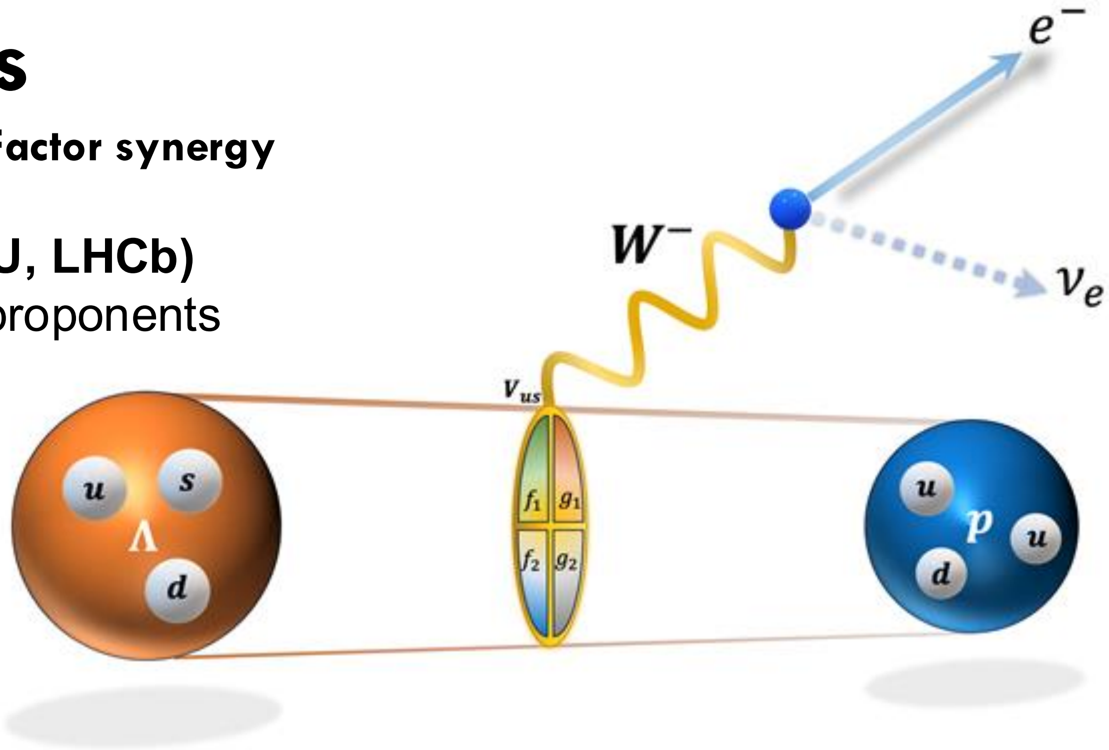
Names:
P. Adlarson, C. Alexandrou, S. Bacchio,
V. Batozskaya, J. Bijnens, G. Eichmann,
C. Fischer, A. Kupsc, A. Brea Rodriguez,
T. Peña, P. Salabura
+ others

V_{us} BFFs

Branching fraction Form Factor synergy

Patrik Adlarson (UU, LHCb)
On behalf of the LoI proponents



LHCb experiment (CERN)
EPFL, NCBJ Warsaw, Universidade da Coruña, Uppsala University
CBM Collaboration (FAIR)
Lattice QCD
University of Cyprus
Theory and Phenomenology
Lund University, NCBJ Warsaw, Uppsala University, University of Giessen, University of Graz, LIP/ IST University of Lisboa

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Weak vector and axial vectors

Semi-leptonic hyperon decays $B_1 \rightarrow B_2\, l\, \bar{\nu}_l$

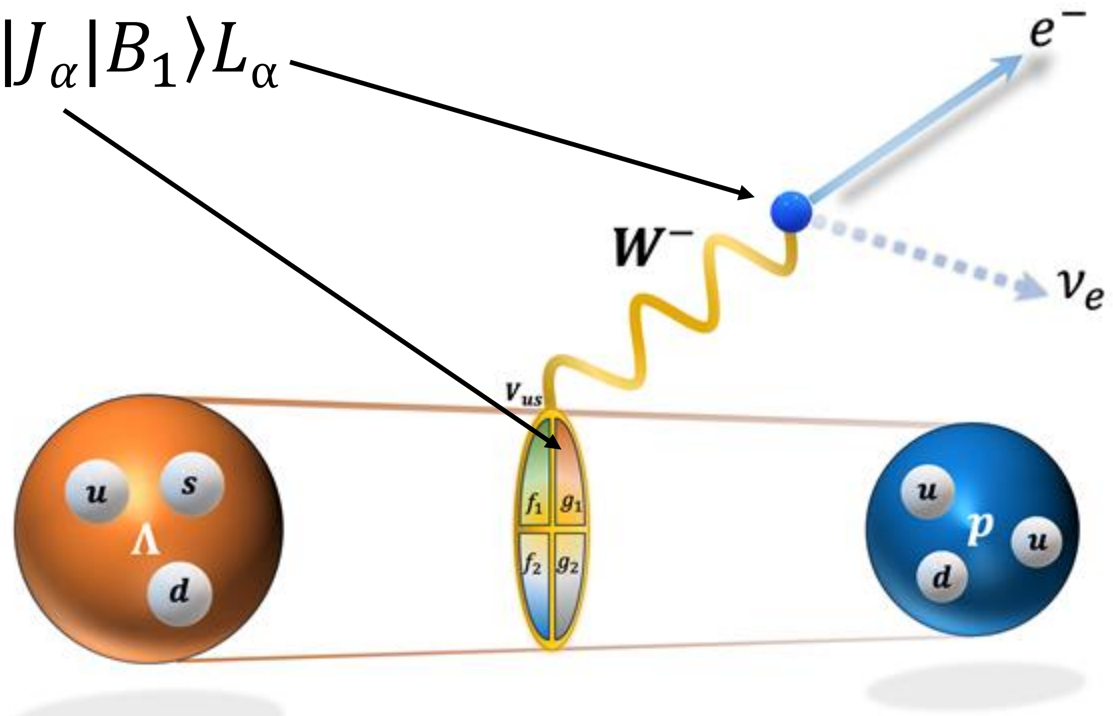
Weak transitions for spin-½ baryons, has vector (V) and axial-vector currents (A)

$$\mathcal{M}(\Lambda \rightarrow p\, l\, \bar{\nu}_l) = \frac{G_F}{\sqrt{2}} V_{us} \langle \Lambda | J_\alpha | B_1 \rangle L_\alpha$$

Vector determined from lepton-nucleon scattering

$$J_\alpha = \mathrm{V}_\alpha - \mathrm{A}_\alpha$$

Axial vector from neutrino-nucleon scattering – low cross-sec



Semi-leptonic decays can be used to measure axial vector contributions!

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Semi-leptonic decays

Semi-leptonic hyperon decays $B_1 \to B_2\, l\, \bar{\nu}_l$

PRD 70, 114036 (2004)

Weak transitions for spin-½ baryons, has vector (V) and axial-vector currents (A)

$$\langle B_2|V_\alpha|B_1\rangle = \boxed{V_{CKM}}\, \bar{u}_{B_2}(p_2)\left[\boxed{f_1(q^2)}\,\gamma_\alpha + \frac{\boxed{f_2(q^2)}}{M_1}\sigma_{\alpha\beta}q^\beta + \frac{\boxed{f_3(q^2)}}{M_1}q_\alpha\right]u_{B_1}(p_1)$$

$$\langle B_2|A_\alpha|B_1\rangle = \boxed{V_{CKM}}\, \bar{u}_{B_2}(p_2)\left[\boxed{g_1(q^2)}\,\gamma_\alpha + \frac{\boxed{g_2(q^2)}}{M_1}\sigma_{\alpha\beta}q^\beta + \frac{\boxed{g_3(q^2)}}{M_1}q_\alpha\right]\gamma_5 u_{B_1}(p_1)$$

q four-momentum transfer

f_1 - vector
g_1 - axial vector

f_2 – weak magn ff
g_2 – electric ff

f_3 – induced sc
g_3 – induced psc

The transition form factors are q^2-dependent and range close to 0

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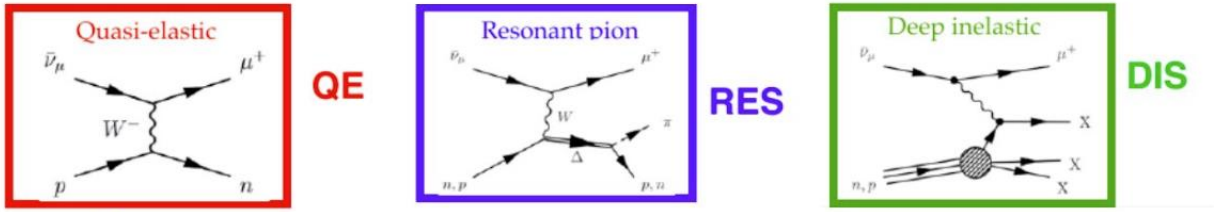
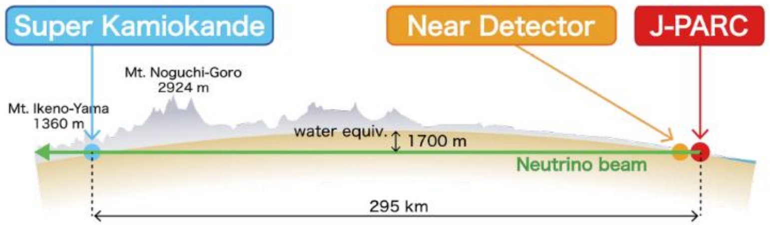
low q^2 gives access to weak charge radii

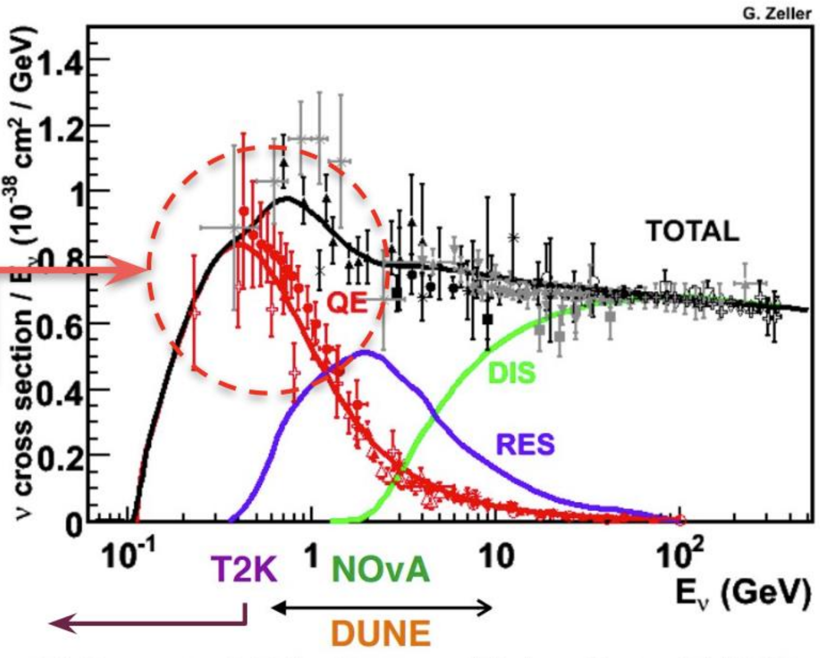
Slide from
S. Bacchio



We focus on quasi-elastic scattering providing first-principle predictions on axial form factors



T2K: Tokai to Super-Kamiokande
E = 0.6 GeV, L/E ≈ 500 km/GeV.



J.A. Formaggio, G. Zeller, Reviews of Modern Physics, 84 (2012)

q^2 low 0 – ~0.04 GeV^2 – access to weak charge radii

$$F_i(q^2) \approx F_i(0)\left[1 + \frac{1}{6} r_i^2\, q^2\right] \longrightarrow \langle r^2 \rangle = 6 \left.\frac{\mathrm{d}\ln F_i(q^2)}{\mathrm{d}q^2}\right|_{q^2=0}$$

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This also serves the neutrino physics community, as MC needs input on the differential cross section to reconstruct the energy of the neutrino from the momentum of the detected charged lepton

Semi-leptonic decays

	Process	ΔM [MeV]	ΔS	μ-mode	BF(e-mode) $\times 10^{-5}$
1	$\Sigma^+ \to \Lambda e^+ \nu_e$	74	0	–	2
2	$\Sigma^- \to \Lambda e^- \bar{\nu}_e$	82	0	–	6
3	$\Lambda \to p e^- \bar{\nu}_e$	177	1	yes	83
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
4	$\Xi^- \to \Lambda e^- \bar{\nu}_e$	206	1	yes	56
	$\Xi^- \to \Sigma^0 e^- \bar{\nu}_e$	129	1	yes	9
	$\Xi^0 \to \Sigma^+ e^- \bar{\nu}_e$	126	1	yes	25
	$\Xi^- \to \Xi^0 e^- \bar{\nu}_e$	7	0	–	–
	$\Sigma^- \to \Sigma^0 e^- \bar{\nu}_e$	5	0	–	–
5	$\Sigma^- \to p \pi^- e^- \bar{\nu}_e$	120	1	yes	–
6	$\Xi^0 \to \Lambda \pi^+ e^- \bar{\nu}_e$	64	1	–	–
	$\Omega^- \to \Xi^0 e^- \bar{\nu}_e$	357	1	yes	560
7	$\Omega^- \to \Xi^{*0} e^- \bar{\nu}_e$	142	1	yes	–

Many different decays

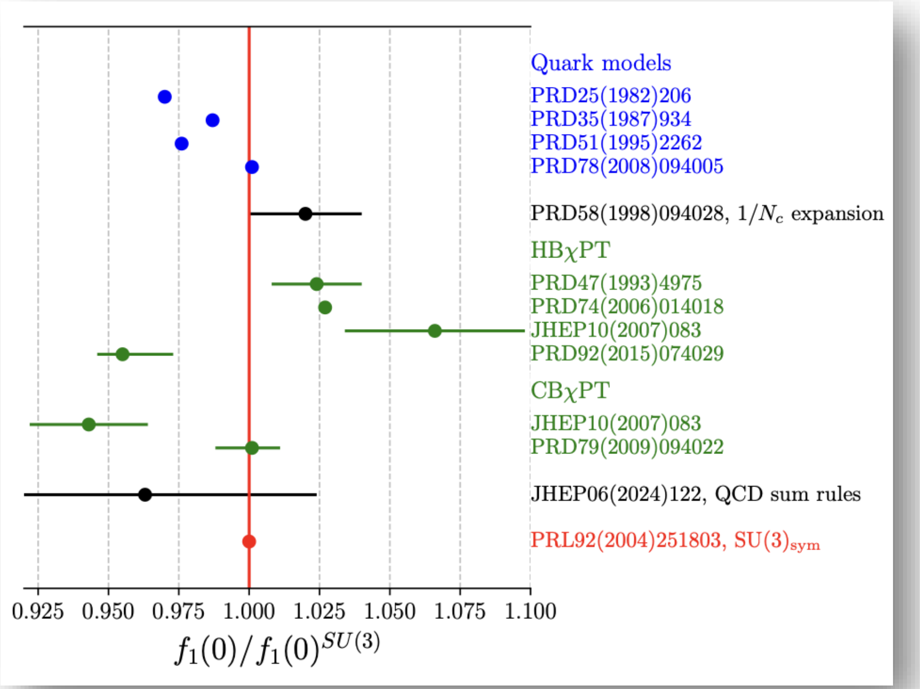
Our focus for this call will be mainly on $\Lambda \to p$ and $\Xi \to \Lambda$

(For CBM@GSI also $\Sigma \to \Lambda$)

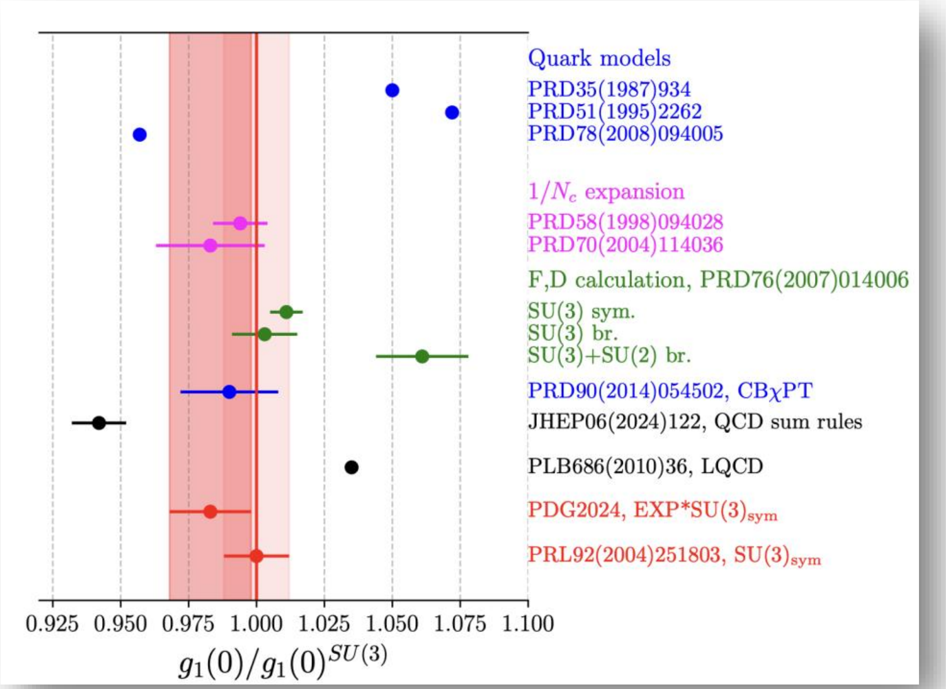
SU(3) breaking effects

If SU(3) is **exact**, then different hyperon sl-decays are related to reduced Form Factors and Clebsch-G. coefficients

$f_{1,SU(3)} = -\sqrt{3/2}$



g1(0) =−(D+ 3F)/√6 =−0.730(12)



V. Batozskaya
Krakow Workshop 25

SU(3) symmetry breaking occurs, but these are interrelated, which means many independent hyperon sl measurements can be used to constrain V_{us}

For semi-leptonics w. electrons f_3 and g_3 are neglected

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BF, FFs, V_{us} and all that jazz

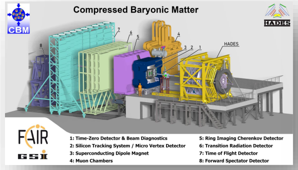
No $\Lambda \to p$ form factor measurements since the 90s. Latest by NA48 and KTeV for $\Xi^0 \to \Sigma^+$

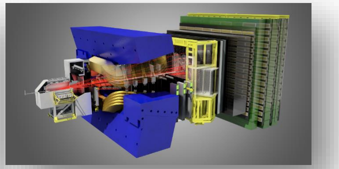
Little theoretical progress since 2005

Our proposal: a *synergy* between LatticeQCD, experiment and theory

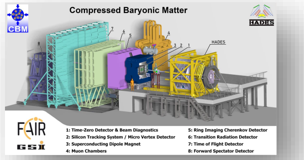
$$\boxed{\mathcal{B}} = \frac{\tau_\Lambda}{\hbar} G_F^2 \left|\boxed{V_{us}}\right|^2 \frac{\beta^5 M_\Lambda{}^5}{60\pi^3}\left[\left(1-\frac{3}{2}\beta\right)\boxed{\left(f_1^2+3g_1^2\right)} - 4\beta \boxed{g_1 g_2} + \frac{2}{7}\beta^2 \mathcal{F}_2 + \mathcal{O}(\beta^3)\right]$$

CBM and LHCb





CBM and LQCD **CBM and LQCD**



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Comment: This was one of the branches that evolved from PrecisionSM of STRONG 2020

What we want to do

$$\boxed{\mathcal{B}} = \frac{\tau_\Lambda}{\hbar} G_F^2 |\boxed{V_{us}}|^2 \frac{\beta^5 M_\Lambda{}^5}{60\pi^3} \left[\left(1 - \frac{3}{2}\beta\right)\boxed{\left(f_1^2 + 3g_1^2\right)} - 4\beta \boxed{g_1 g_2} + \frac{2}{7}\beta^2 \mathcal{F}_2 + O(\beta^3) \right]$$

$$\beta = (M_\Lambda - M_p)/M_\Lambda \sim 0.159 \text{ for } \Lambda \to p l^- \bar{\nu}_l$$

1) Experimentally determine BF (LHCb).

2) Feasibility studies (CBM) BF and f_1/g_1 f_2/f_1.

3) Determine the BF, form factor ratios with LQCD

4) Theory developments (Dyson-Schwinger, quark models, or dispersion theories)

With more precise determination of transition form factors, more precise V_{us} determination

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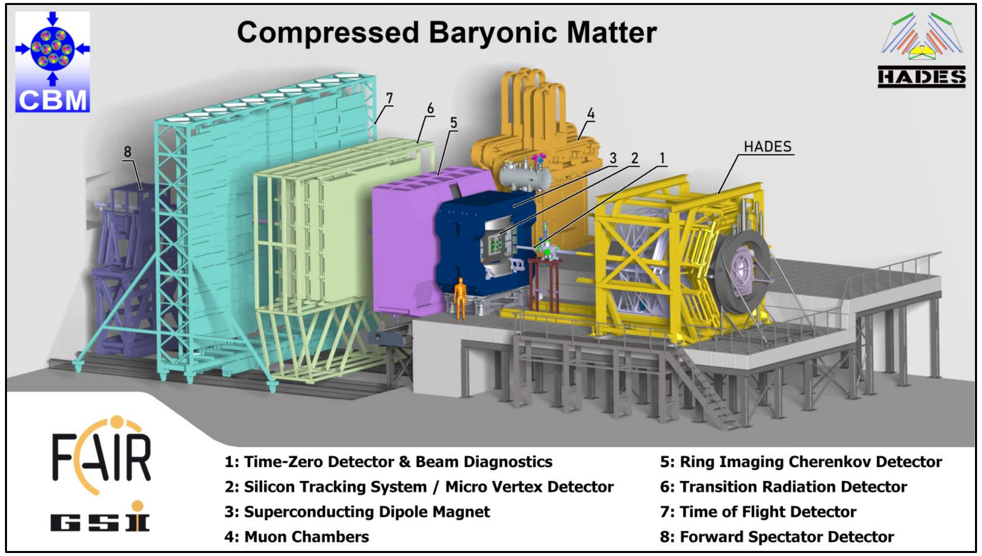
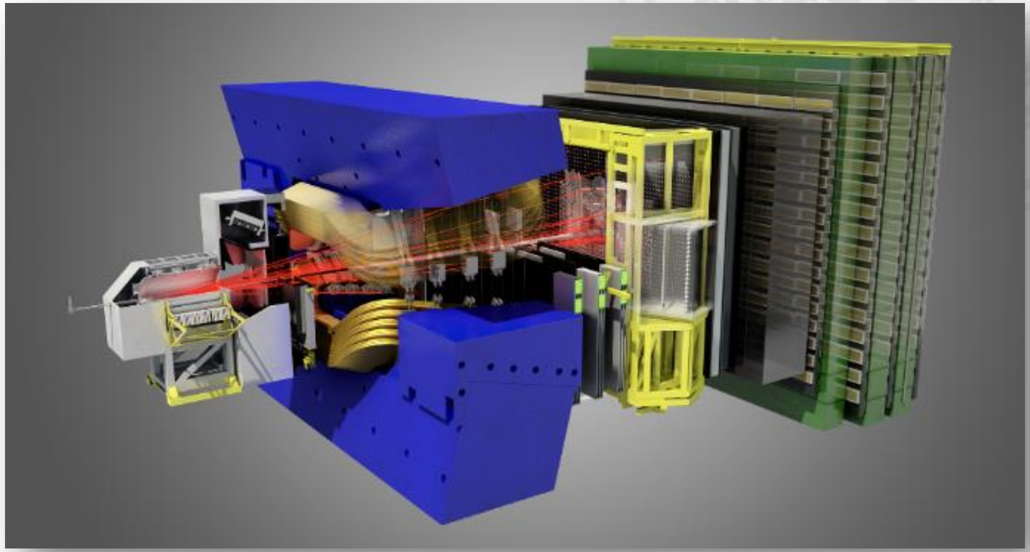
CBM + LHCb





$\Lambda \rightarrow p\, l\, \bar{\nu}_l$ $\quad \Xi \rightarrow \Lambda\, l\, \bar{\nu}_l$ $\quad \Sigma^{\pm} \rightarrow \Lambda\, l^{\pm}\, \bar{\nu}_l$

FAIR: 30 GeV/c @ 10 MHz Interactions, i.e

Ξ $\sigma \cong 40$ μb about 10^5 sl decays/day expected

Semileptonic complemented by Dalitz Decays (transition ff)

Semileptonic unexplored, feasibility studies + pheno needed

$\underline{\Lambda \rightarrow p\, \mu\, \bar{\nu}_\mu}$ $\quad \Xi \rightarrow \Lambda\, \mu\, \bar{\nu}_\mu$

Run 3 data (ends mid-2026)

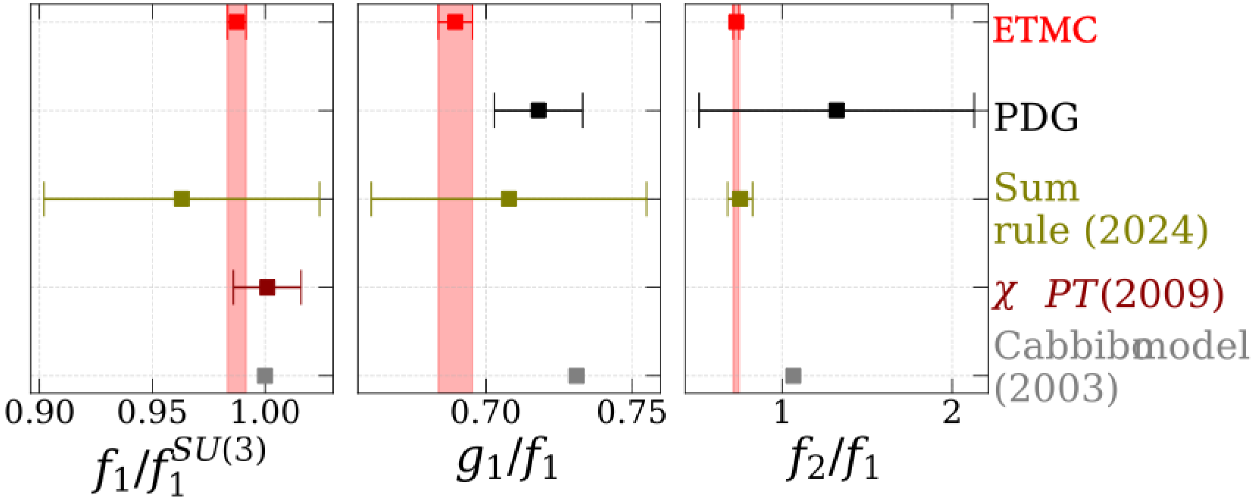
Analysis from Run 2 will be out very soon

Rel BF tot unc ($\Lambda \rightarrow p$) ~3% (now 21%)

Also: Lepton Universality Test as bonus

Lattice QCD Work in Progress

Work in Lattice QCD is already in progress. Analysis led by Constantia Alexandrou and Simone Bacchio



Based on one **state-of-the-art ab initio lattice QCD simulation** using physical quark masses, with all necessary quantities needed in LQCD

No SU(3) symmetry assumptions and **no form factors set to zero (as in the Cabibbo model)**

Results are at a **single lattice spacing**, but **ratios of form factors are expected to be stable.**

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V_{us}

With Lattice and new data, input form factors extract V_{us}

Current precision of V_{us} from mesons, tensions with unitarity and τ decay extractions of V_{us}

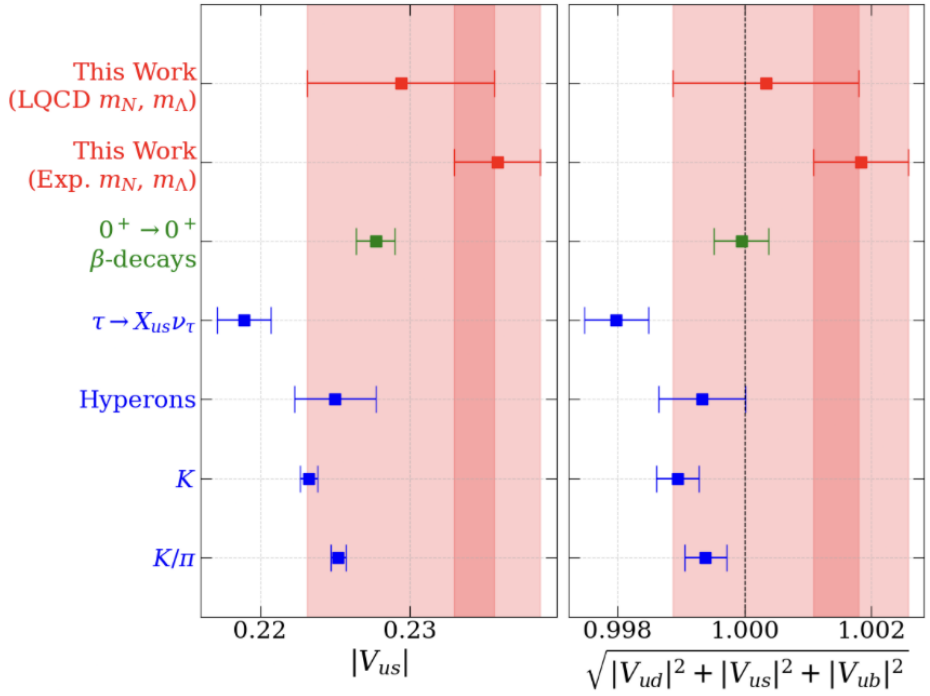
Hyperon V_{us}: stalemate as exp and theory come with large uncertainties

Two ways to extract V_{us}:

$$\text{①} \quad \frac{\mathcal{B}}{\tau_\Lambda} \simeq |V_{us}|^2 f_1^2 \left[(1 - \tfrac{3}{2}\beta)(1 + 3g_{av}^2) + \tfrac{2}{4}\beta^2 \frac{\mathcal{F}_2}{f_1^2} \right]$$

① Experiment: $\{\mathcal{B}, \tau_\Lambda, g_{av}, M_{\Lambda,p}\}$ and Theory: $\{f_1 \text{ or } g_1\}$

② Experiment: $\{\mathcal{B}, \tau_\Lambda, M_{\Lambda,p}\}$ and Theory: $\{f_1, g_1 \to g_{av}\}$



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Preliminary work LQCD

Budget for 4 years

In LoI, we wrote 400 kEUR – now downscaled

Two experimental 2 Ph.D. students and common workshops

1. One Ph.D. student (CBM): **80 kEUR**
Feasibility studies are needed for semileptonic decay for CBM.
Based in Poland
Deliverable: feasibility studies and extraction of form factors

2. One Ph.D. student (LHCb), $\Lambda \to p\ \mu\ \bar{\nu}_\mu$ **BF~3% total uncertainty** **100 kEUR**
Based in Poland but with research visits to *Universidade da Coruña, Uppsala University*
Deliverable: Publication in OA journal on Run 3 data

3. Four workshops (4 x 15 kEUR) (ECT*) **60 kEUR**
Common meetings between theory, phenomenology, experiment and LatticeQCD

SUM **240 kEUR**

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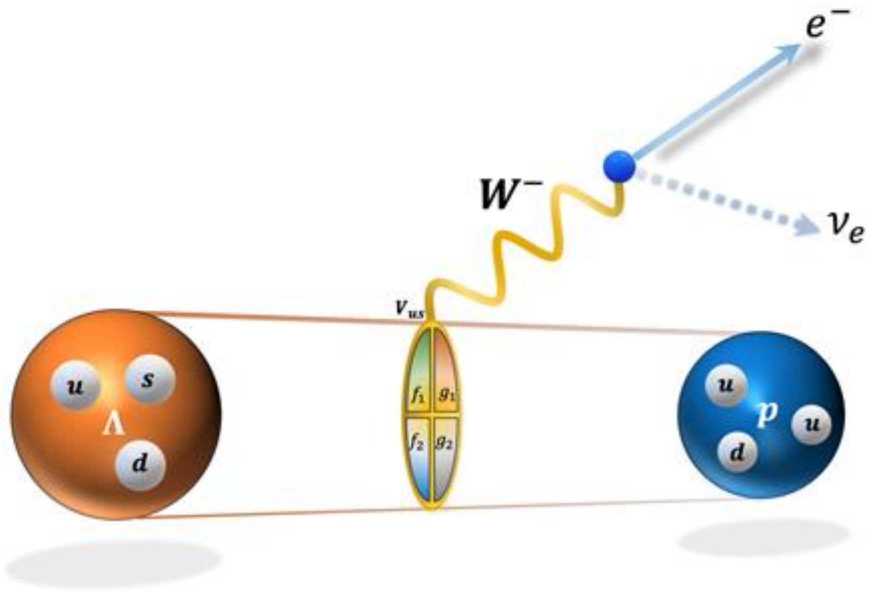
Thank you for your attention



1) Experimentally determine BF (LHCb). 100kEUR

2) Feasibility studies (CBM) and determination BF and f_1/g_1 f_2/f_1. 80 kEUR

3) Determine the BF, form factor ratios with LQCD

4) Theory and phenomenology developments

60 kEUR

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Spare Slides

Weak Transition Form Factors

Semi-leptonic hyperon decays $B_1 \rightarrow B_2\, l\, \bar{\nu}_l$

Weak transitions for spin-½ baryons, has vector (V) and axial-vector currents (A)

$$\langle B_2|V_\alpha|B_1\rangle = \boxed{V_{CKM}}\, \bar{u}_{B_2}(p_2)\left[\boxed{f_1(q^2)}\,\gamma_\alpha + \frac{\boxed{f_2(q^2)}}{M_1}\sigma_{\alpha\beta}q^\beta + \frac{\boxed{f_3(q^2)}}{M_1}q_\alpha\right]u_{B_1}(p_1)$$

$$\langle B_2|A_\alpha|B_1\rangle = \boxed{V_{CKM}}\, \bar{u}_{B_2}(p_2)\left[\boxed{g_1(q^2)}\,\gamma_\alpha + \frac{\boxed{g_2(q^2)}}{M_1}\sigma_{\alpha\beta}q^\beta + \frac{\boxed{g_3(q^2)}}{M_1}q_\alpha\right]\gamma_5 u_{B_1}(p_1)$$

q four-momentum transfer

f_1 - vector g_1 - axial vector	f_2 – weak magn ff g_2 – electricity ff	f_3 – induced sc g_3 – induced psc

Transition depends on six q^2 dependent form factors, 3 vector and 3 axial vector

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PRD 70, 114036 (2004)

Semi-leptonic decays

	Process	ΔM [MeV]	ΔS	μ-mode	BF(e-mode) $\times 10^{-5}$
1	$\Sigma^+ \to \Lambda e^+ \nu_e$	74	0	–	2
2	$\Sigma^- \to \Lambda e^- \bar{\nu}_e$	82	0	–	6
3	$\Lambda \to p e^- \bar{\nu}_e$	177	1	yes	83
	$\Sigma^- \to n e^- \bar{\nu}_e$	258	1	yes	107
4	$\Xi^- \to \Lambda e^- \bar{\nu}_e$	206	1	yes	56
	$\Xi^- \to \Sigma^0 e^- \bar{\nu}_e$	129	1	yes	9
	$\Xi^0 \to \Sigma^+ e^- \bar{\nu}_e$	126	1	yes	25
	$\Xi^- \to \Xi^0 e^- \bar{\nu}_e$	7	0	–	–
	$\Sigma^- \to \Sigma^0 e^- \bar{\nu}_e$	5	0	–	–
5	$\Sigma^- \to p \pi^- e^- \bar{\nu}_e$	120	1	yes	–
6	$\Xi^0 \to \Lambda \pi^+ e^- \bar{\nu}_e$	64	1	–	–
	$\Omega^- \to \Xi^0 e^- \bar{\nu}_e$	357	1	yes	560
7	$\Omega^- \to \Xi^{*0} e^- \bar{\nu}_e$	142	1	yes	–

Motivation- LU tests

TABLE II. SHD data for $g_1(0)/f_1(0)$ and theoretical determinations of $f_{S,T}(0)/f_1(0)$ at $\mu = 2$ GeV used in this work. The corresponding $r_{S,T}$ are shown in the last two lines.

	$\Lambda \to p$	$\Sigma^- \to n$	$\Xi^0 \to \Sigma^+$	$\Xi^- \to \Lambda$
$g_1(0)/f_1(0)$	0.718(15)	−0.340(17)	1.210(50)	0.250(50)
$f_S(0)/f_1(0)$	1.90(10)	2.80(14)	1.36(7)	2.25(11)
$f_T(0)/f_1(0)$	0.72	−0.28	1.22	0.22
r_S	1.60	4.1	0.56	3.7
r_T	5.2	1.7	7.2	1.1

PRL 114, 161802 (2015)

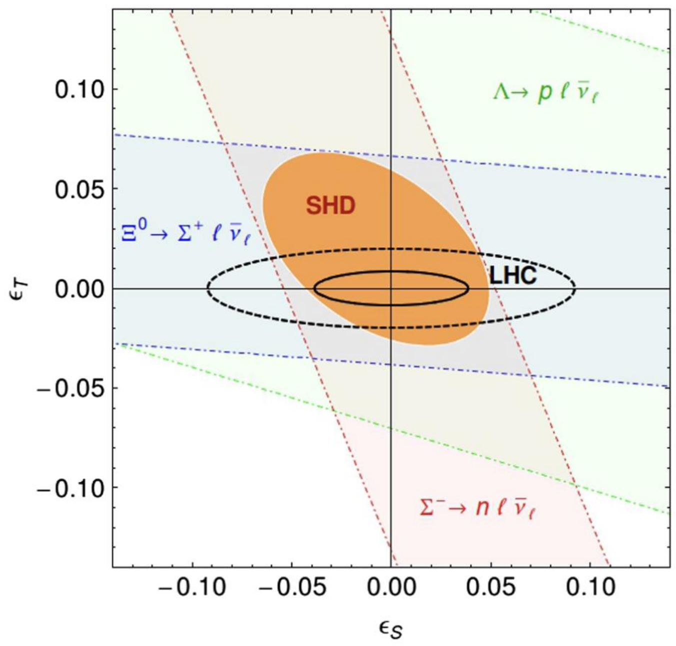


FIG. 1 (color online). 90% C.L. constraints on $\epsilon_{S,T}$ at $\mu = 2$ GeV from the measurements of $R^{\mu e}$ in different channels (dot-dashed lines) and combined (filled ellipse). LHC bounds obtained from CMS data at $\sqrt{s} = 8$ TeV (7 TeV) are represented by the black solid (dashed) ellipse.

$$R^{\mu e} = \frac{\Gamma(B_1 \to B_2 \mu^- \bar{\nu}_\mu)}{\Gamma(B_1 \to B_2 e^- \bar{\nu}_e)} \qquad \frac{R^{\mu e}}{R^{\mu e}_{\rm SM}} = 1 + r_S \epsilon_S + r_T \epsilon_T$$

$$\epsilon_S = 0.003(40), \qquad \epsilon_T = 0.017(34)$$ at 90% CL from SLWD

$$\sigma(pp \to e + \mathrm{MET} + X)$$

Potential for $|V_{us}|$ determination and test of BSM searches from determination of Wilson coefficients ε_S and εT

Nice example where precision experiments combine with direct searches in collider experiments, CMS

Nonstandard Semileptonic Hyperon Decays

Potential for precise constraint on BSM from Semi-leptonic hyperon decays

$$\mathcal{L}_{\text{eff}} = -\frac{G_F V_{us}}{\sqrt{2}}(1+\epsilon_L+\epsilon_R)\sum_{\ell=e,\mu}\{\bar{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell\cdot\bar{u}[\gamma^\mu-(1-2\epsilon_R)\gamma^\mu\gamma_5]s$$
$$+\bar{\ell}(1-\gamma_5)\nu_\ell\cdot\bar{u}[\epsilon_S-\epsilon_P\gamma_5]s+\epsilon_T\bar{\ell}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell\cdot\bar{u}\sigma^{\mu\nu}(1-\gamma_5)s\}+\text{H.c.}$$

Beyond the SM, the most general effective Lagrangian*

Assuming NP above electroweak symmetry breaking scale 246 GeV one is left with Wilson Coefficients, ε assuming real since CP-even

$$\Gamma_{e,\text{SM}} \simeq \frac{G_F^2|V_{us}f_1(0)|^2\Delta^5}{60\pi^3}\left[\left(1-\frac{3}{2}\delta\right)+3\left(1-\frac{3}{2}\delta\right)\frac{g_1(0)^2}{f_1(0)^2}-4\delta\frac{g_2(0)}{f_1(0)}\frac{g_1(0)}{f_1(0)}\right]$$

Δ and δ mass dep. terms, vector FF: $f_1(q^2\sim0)$ - $f_3(0)$ axial vector FF $f_1(0)$ - $g_3(0)$
In electron mode f_3 and g_3 scale with m_e/m_Λ

PRL 114, 161802 (2015)

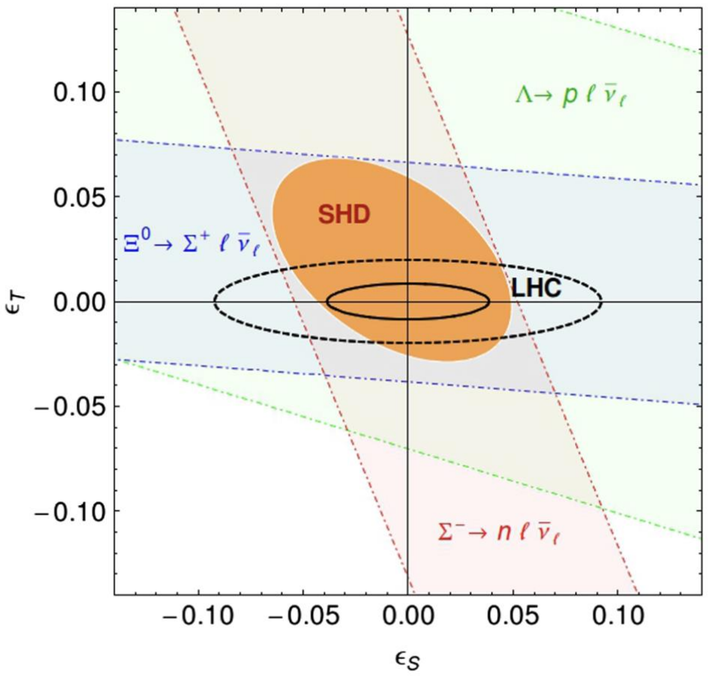
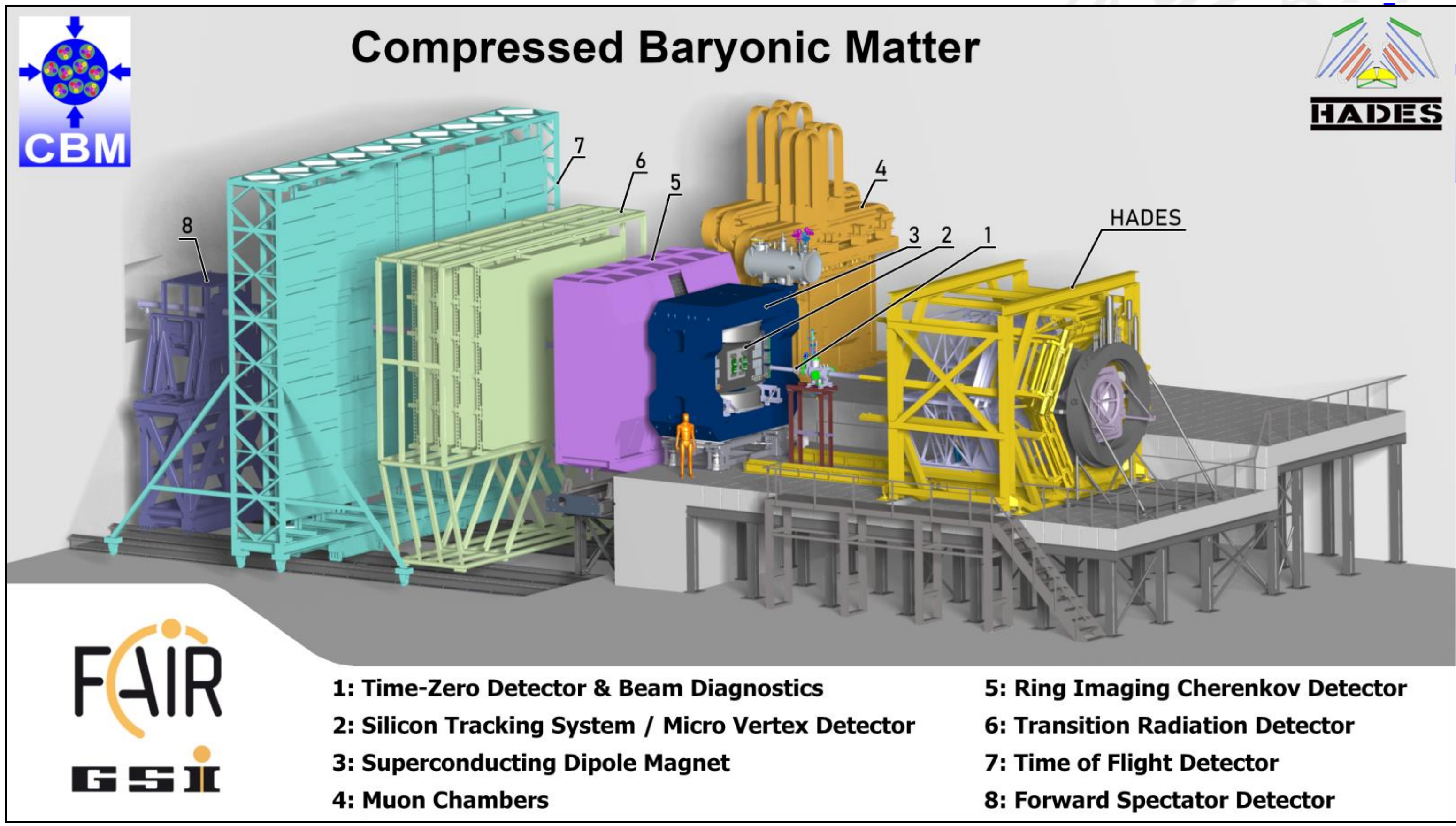


FIG. 1 (color online). 90% C.L. constraints on $\epsilon_{S,T}$ at $\mu = 2$ GeV from the measurements of $R^{\mu e}$ in different channels (dot-dashed lines) and combined (filled ellipse). LHC bounds obtained from CMS data at $\sqrt{s} = 8$ TeV (7 TeV) are represented by the black solid (dashed) ellipse.

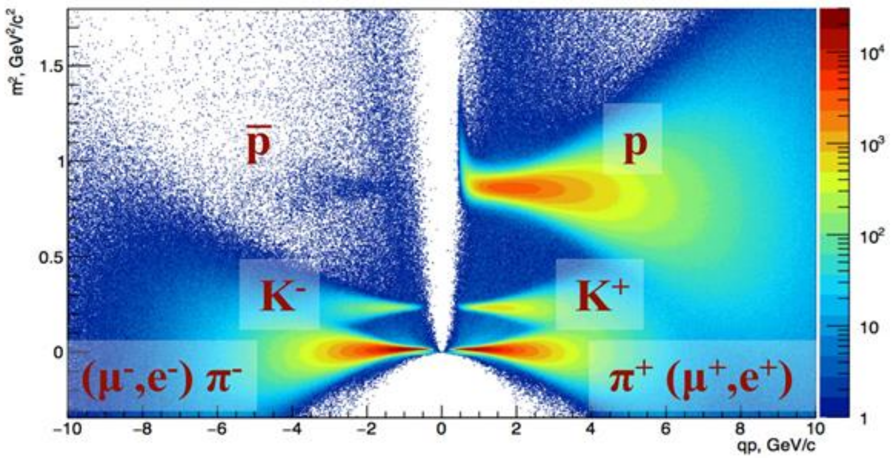
* Neglecting O(ε2), only SM field relevant at μ=1 GeV, demanding operators color and EM singlets

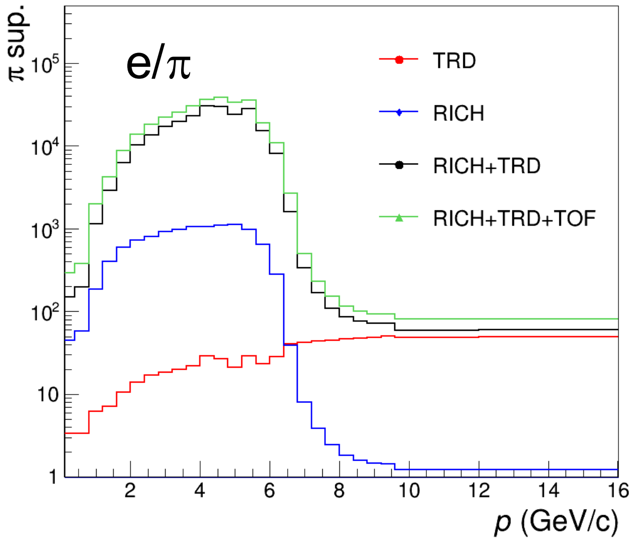
CBM

- Fixed target experiment at FAIR
  - Proton beam p_{max}=30 GeV/c
  - Beam intensity up to $10^{13} p/s$
- Versatile detector systems
  - PID: e/π/K/p
- Tracking based entirely on silicon
  - Δp/p < 2% (p > 1 GeV/c, 1 Tm field)
  - Vertex resolution ~ 50 μm (MVD)
- Free-streaming read-out 10 MHz
  - nearly dead-time free data-taking
- Online event selection
  - highly selective data reduction

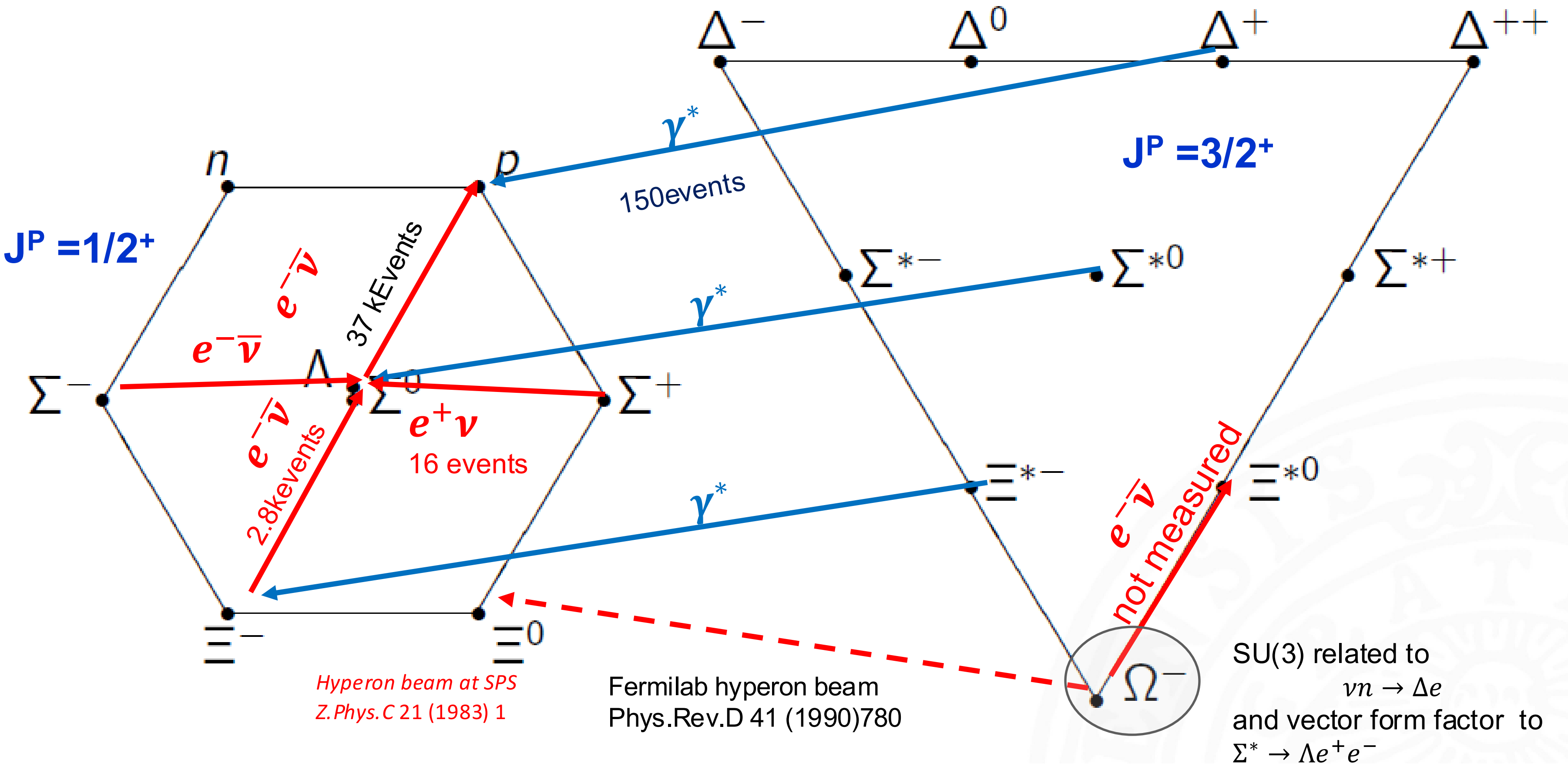


PID (TOF) hadrons





Electromagnetic and Weak (semileptonic) transistions



- PDG for Λ and Ξ semileptonic decays entries based on 1-2 experiments with hyperon beams

FAIR: 30 GeV/c @ 10 MHz Interactions , i.e Ξ σ ≅40 μb and BR=10^{-4} about 10^5 decays/day expected

exclusive reconstruction : e.g: pp→$pK^+K^+\Xi^-(\to \Lambda e^-\bar{\nu})$, pp→$pK^+\Lambda\ (\to pe^-\bar{\nu})$

- Semileptonic decays and Dalitz have similar BR ~O(10^{-4} -10^{-5})

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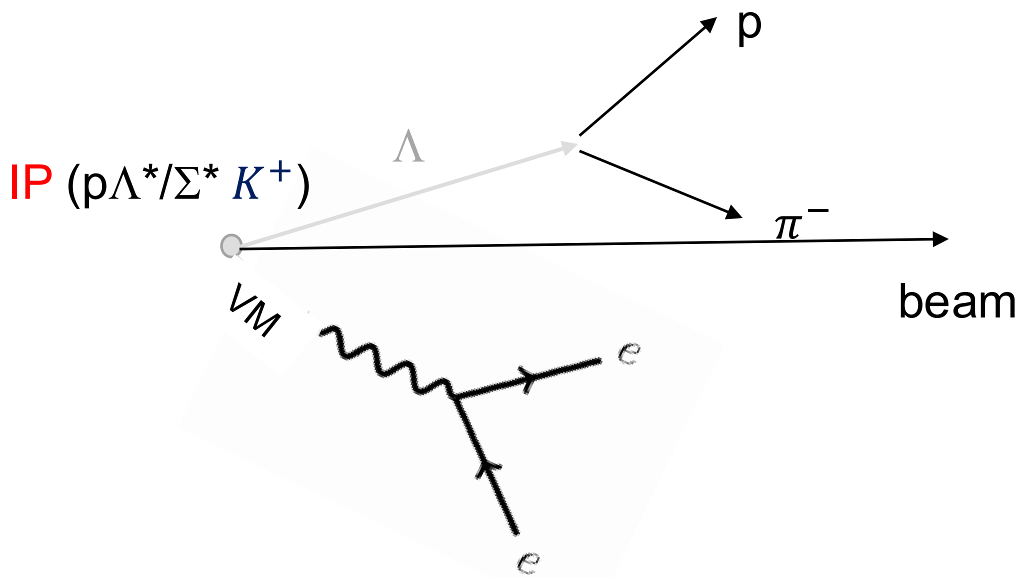
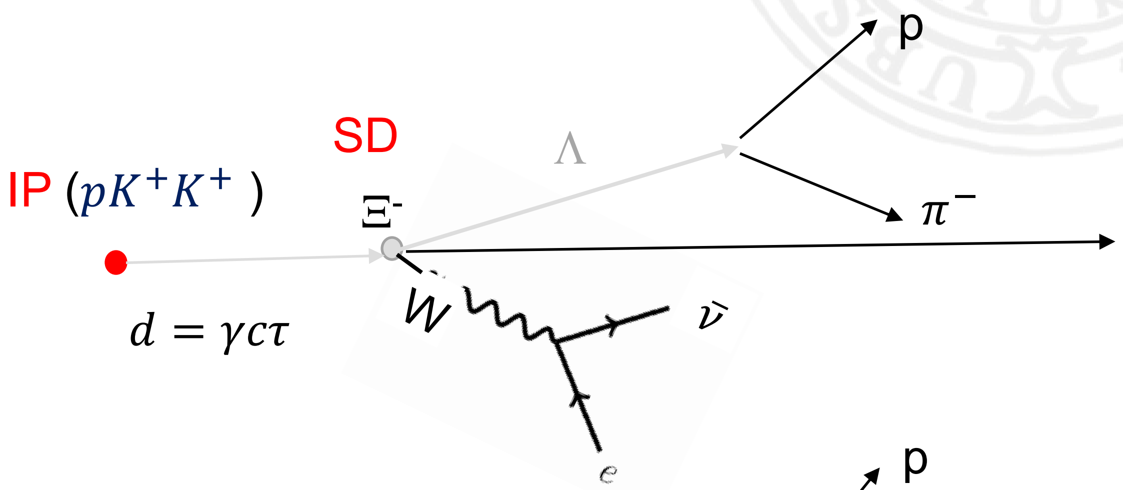
Decay patterns: semileptonic vs Dalitz

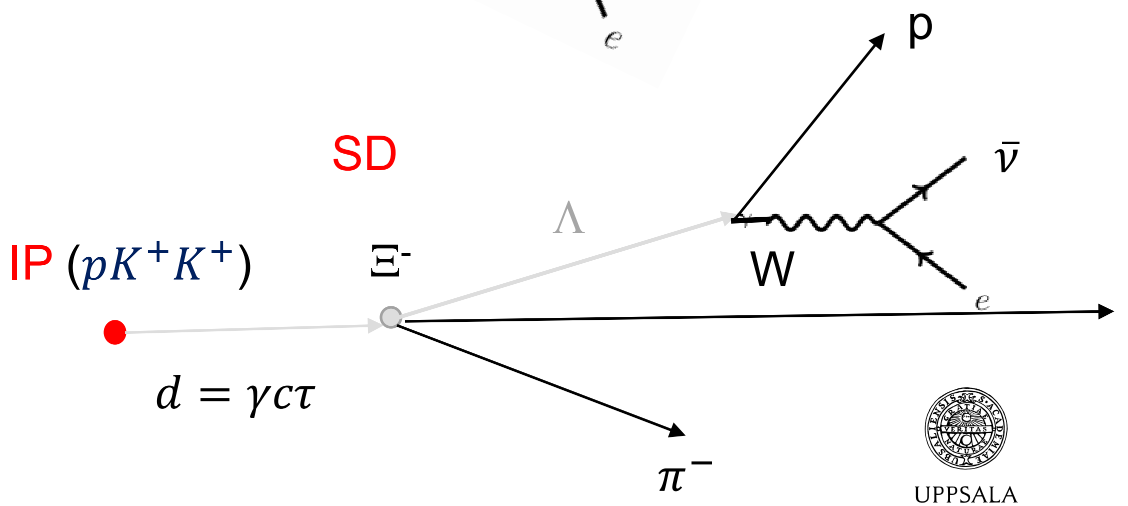
Dalitz (electromagnetic transition form-factors)



Semileptonic (vector and axial form-factors)

Polarization of the outgoing (Λ) baryon can be measured





- Transition form factors of baryons (vector): Dalitz decays e.g $\Lambda^*/\Sigma^* \to \Lambda/\Sigma\, l^+l^-$
- Semileptonic weak transistions in $1/2^+$ octet: Vector (f_1, f_2) and Axial Vector (g_1) form factors
- Feasibility studies : exclusive reconstruction:

Vertex separation (IP-SD), e/π, correlated background ($\Lambda\,\pi^0$,..), offline trigger

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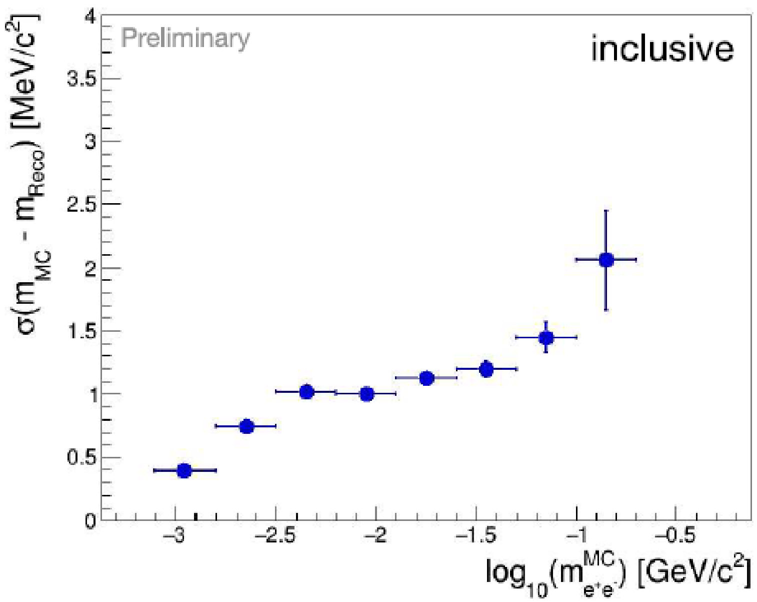
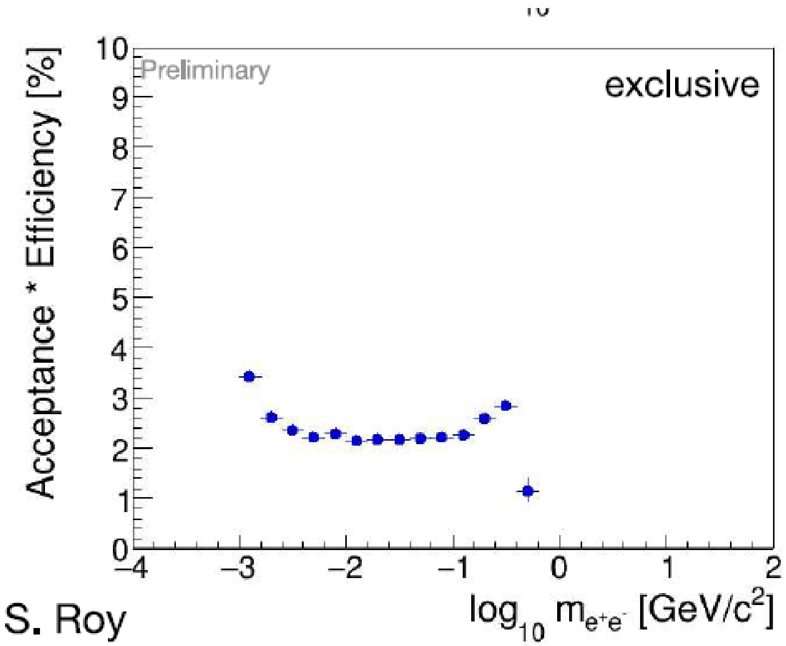
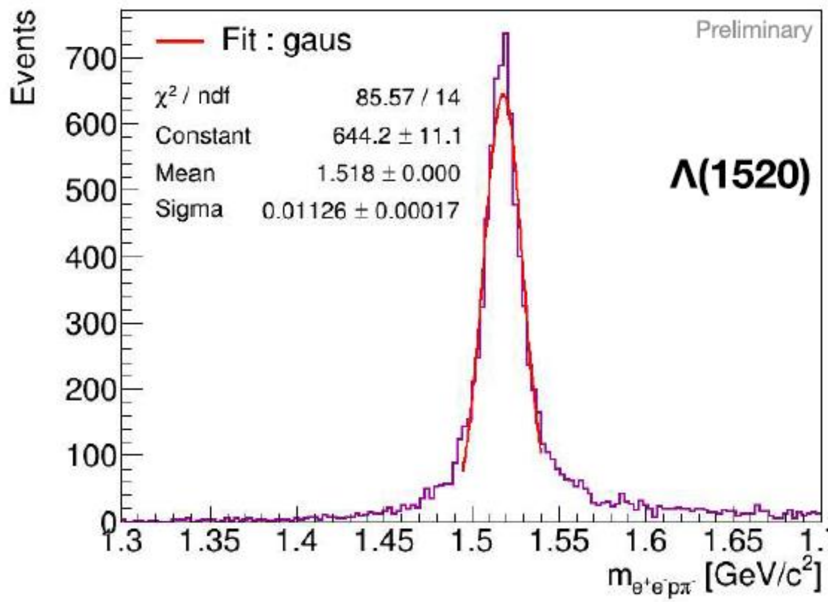
Polarization of the incoming (Ξ) baryon can be measured

Performance plots: Dalitz Decay of $pK^+\Lambda^*(1520)(\to \Lambda\, e^+e^-)$ Acceptance, resolutions





S. Roy



Large acceptance, very good mass resolutions- as a starting point to more challenging semileptonic decays

Feasibility studies are needed for semileptonic decay for CBM. Besides experimental aspects, important is the development of methods to extract g_1/f_1 , f_1/f_2 from data requires methods to be developed by Uppsala

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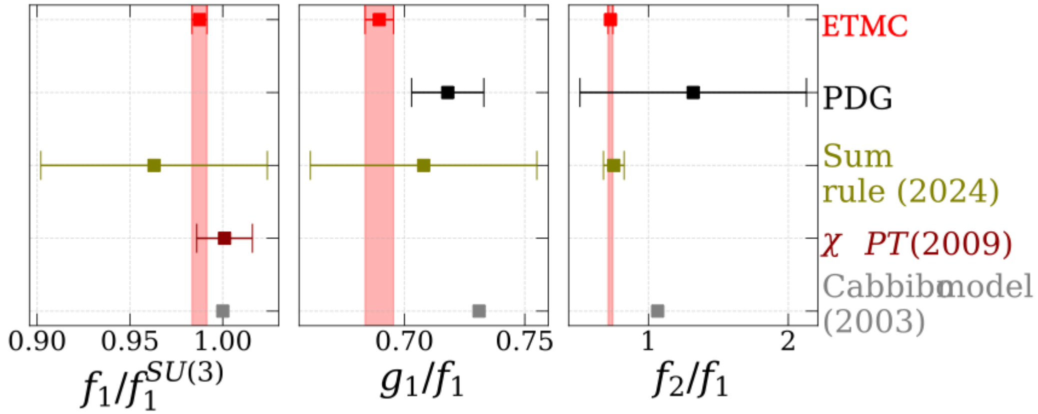
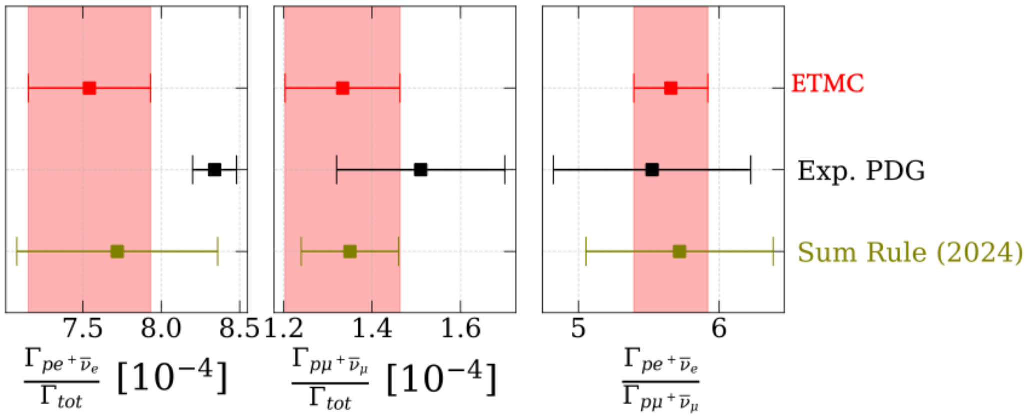
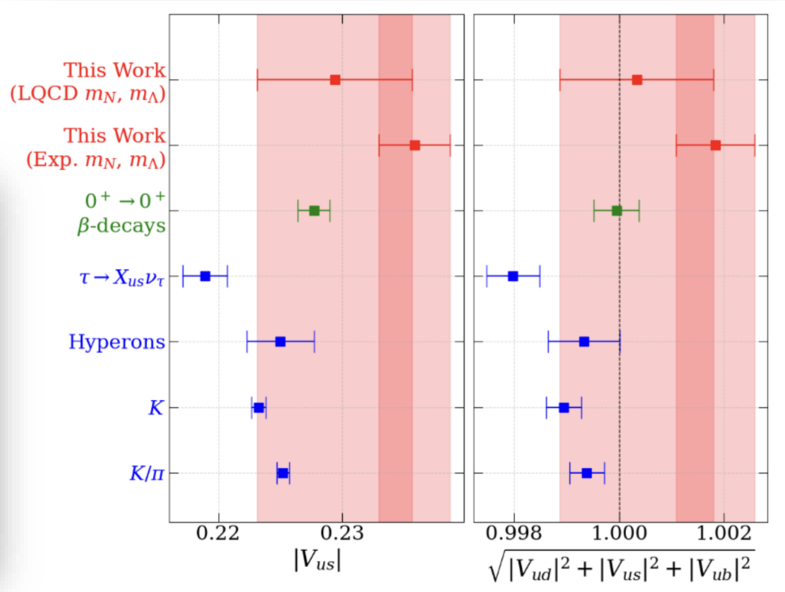
Lattice QCD all plots





f_1	f_2	f_3
1.2028(64)	0.878(20)	1.662(25)
$\langle r^2_{F_1} \rangle$	$\langle r^2_{F_2} \rangle$	$\langle r^2_{F_3} \rangle$
4.99(39)	14.3(16)	11.22(38)
g_1	g_2	g_3
0.8329(70)	-0.062(29)	-5.26(14)
$\langle r^2_{G_1} \rangle$	$\langle r^2_{G_2} \rangle$	$\langle r^2_{G_3} \rangle$
5.17(62)	7(43)	22.2(15)



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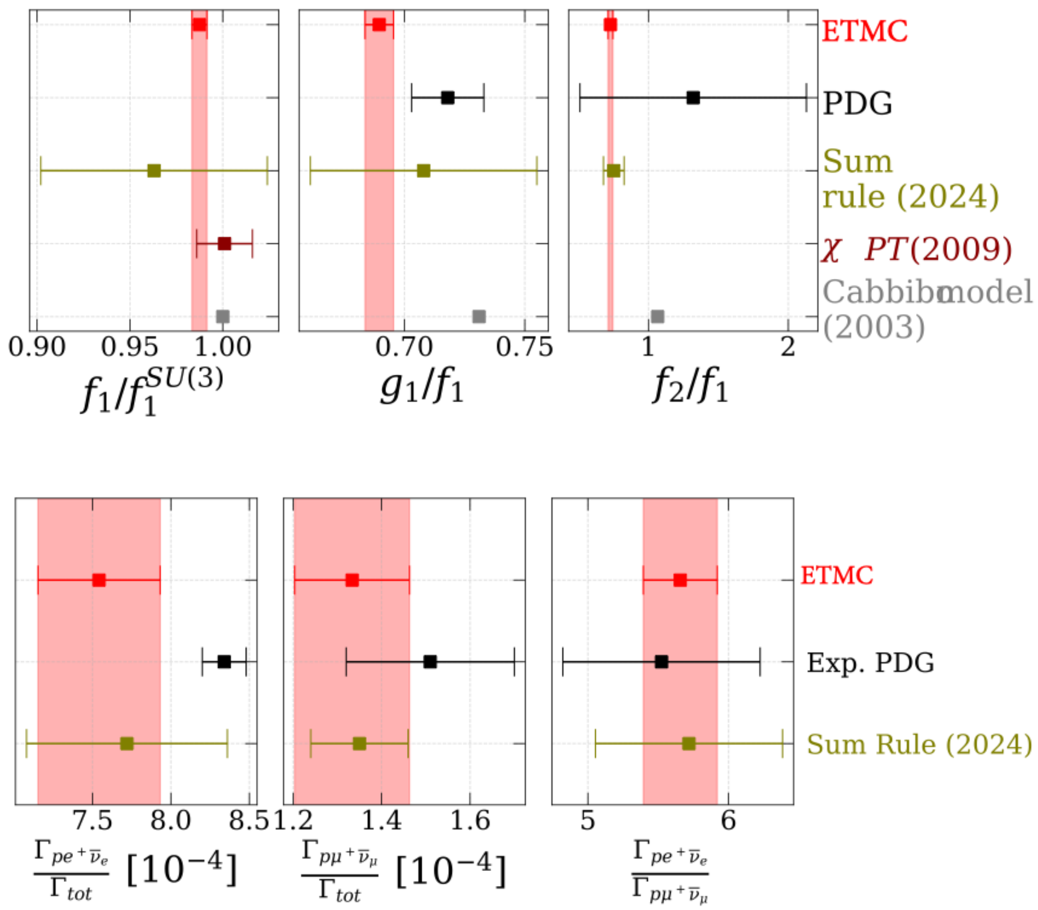
Lattice QCD all plots



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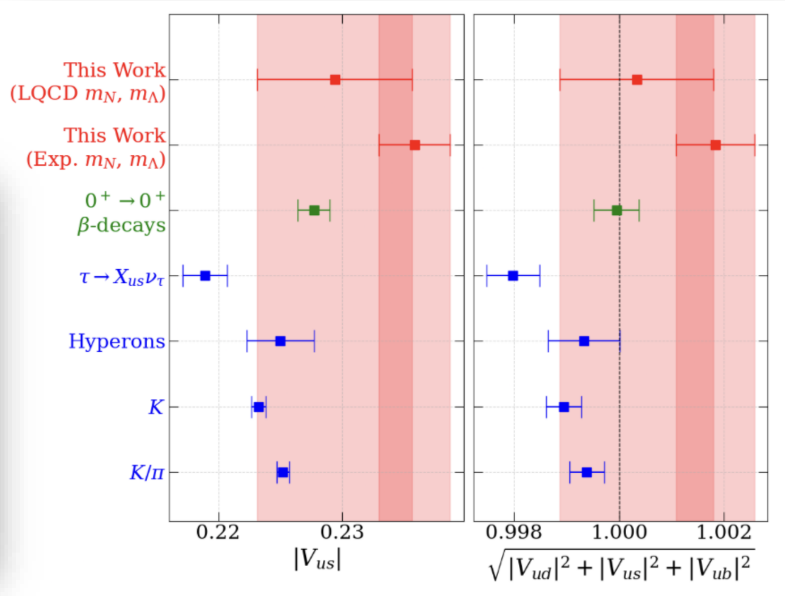

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