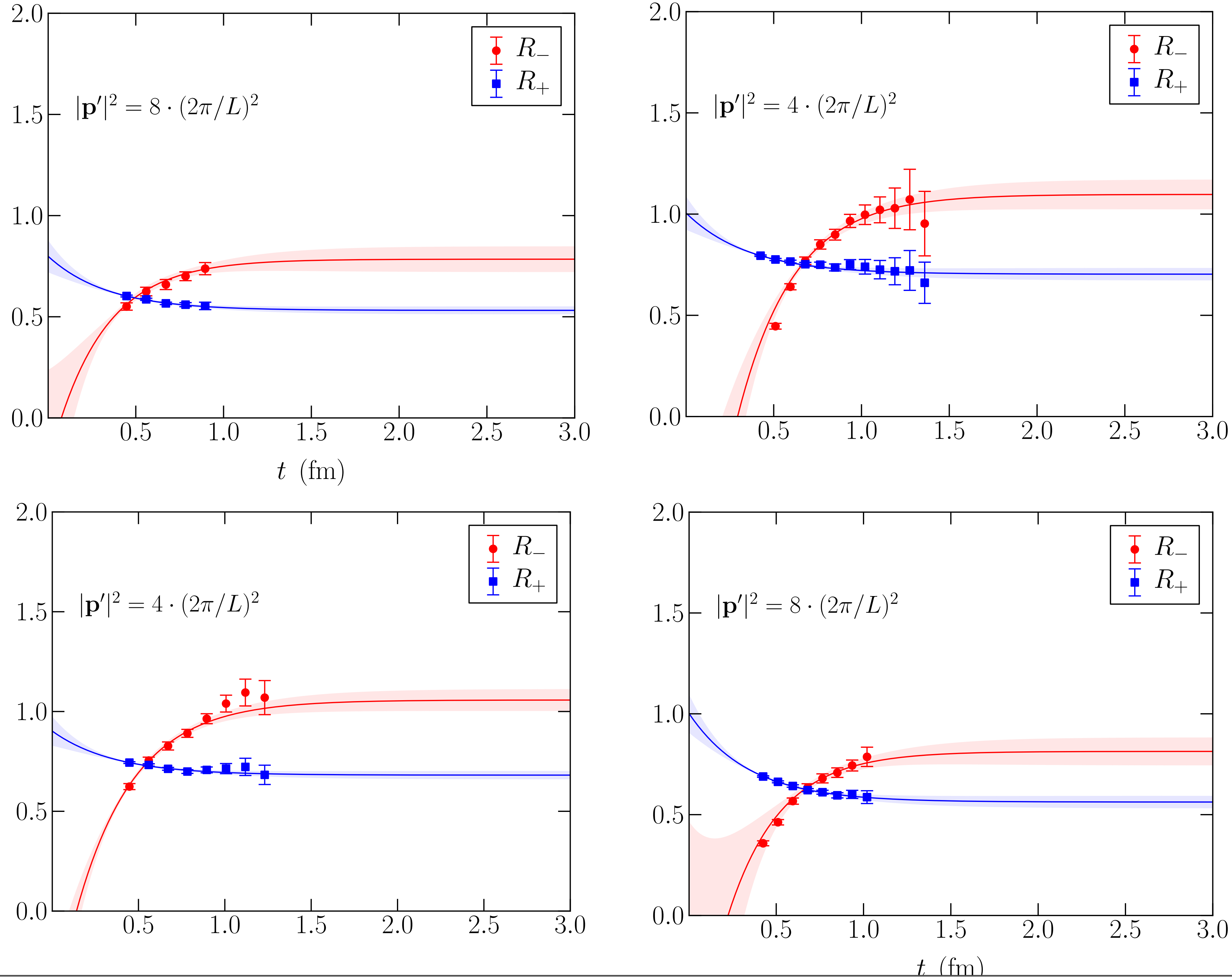
Source sink separation

- Extrapolate to infinite source-sink separation to extract ground state matrix elements
    - Allow for single exponential contamination

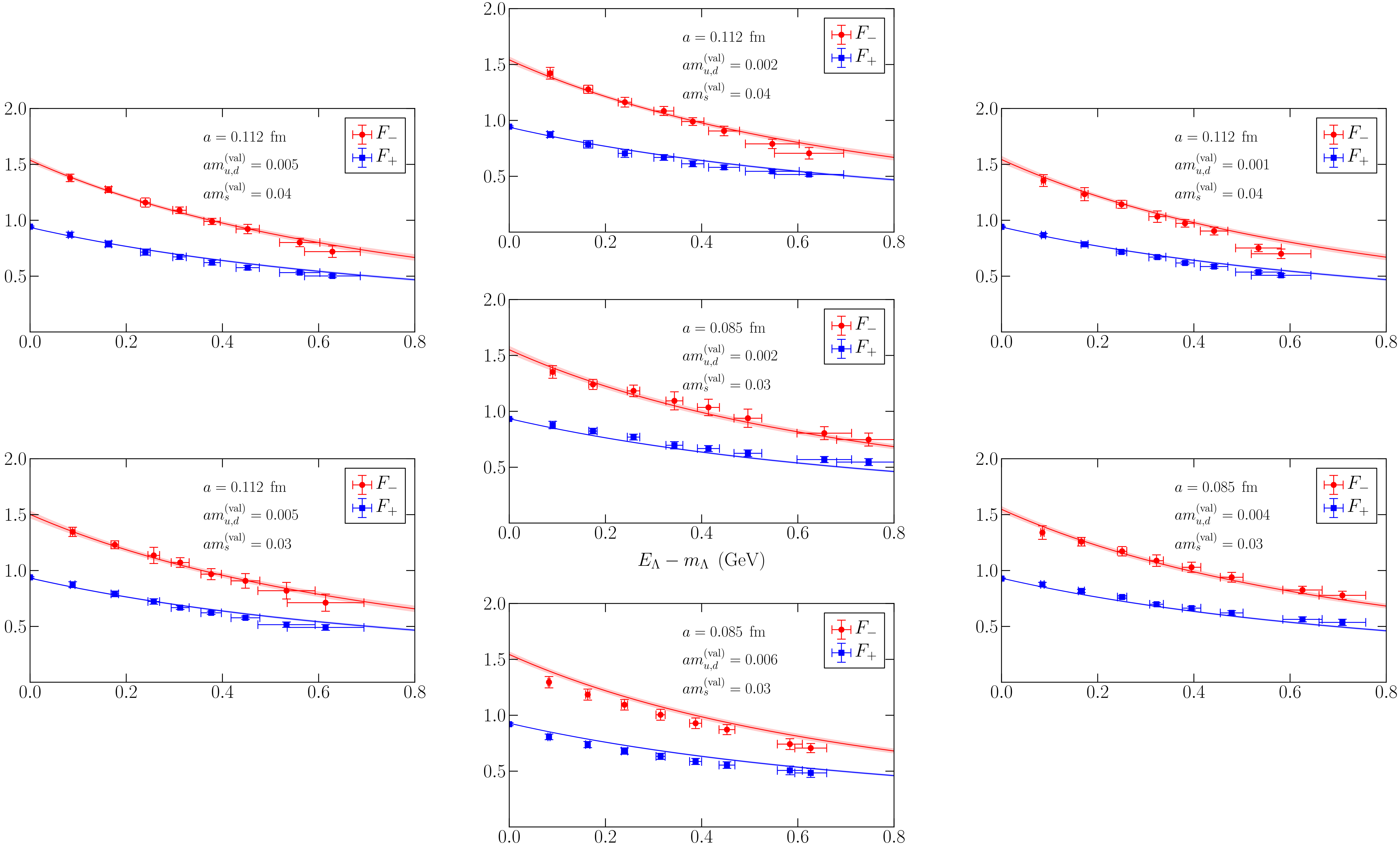
$$R_{\pm}^{i,n}(t) = F_{\pm}^{i,n} + A_{\pm}^{i,n}\ \exp[-\delta^{i,n}\ t]$$

    - Constrain energy gap to be positive and to be similar between the fits to the different ensembles
- Systematic fitting uncertainty assessed by adding a second exponential contamination and by dropping data at short t

Source sink separation



Form factors



Extrapolation of form factors

- Form factors extracted at non-zero lattice spacing, unphysical quark masses and for a limited range of momenta
- Coupled extrapolations performed using the form

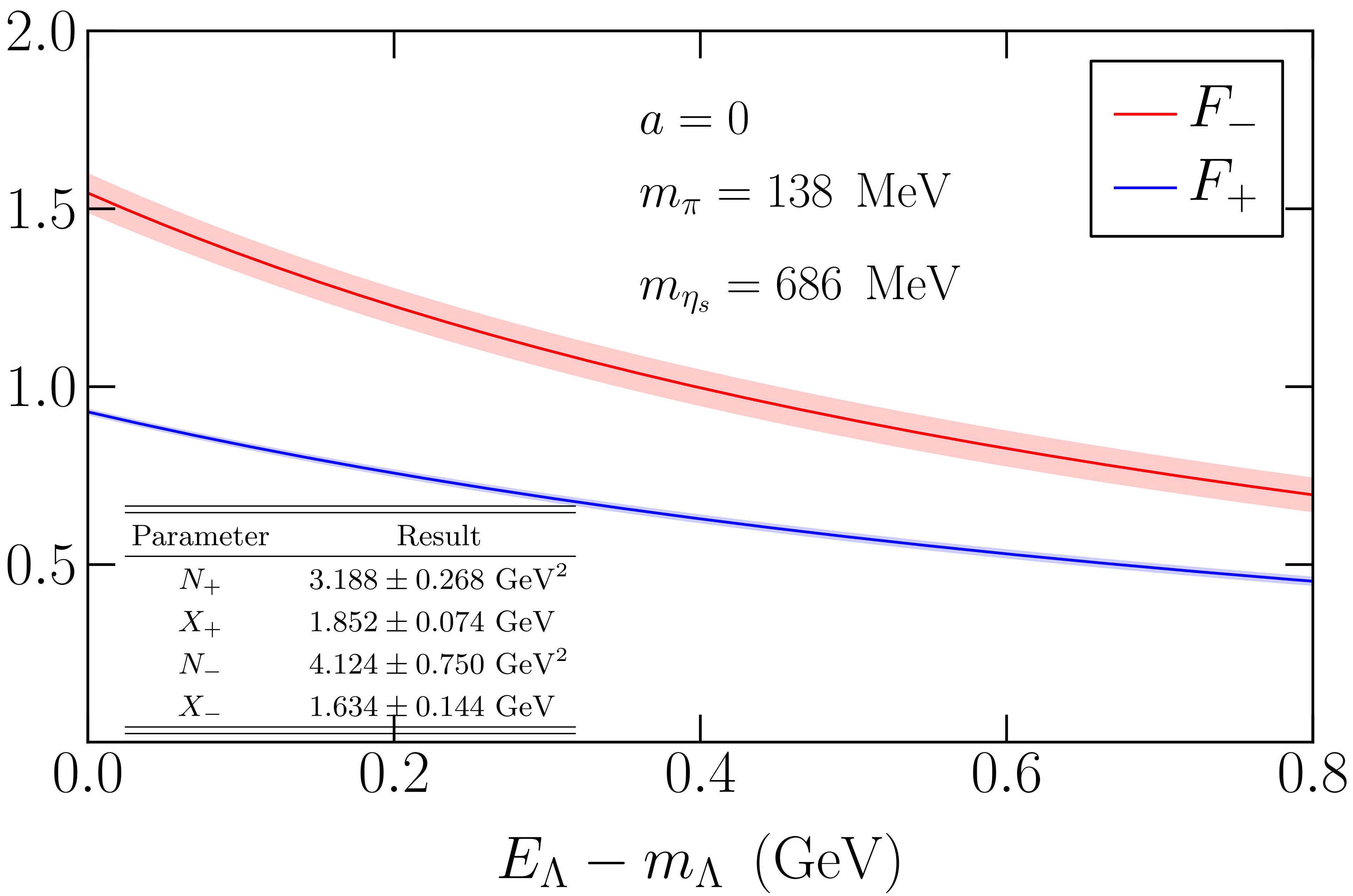
$$F_\pm^{i,n} = \frac{N_\pm}{(X_\pm^i + E_\Lambda^{i,n} - m_\Lambda^i)^2} \cdot [1 + d_\pm (a^i E_\Lambda^{i,n})^2]$$

with $X_\pm^i = X_\pm + c_{l,\pm} \cdot \left[(m_\pi^i)^2 - (m_\pi^{\rm phys})^2\right] + c_{s,\pm} \cdot \left[(m_{\eta_s}^i)^2 - (m_{\eta_s}^{\rm phys})^2\right]$

- Simple modified dipole form
  - Necessarily phenomenological (momenta of Λ beyond range of applicability of χPT)
  - Lattice spacing and light and strange quark mass dependence through c's and d's

Form factors

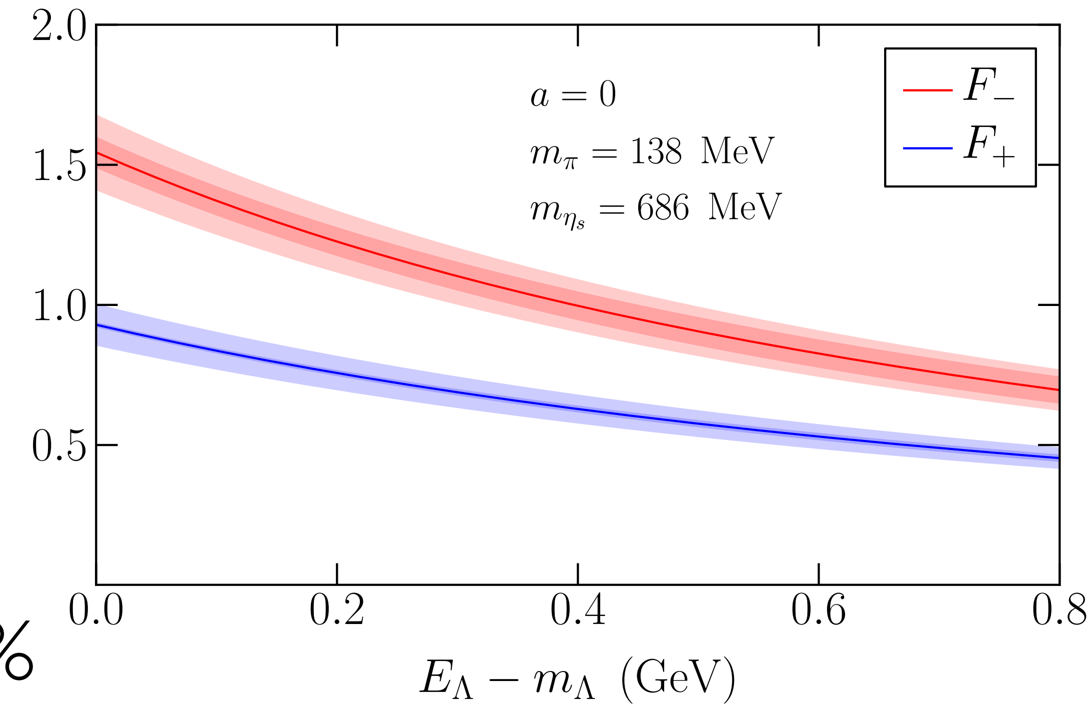
- Fit has χ^2/dof < 1 and fitted lattice spacing and quark mass parameters consistent with zero

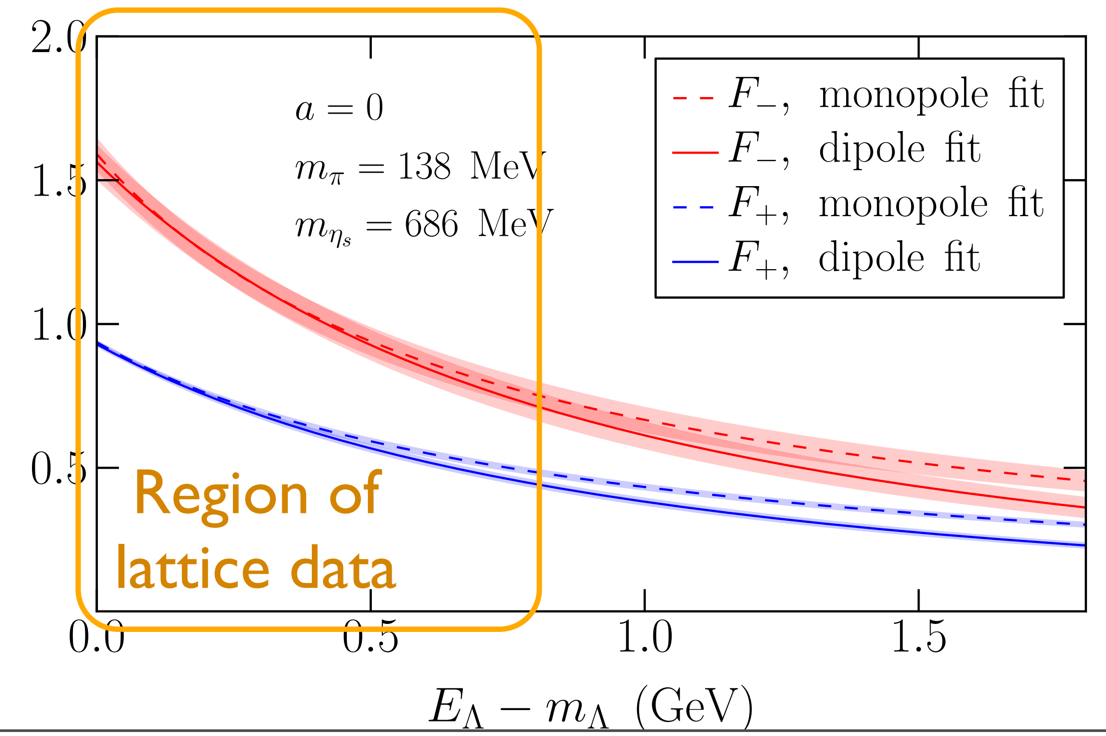


Parameter	Result
N_+	3.188 ± 0.268 GeV^2
X_+	1.852 ± 0.074 GeV
N_-	4.124 ± 0.750 GeV^2
X_-	1.634 ± 0.144 GeV

Systematic Uncertainties

- Main sources of systematic uncertainty in FFs are
  - Higher order effects in renormalisation of currents ~6%
  - Finite volume ~3%
  - Chiral extrapolation ~5%
  - Residual discretisation effects ~4%
- Extrapolation functional form
  - Dipole vs monopole vs ...
  - Agree in data region
    Uncertainty hard to quantify





Differential branching fraction

- Taking SM Wilson coefficients from the literature we can compute the SM decay rate

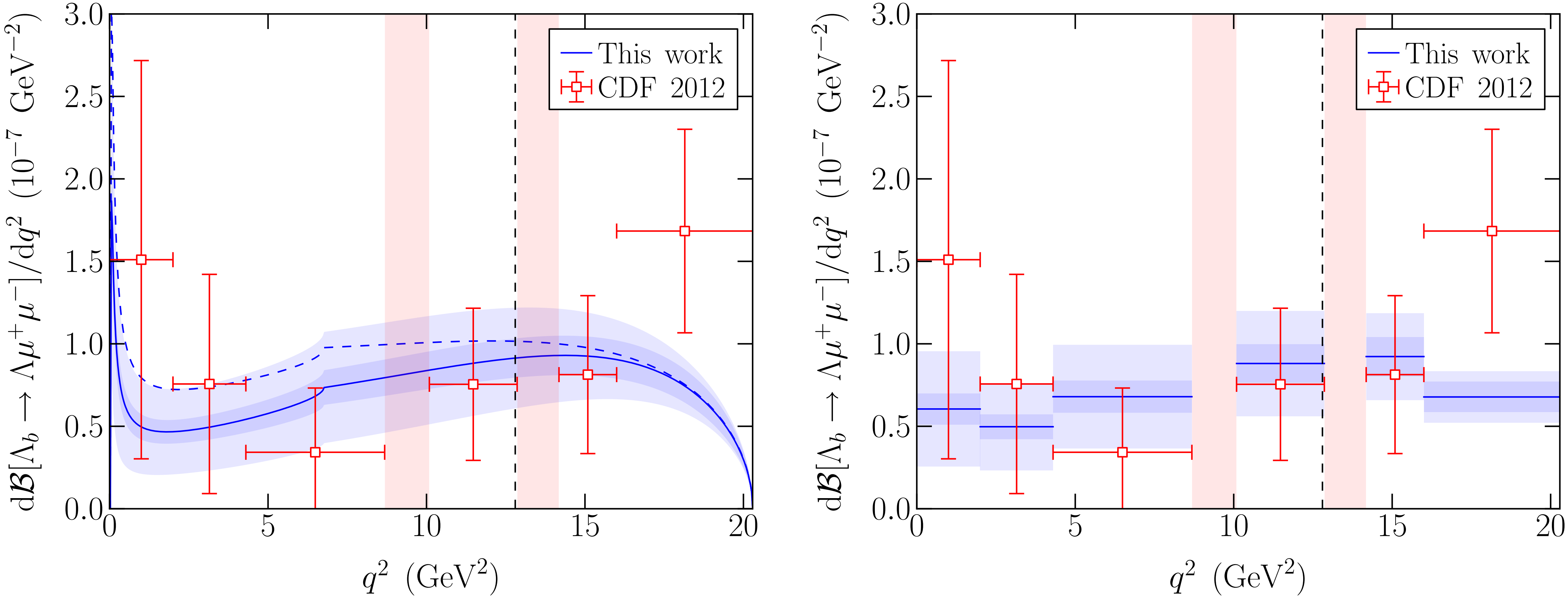
$$\frac{d\Gamma}{dq^2} = \frac{\alpha_{em}^2 G_F^2 |V_{tb}V_{ts}^*|^2}{6144\,\pi^5\,q^4\,m_{\Lambda_b}^5}\sqrt{1-\frac{4m_l^2}{q^2}}\sqrt{((m_{\Lambda_b}-m_\Lambda)^2-q^2)((m_{\Lambda_b}+m_\Lambda)^2-q^2)}$$
$$\times\Big[q^2|C_{10,\text{eff}}|^2\mathcal{A}_{10,10}+16c_\sigma^2 m_b^2(q^2+2m_l^2)|C_{7,\text{eff}}|^2\mathcal{A}_{7,7}+q^2(q^2+2m_l^2)|C_{9,\text{eff}}(q^2)|^2\mathcal{A}_{9,9}$$
$$+8q^2c_\sigma m_b(q^2+2m_l^2)m_{\Lambda_b}\Re[C_{7,\text{eff}}\,C_{9,\text{eff}}(q^2)]\mathcal{A}_{7,9}\Big],$$

$$\mathcal{A}_{10,10}=\Big[\left(2c_\gamma^2+2c_\gamma c_v+c_v^2\right)\left(2m_l^2+q^2\right)\left(m_{\Lambda_b}^4-2m_{\Lambda_b}^2m_\Lambda^2+\left(q^2-m_\Lambda^2\right)^2\right)$$
$$+2m_{\Lambda_b}^2q^2\left(4c_\gamma^2\left(q^2-4m_l^2\right)-\left(2c_\gamma c_v+c_v^2\right)\left(q^2-10m_l^2\right)\right)\Big]\mathcal{F}+4c_\gamma\left(c_\gamma+c_v\right)\left(2m_l^2+q^2\right)\mathcal{G}F_+F_-,$$
$$\mathcal{A}_{7,7}=\left(m_{\Lambda_b}^4+m_{\Lambda_b}^2\left(q^2-2m_\Lambda^2\right)+\left(q^2-m_\Lambda^2\right)^2\right)\mathcal{F}+2\mathcal{G}F_+F_-,$$
$$\mathcal{A}_{9,9}=\Big[\left(2c_\gamma^2+2c_\gamma c_v+c_v^2\right)\left(m_{\Lambda_b}^4+\left(q^2-m_\Lambda^2\right)^2\right)-2m_{\Lambda_b}^2\left(2c_\gamma^2\left(m_\Lambda^2-2q^2\right)+\left(2c_\gamma c_v+c_v^2\right)\left(m_\Lambda^2+q^2\right)\right)\Big]\mathcal{F}$$
$$+4c_\gamma\left(c_\gamma+c_v\right)\mathcal{G}F_+F_-,$$
$$\mathcal{A}_{7,9}=3c_\gamma\left(m_{\Lambda_b}^2-m_\Lambda^2+q^2\right)\mathcal{F}+2\left(3c_\gamma+c_v\right)\left(m_\Lambda^4-2m_\Lambda^2\left(m_{\Lambda_b}^2+q^2\right)+\left(q^2-m_{\Lambda_b}^2\right)^2\right)F_+F_-,$$

$$\mathcal{F}=((m_{\Lambda_b}-m_\Lambda)^2-q^2)F_-^2+((m_{\Lambda_b}+m_\Lambda)^2-q^2)F_+^2,$$
$$\mathcal{G}=m_{\Lambda_b}^6-m_{\Lambda_b}^4\left(3m_\Lambda^2+q^2\right)-m_{\Lambda_b}^2\left(q^2-m_\Lambda^2\right)\left(3m_\Lambda^2+q^2\right)+\left(q^2-m_\Lambda^2\right)^3$$

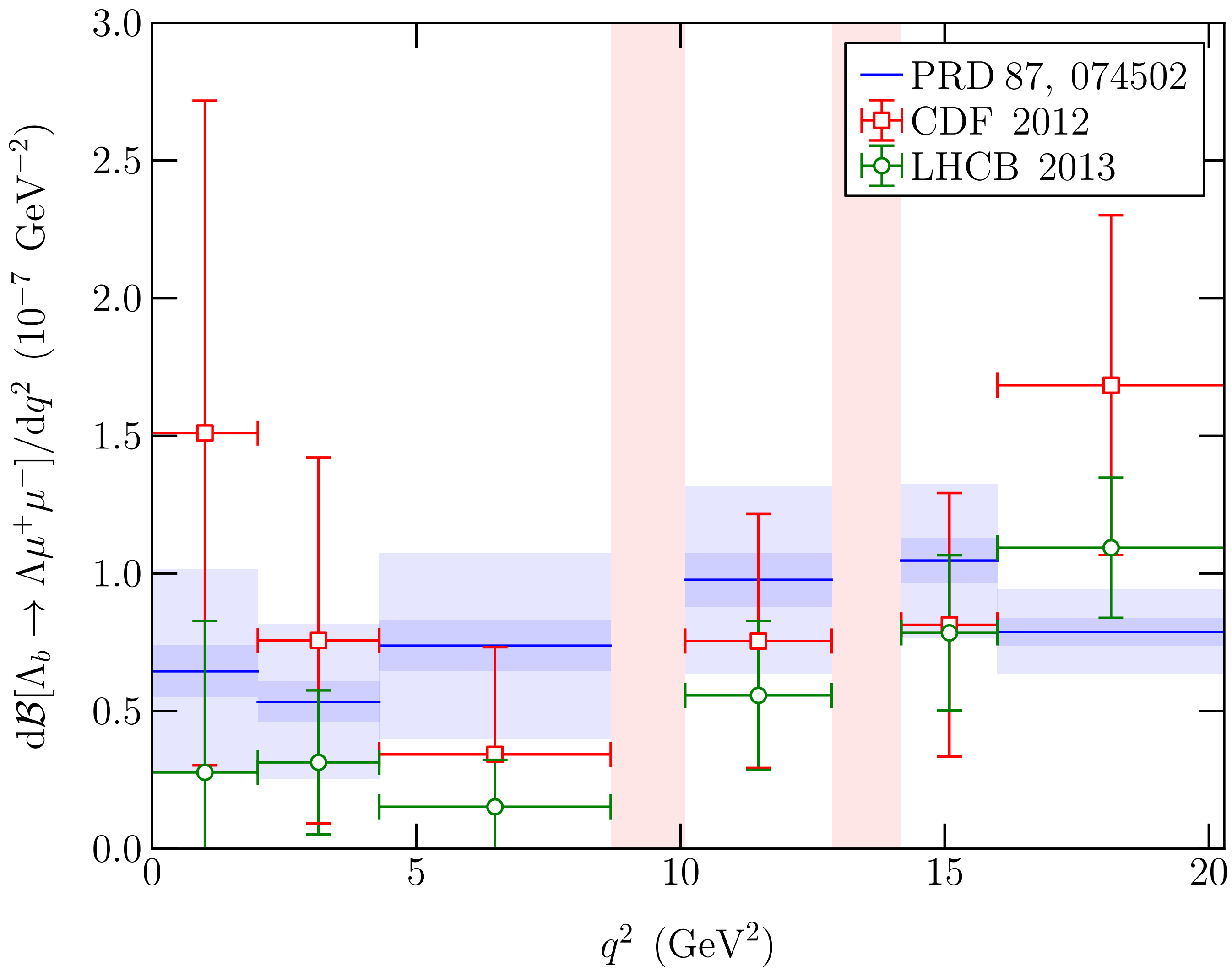
Differential branching fraction

- Evaluate using lattice FFs
- Additional systematic uncertainty from using static limit FFs taken as $\sqrt{|\vec{p}|^2 + \Lambda_{\rm QCD}^2} \Big/ m_b$
- Comparison to CDF measurements (RHS binned)



Differential branching fraction

- New LHCb data are more precise (and will become even more so)



- LQCD calculation will also improve (relativistic heavy quarks)

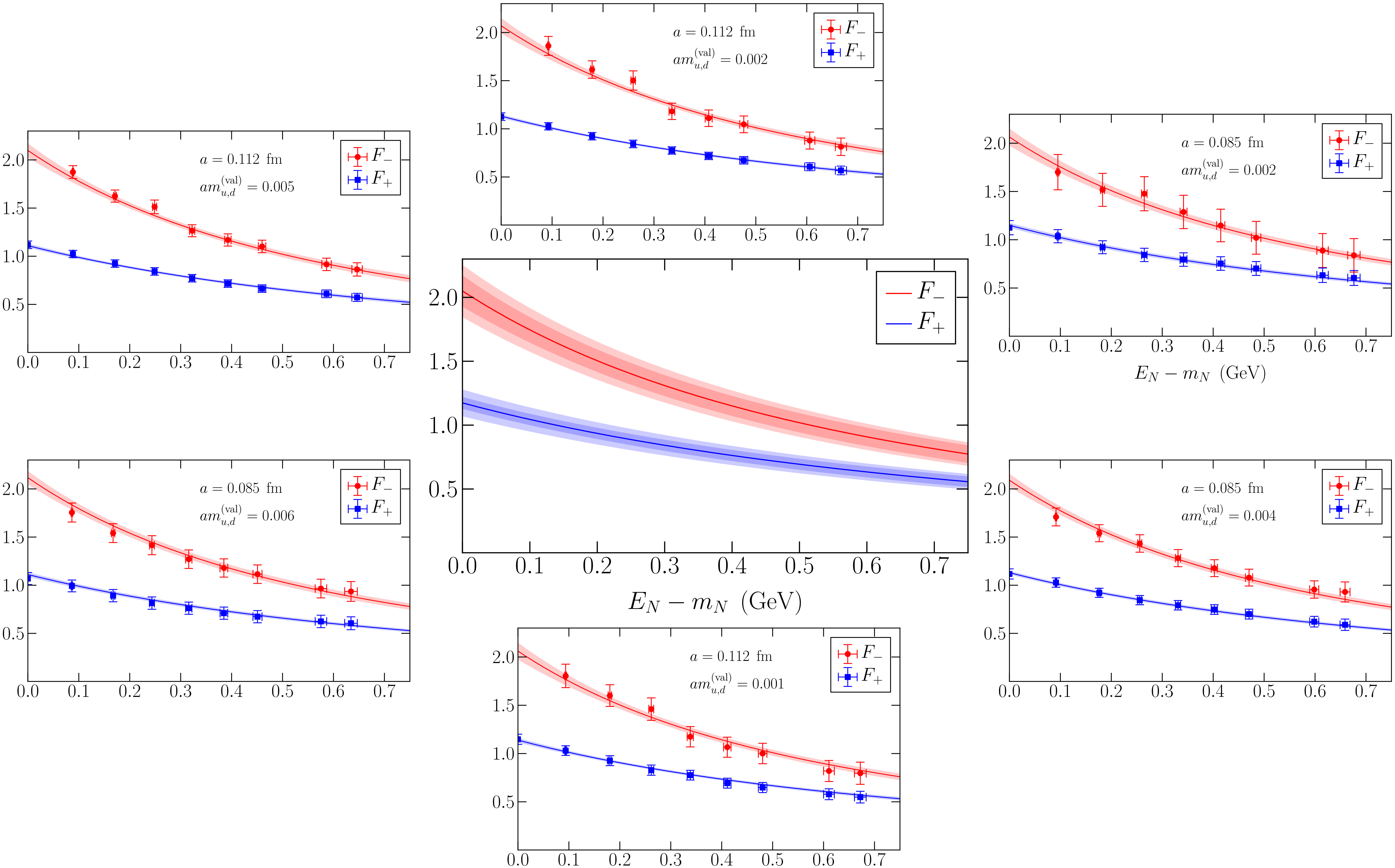
Rare decay: $\Lambda_b \to p\, \mu^- \bar{\nu}$ and $|V_{ub}|^2$

- Puzzle in current determinations of V_{ub} [PDG]
  - Inclusive $B \to X_u$ decays: $|V_{ub}|_{\text{incl.}} = (4.41 \pm 0.15^{+0.15}_{-0.17}) \cdot 10^{-3}$
  - Exclusive $B \to \pi$ decays: $|V_{ub}|_{\text{excl.}} = (3.23 \pm 0.31) \cdot 10^{-3}$
- Worryingly discrepant: likely not new physics, but an independent determination would be useful
- The baryonic decay $\Lambda_b \to p\, \mu^- \bar{\nu}$ also depends on $|V_{ub}|^2$
  - At the LHC, this may be easier to measure than $B \to \pi\, \mu^- \bar{\nu}$ as the final state is more distinctive [U Egede]
  - Extraction requires calculation of hadronic matrix elements

Matrix elements & form factors

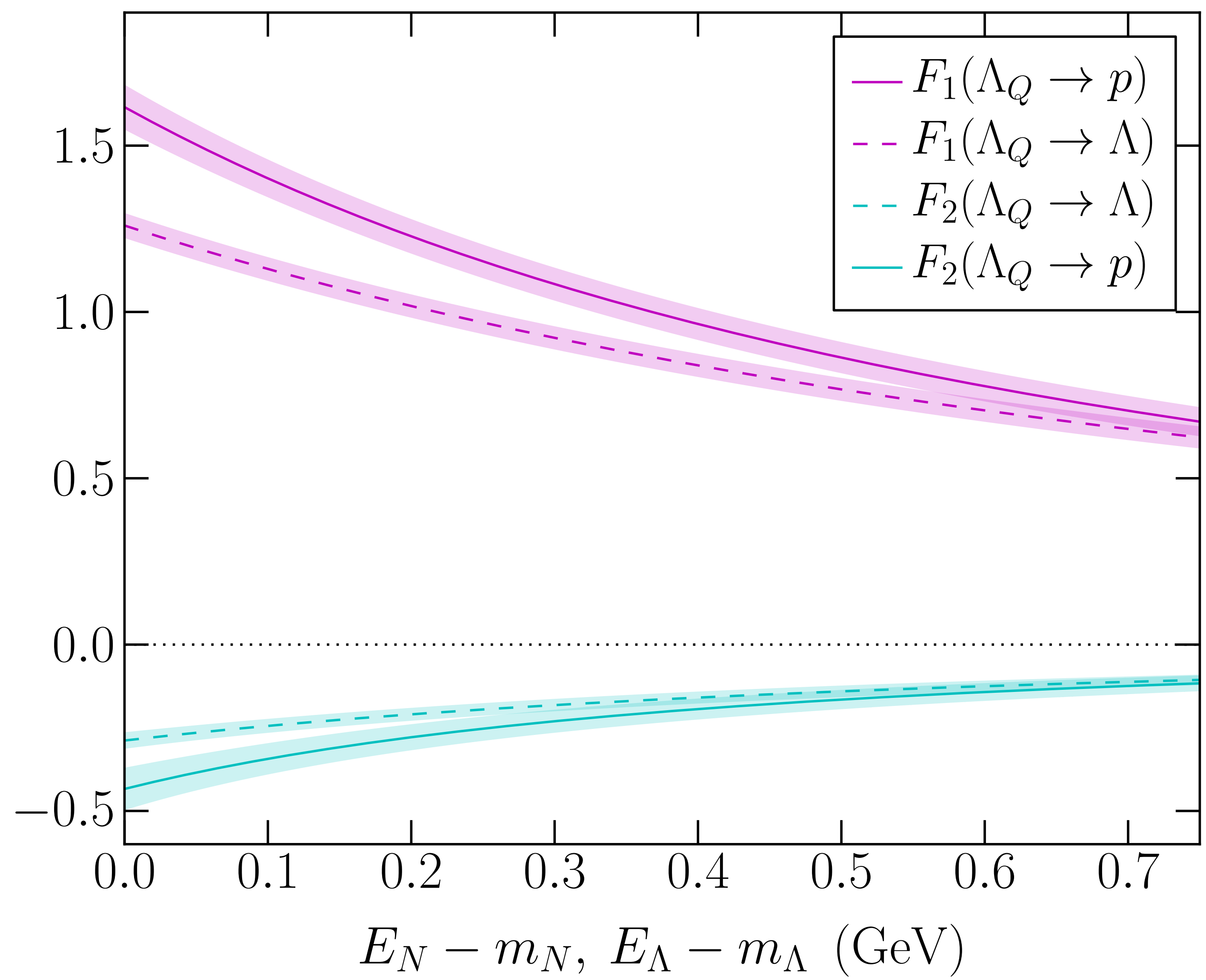
- Calculational details are very similar to previous case
  - Static limit again reduces to two form factors
  - Somewhat simpler as only need vector and axial-vector currents
  - Contractions involve extra term
  - Behaviour of correlators and ratios similar
    Uncertainties a little larger

$\Lambda_b \to$ p *form factors*



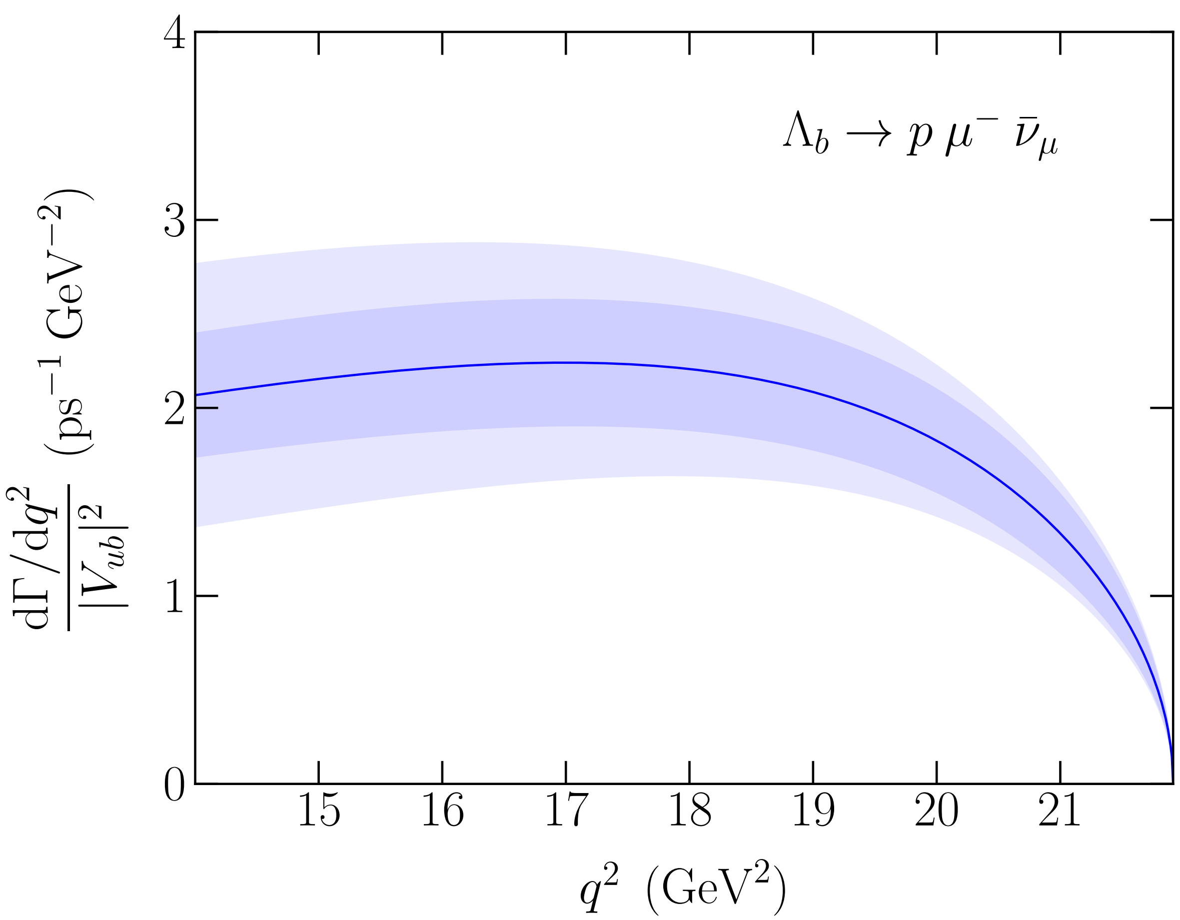
$\Lambda_b \to p$ vs $\Lambda_b \to \Lambda$

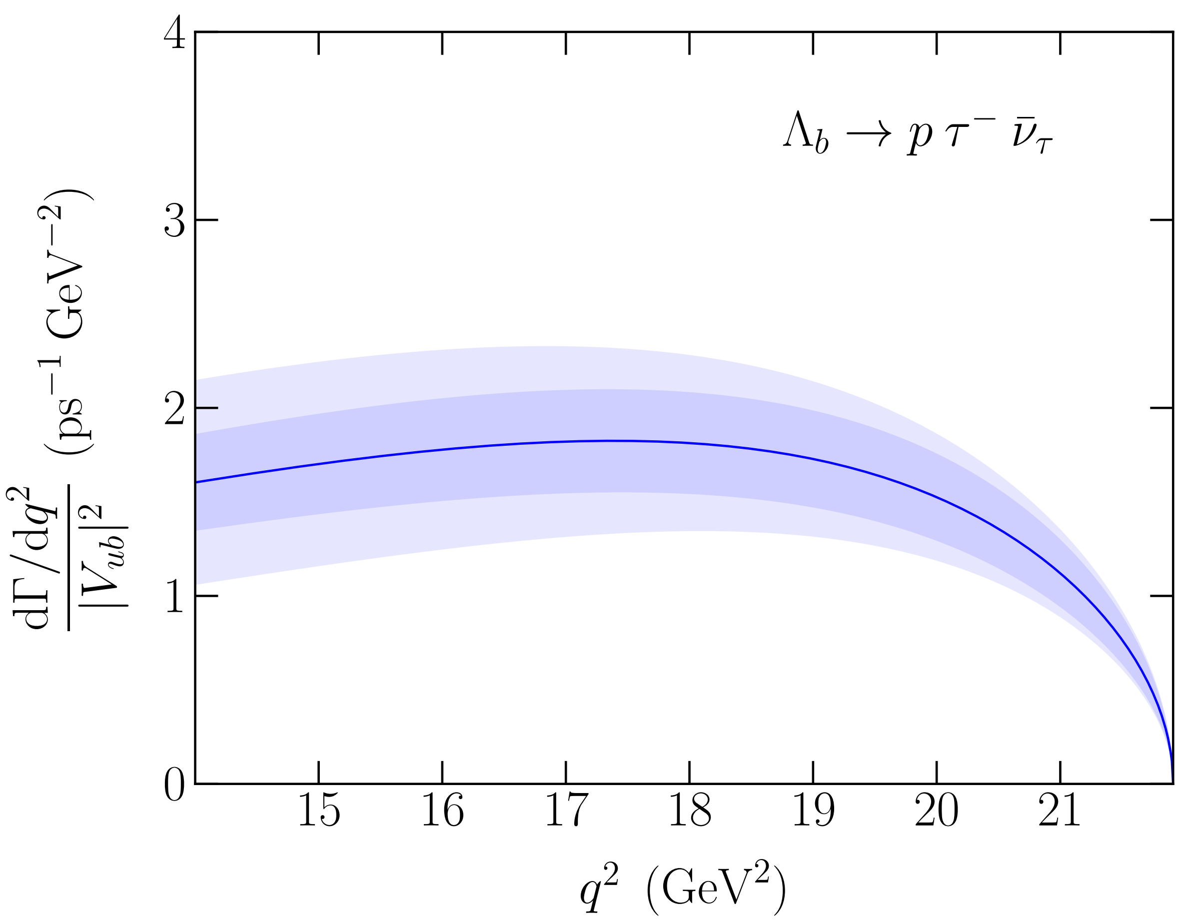
- Form factors larger for proton final state than for $\boldsymbol{\Lambda}$
- Significantly different than model estimates



$\Lambda_b \rightarrow p\, l\, \bar{\nu}$ decay rate

- Differential decay rate again computed using extracted form factors
- Shown for μ and τ final states (electron is identical to μ) and only in regime where momentum dependence is controlled by lattice data





$|V_{ub}|^2$ extraction

- Results are promising for extraction of V_{ub} from this channel
- Construct partially integrated decay rate

$$\frac{1}{|V_{ub}|^2}\int_{14\ \mathrm{GeV}^2}^{q^2_{\max}}\frac{\mathrm{d}\Gamma(\Lambda_b\to p\,\ell^-\bar{\nu}_\ell)}{\mathrm{d}q^2}\mathrm{d}q^2=\begin{cases}15.3\pm2.4\pm3.4\ \ \mathrm{ps}^{-1} & \text{for}\quad \ell=e,\\ 15.3\pm2.4\pm3.4\ \ \mathrm{ps}^{-1} & \text{for}\quad \ell=\mu,\\ 12.5\pm1.9\pm2.7\ \ \mathrm{ps}^{-1} & \text{for}\quad \ell=\tau.\end{cases}$$

- Theory uncertainty on V_{ub} about 15%
- Theoretical uncertainties smaller than difference between current inclusive and exclusive extractions
- We need to wait for experimental results from LHCb (studies are underway)

Summary

- Flavour physics alive and well in the LHC era
- First calculations of hadronic form factors for $\Lambda_b \to p$ and $\Lambda_b \to \Lambda$ transitions allow
  - Tests of the Standard Model in $\Lambda_b \to \Lambda \mu^+ \mu^-$
  - Independent extraction of V_{ub} from $\Lambda_b \to p\, l\, \nu$ decays
- Calculations will be improved in the future using improved discretisations of *b* quarks, lighter light quarks and non-perturbative renormalisation of currents