Precision Studies of Heavy Baryons

Lattice 2026, University of Maryland

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Indian Institute of Science
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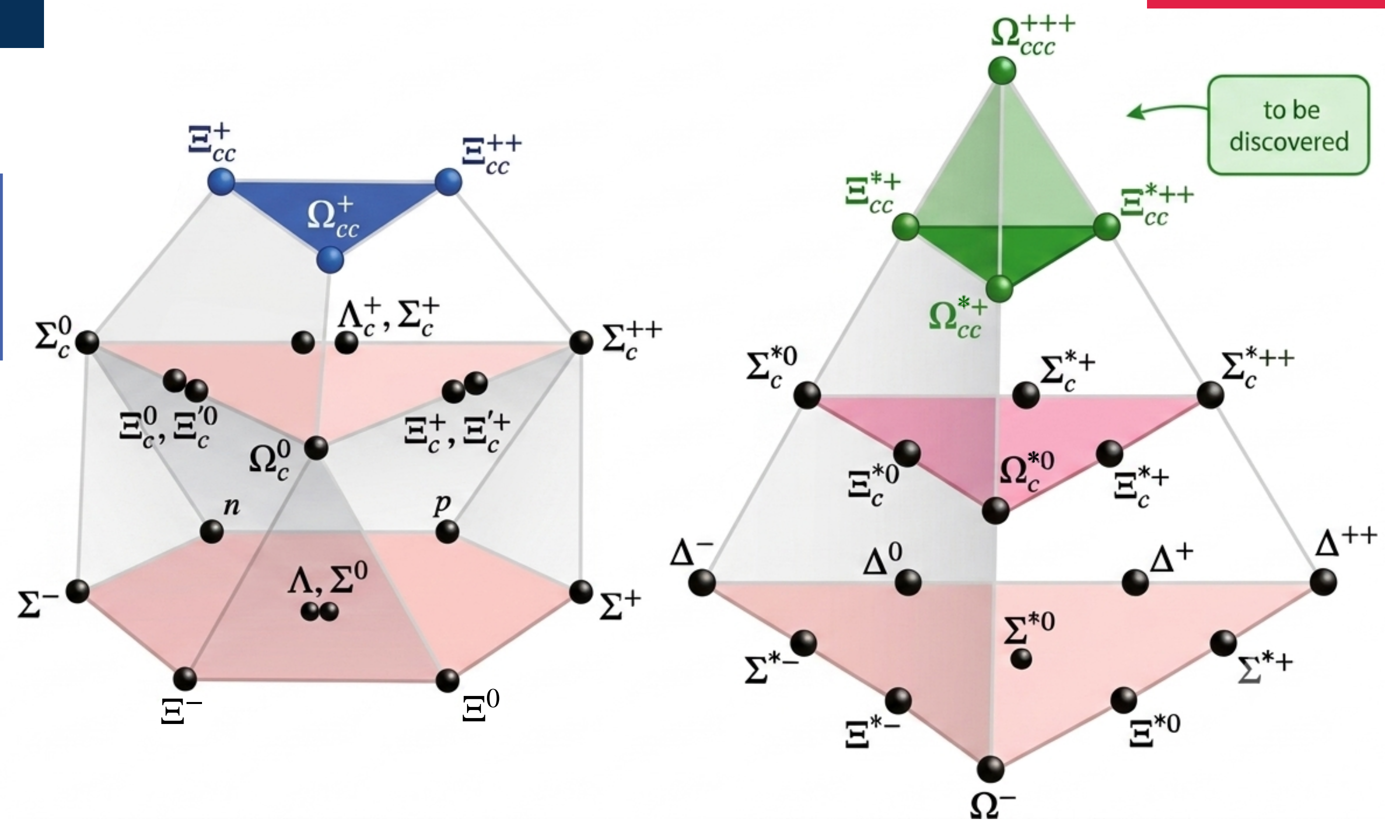
In collaboration with: Gunnar Bali, Sara Collins, Nilmani Mathur, Wolfgang Söldner

Heavy Baryons

Experimental Status

Established Ξ_{cc}^{++} in 2017, but the other two remained inconclusive



Charm Sector

Heavy Baryons

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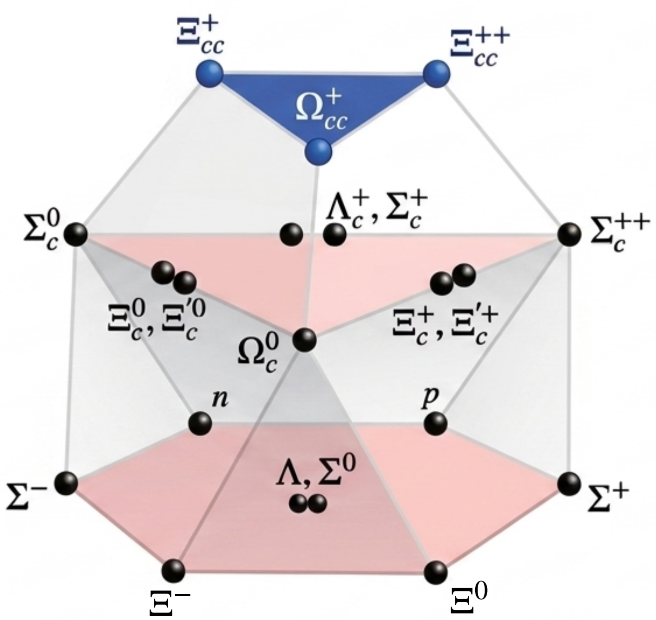
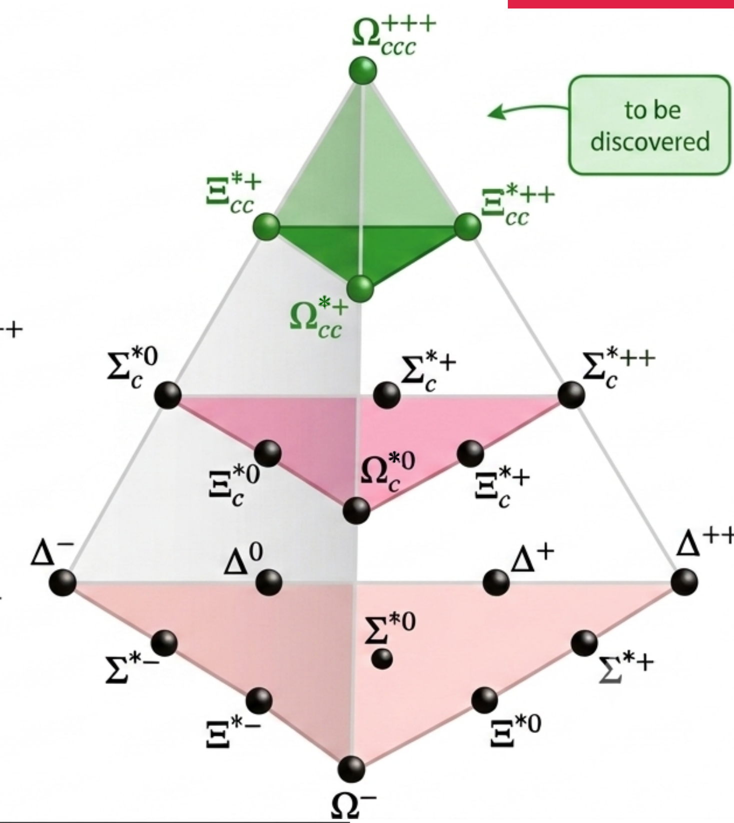
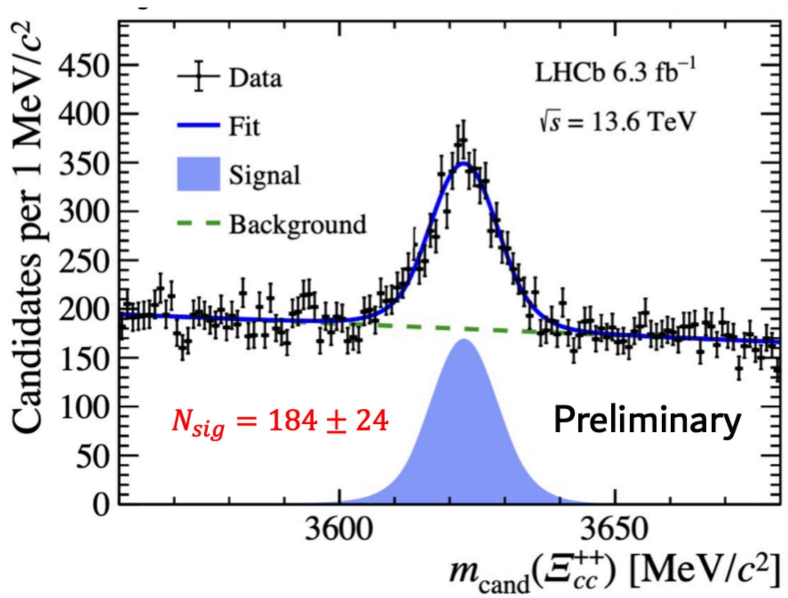
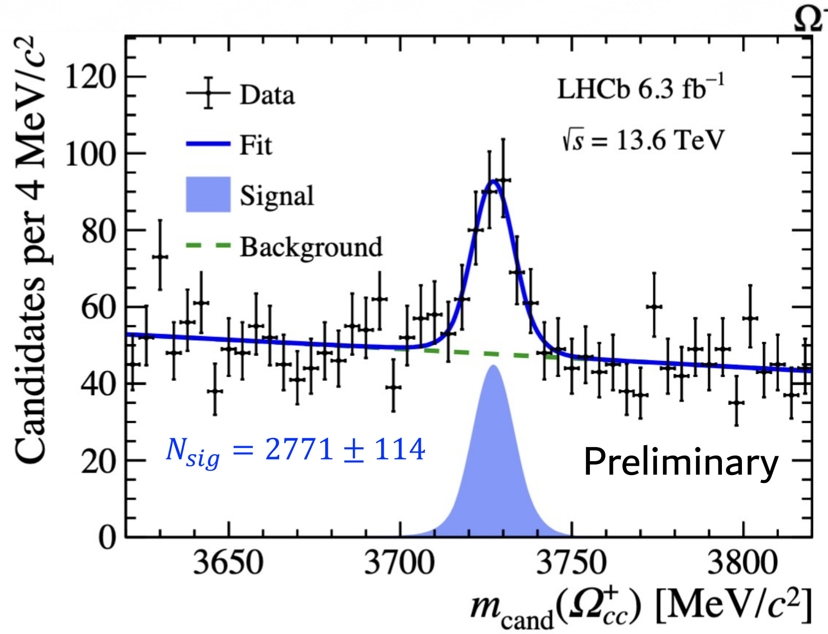




Charm Sector





Missing Doubly Charmed baryons!

Yuhao Wang : Talk, Beauty 2026

PHYSICAL REVIEW LETTERS **137,** 021902 (2026)

Observation of the Doubly Charmed Baryon Ξ_{cc}^{+} with the LHCb Run 3 Detector

R. Aaij *et al.*[*]
(LHCb Collaboration)

(Received 31 March 2026; revised 7 May 2026; accepted 9 June 2026; published 8 July 2026)

CONFERENCE LATEST POSTS OTHER PHYSICS RESULTS

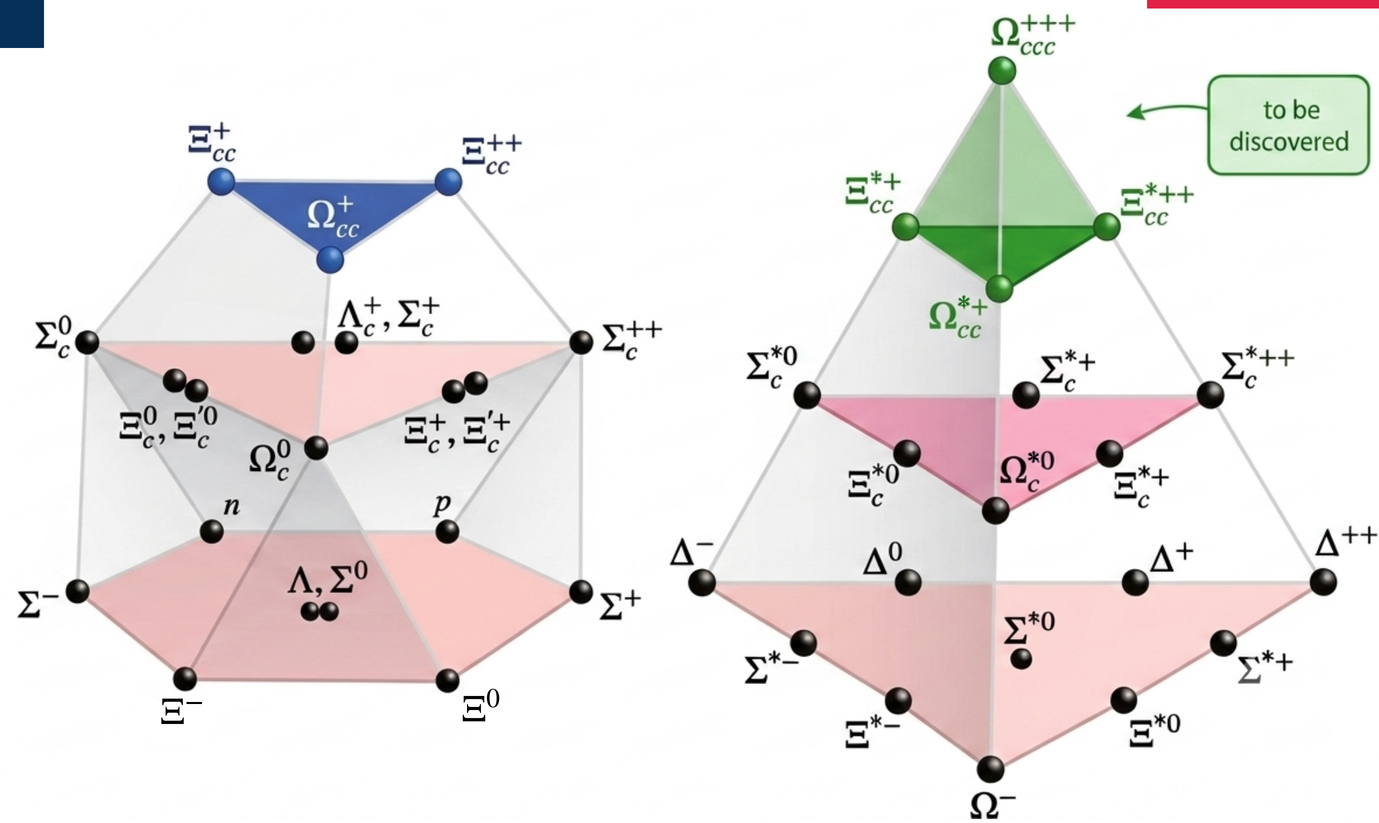
Observation of the doubly charmed baryon Ω_{cc}^{+}

By **Bolek Pietrzyk**
JUN 3, 2026 #baryon, #charm, #omegacc

Heavy Baryons

Experimental Status

All three now seen by LHCb



Charm Sector

Bottom Sector

ssb

	J^P	
Ω_b^-	$1/2^+$	***
$\Omega_b(6316)^-$		***
$\Omega_b(6330)^-$		***
$\Omega_b(6340)^-$		***
$\Omega_b(6350)^-$		***

3/2+ resonance has not been observed

Heavy quark flavor symmetry implies the spectroscopy of the bottom baryons is expected to be similar, up to corrections of order $\Lambda_{QCD}/m_{c,b}$

The ground-state charmed-baryon spectrum at the physical point

- Using CLS ensembles that span a wide range in the quark mass plane along three trajectories to get a complete light/strange and charm quark mass dependence.
- Analyzing the two-point correlation functions to extract the ground state.
- Use SU(3) constraints to quantify light/strange quark mass dependence.
- Perform a combined chiral-continuum extrapolation.

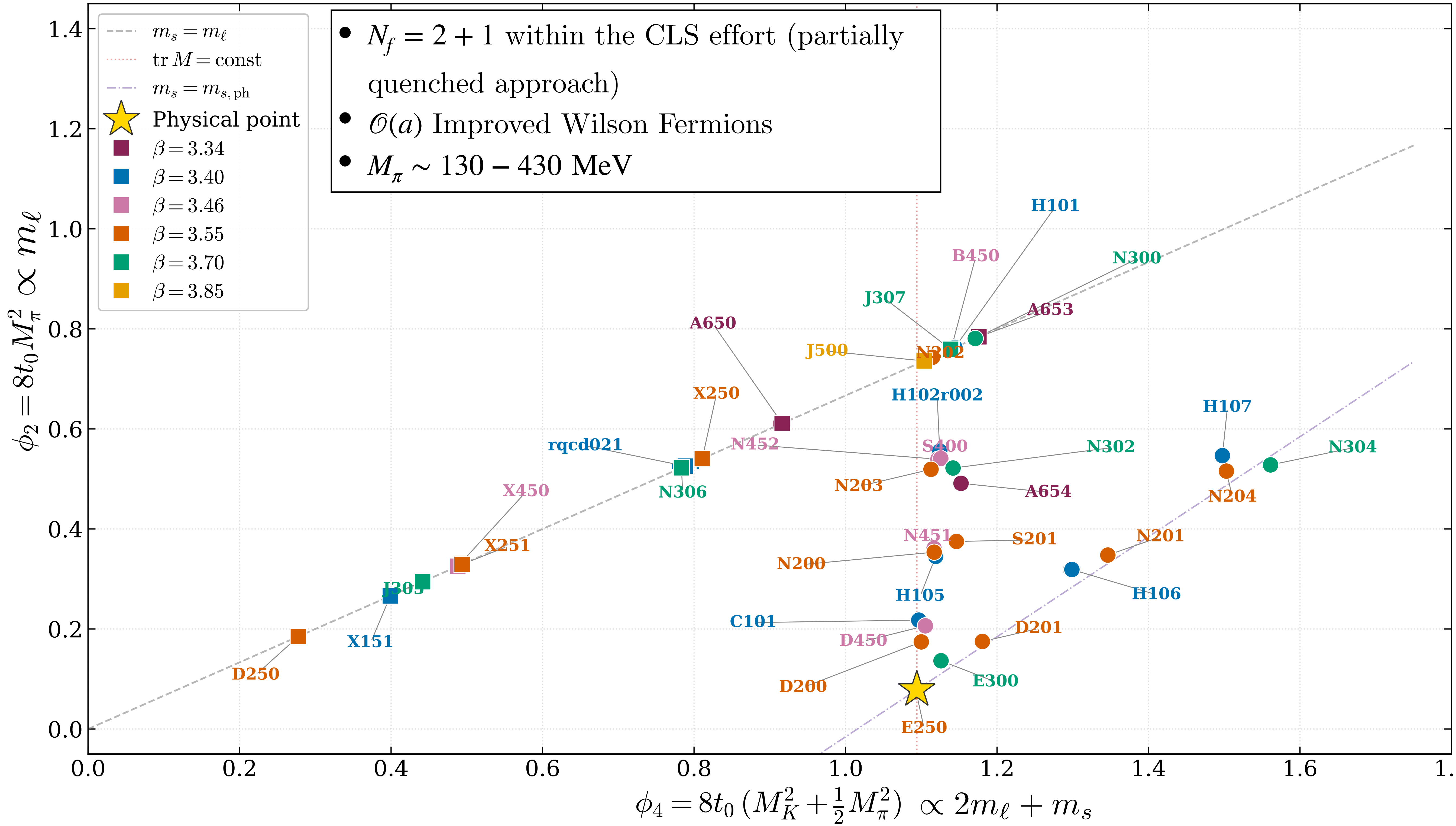
$N_f = 2+1$ CLS Ensembles

Quark Mass Plane

good coverage of the quark mass plane

controlled chiral extrapolation towards the physical point

- $N_f = 2+1$ within the CLS effort (partially quenched approach)
- $\mathcal{O}(a)$ Improved Wilson Fermions
- $M_\pi \sim 130 - 430$ MeV



Archana Radhakrishnan, IISc

$N_f = 2+1$ CLS Ensembles

Quark Mass Plane

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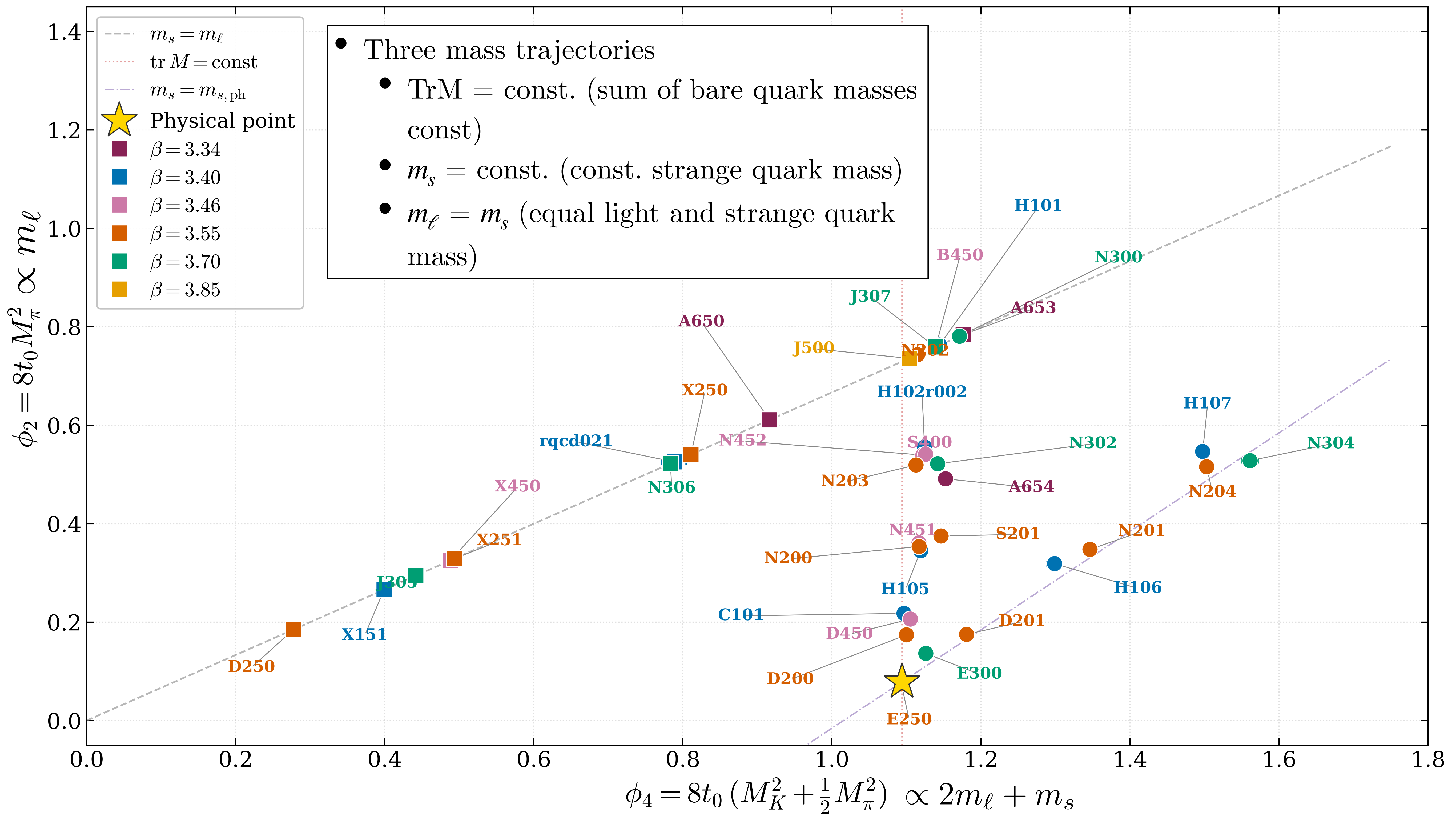
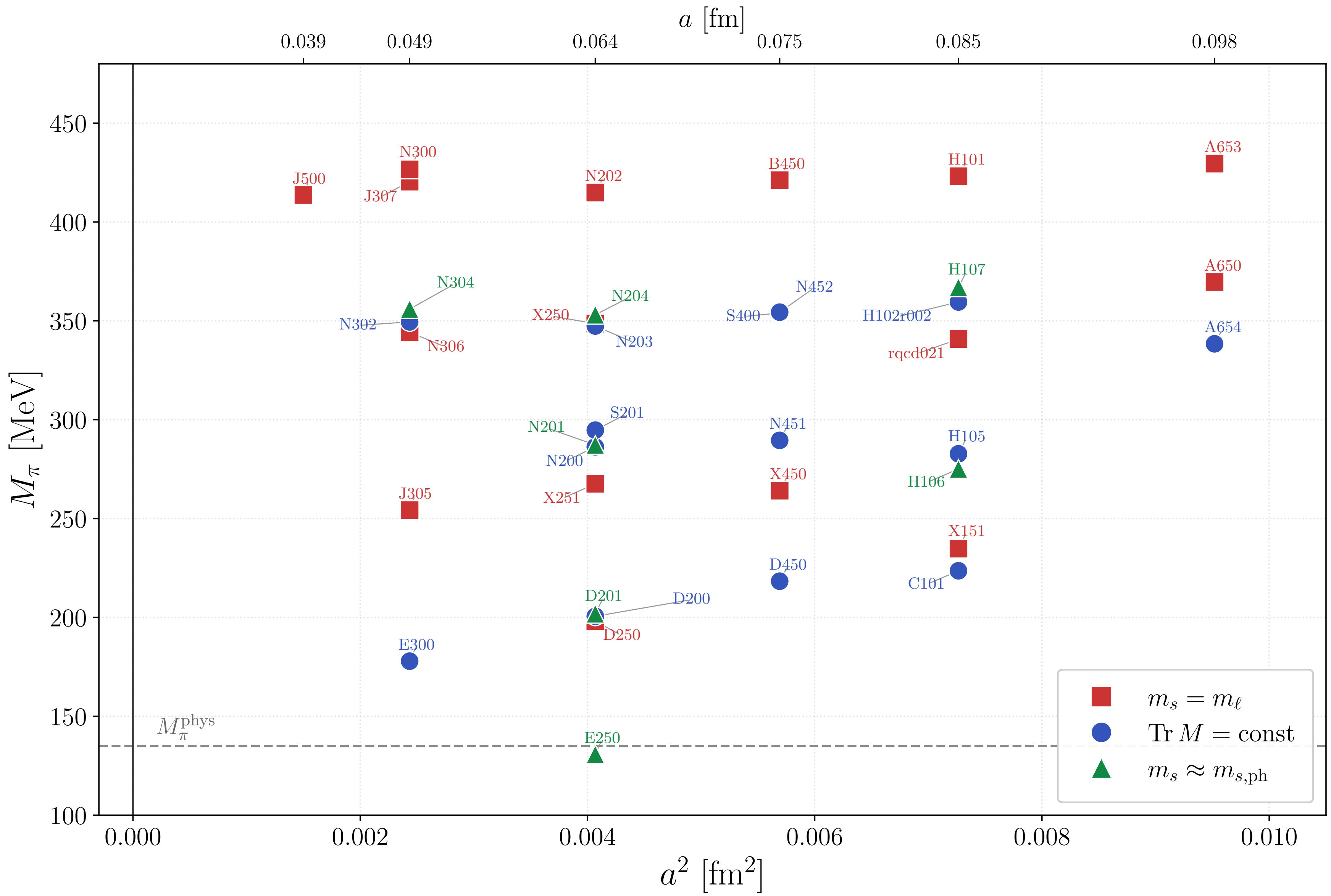
controlled chiral extrapolation towards the physical point



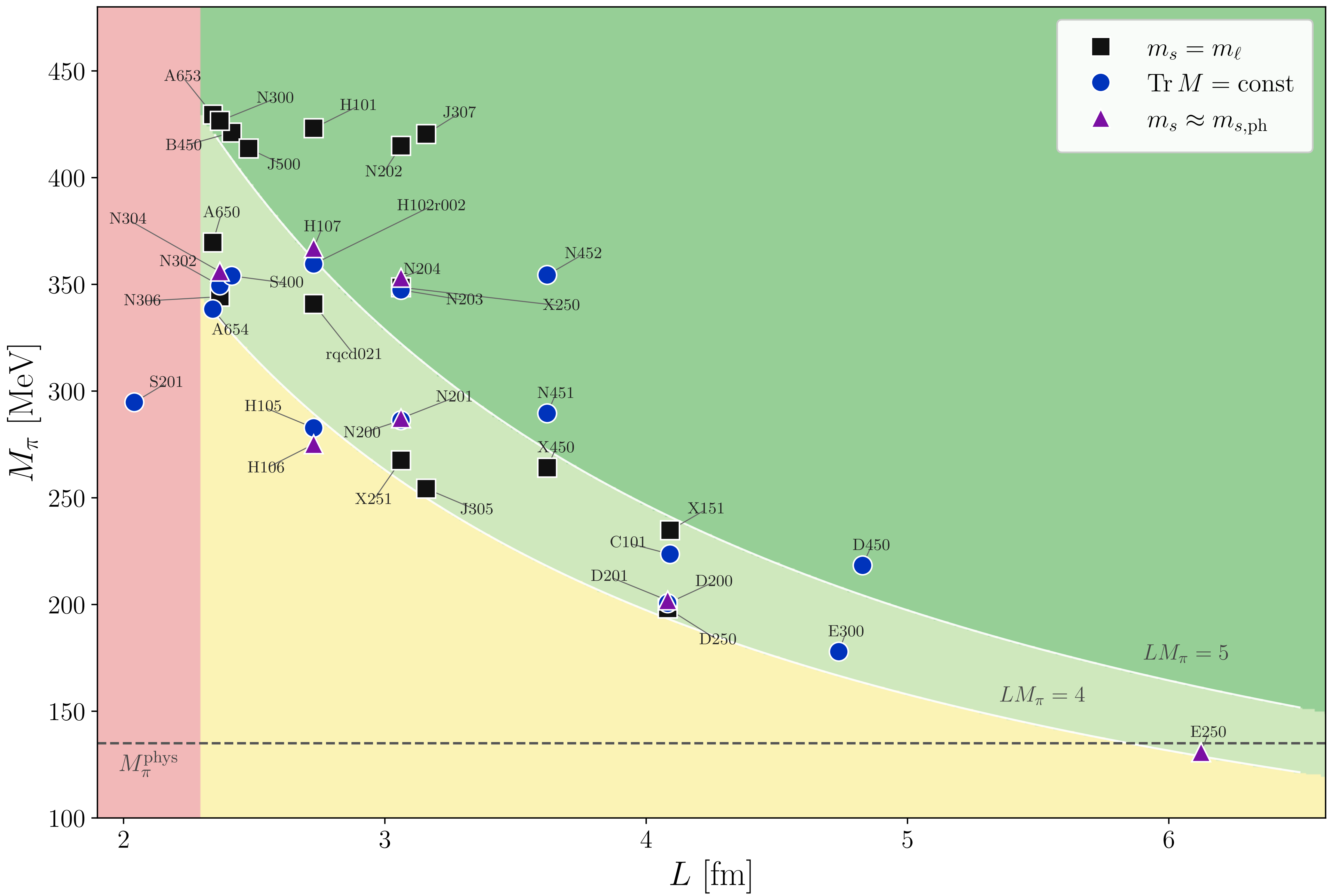
$N_f = 2+1$ CLS Ensembles



- Six different lattice spacings (a ≈ 0.1—0.04 fm)
- OBC for finer lattice spacing to avoid topological freezing
- High statistics ~ 1000 configurations for each ensemble
- Three sources per ensemble
- Two charm masses close to physical per ensemble to interpolate to physical mass
- full parametrization of light/strange/charm quark mass dependence

$N_f = 2 + 1$ CLS Ensembles

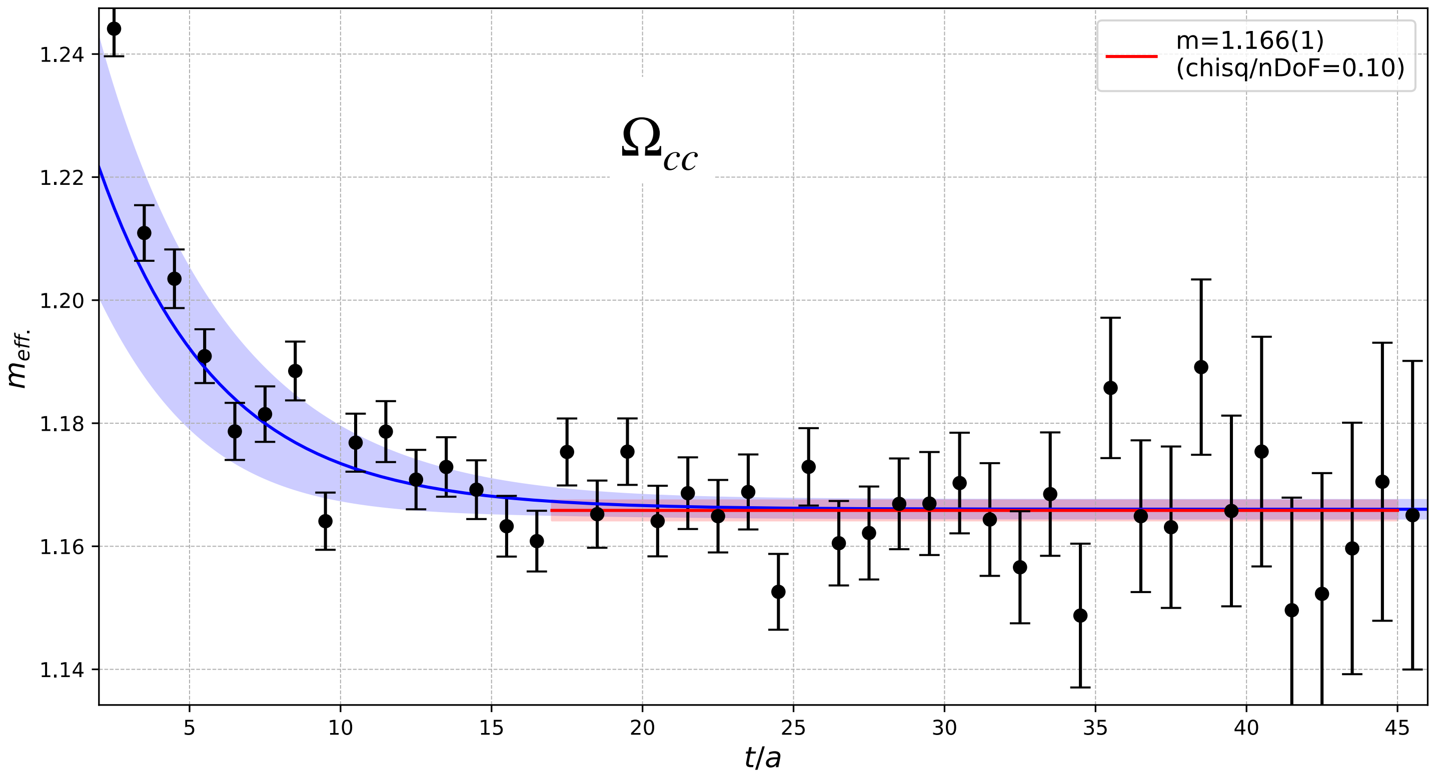
$LM_\pi \leq 4$ | $4 < LM_\pi \leq 5$ | $5 < LM_\pi$ | $L < 2.3$ fm

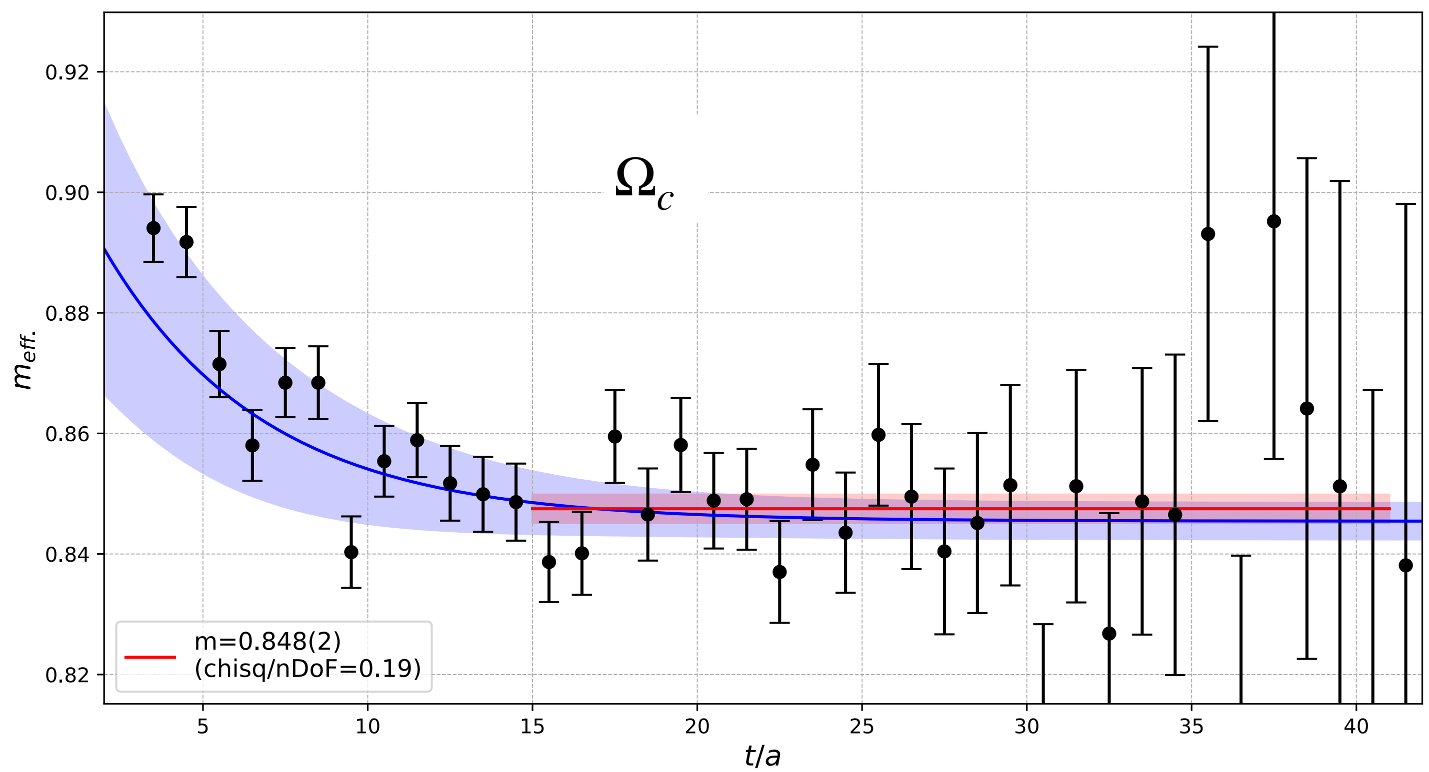


- Ensemble close to the physical point
- Dedicated ensembles to study possible finite volume effects

Baryon Mass

Example of the effective masses on the ensemble at the physical point





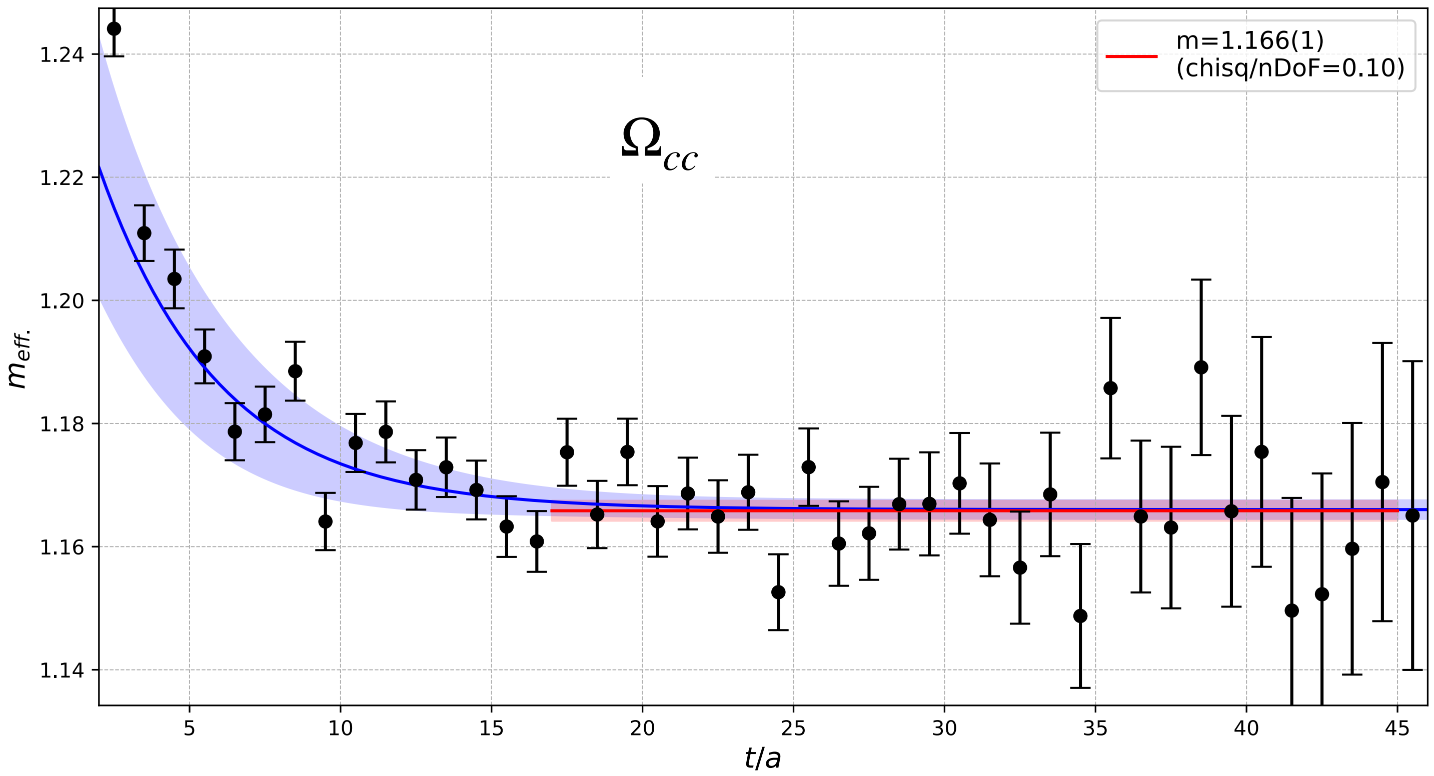
id	L/fm	LM_π	M_π/MeV	M_K/MeV	a/fm
E250	6.12	4.05	131	493	0.064

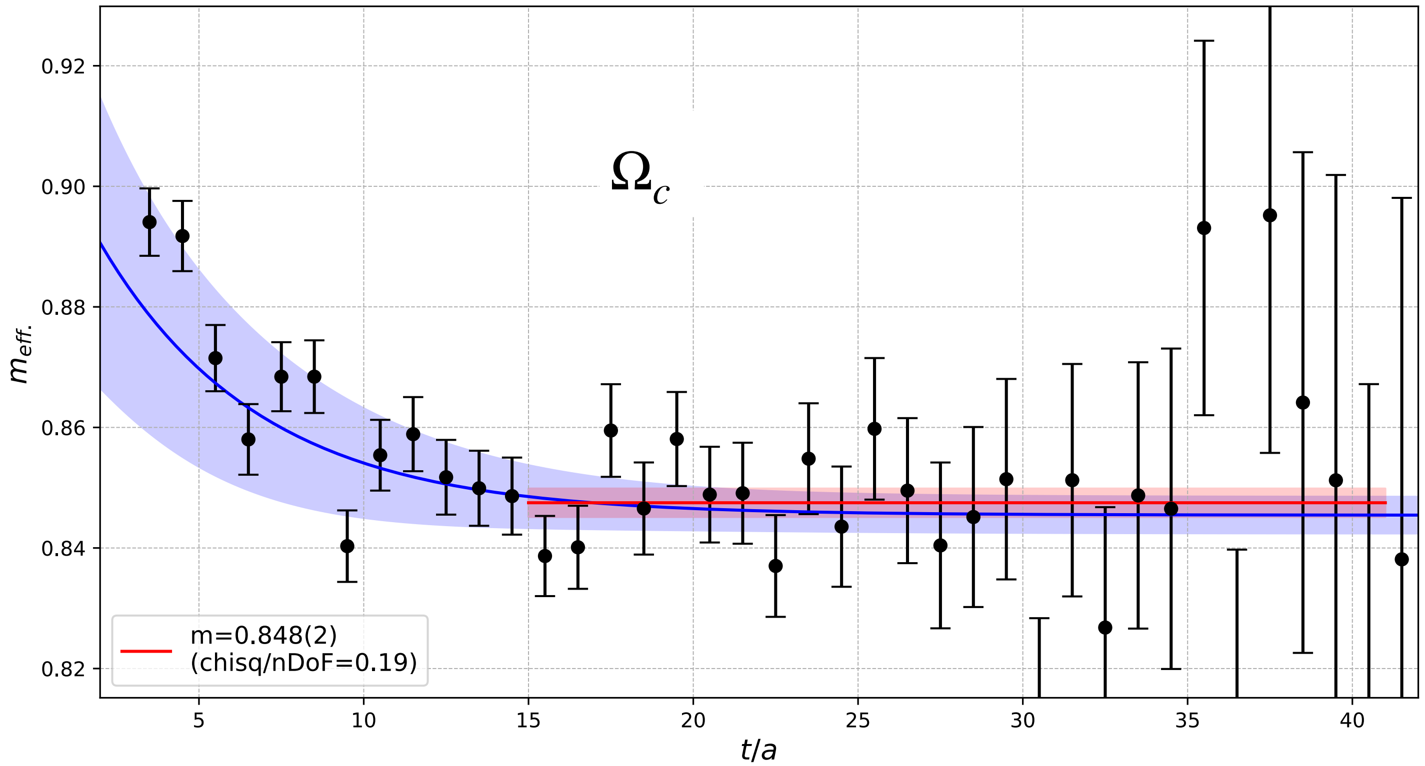
Operators

S	I	$\mathcal{O}$	$J=\frac{1}{2}$
-2	0	$\mathcal{O}_{5\gamma} = \epsilon^{abc}(c^{aT}C\gamma_5 s^b)s^c_\gamma$	Ω_c
-1	0	$\mathcal{O}_{5\gamma} = \epsilon^{abc}(s^{aT}C\gamma_5 c^b)c^c_\gamma$	Ω_{cc}

Baryon Mass

Determination of ground state





- Point-to-all propagators with optimized Gaussian smearing on 3D-APE-smoothed links.
- **Average** correlators over all sources per configuration.
- Fit the two-point correlation function using a two-exponential fit starting from early timeslices to describe the **excited state.**
- The region where the contribution of the two-state exponential is **negligible** determines the start of the single-state fit.
- Perform an **uncorrelated** fit to the correlator.
- Autocorrelations are accounted for using a **bin-size analysis.**

Extrapolation to the physical point

FLAG 2024

Matching condition between isoQCD and QCD+QED ("Edinburgh consensus"):

$$M_\pi = 135\,\mathrm{MeV} \qquad M_K = 494\,\mathrm{MeV}$$

Charm mass fixed by the averaged D-meson mass:

$$M_{\overline{D}} = \frac{2M_D + M_{D_s}}{3} = 1899.4\,\mathrm{MeV}$$

Scale setting through the gradient flow scale t_0, while the physical gradient flow scale $t_{0,ph}$ is obtained from m_Ξ

See talk by Wolfgang - 20/07 @ 10:20 AM

$$t_{0,\mathrm{ph}}^{-1/2} = 1.362(8)\,\mathrm{GeV}$$

RQCD, 2211.03744

All fits are performed on dimensionless quantities $M_\pi^2 t_0$, $M_K^2 t_0$ and $M_{\bar{D}}\sqrt{t_0}$ to cancel $\mathcal{O}(a)$ errors from working with fixed bare couplings

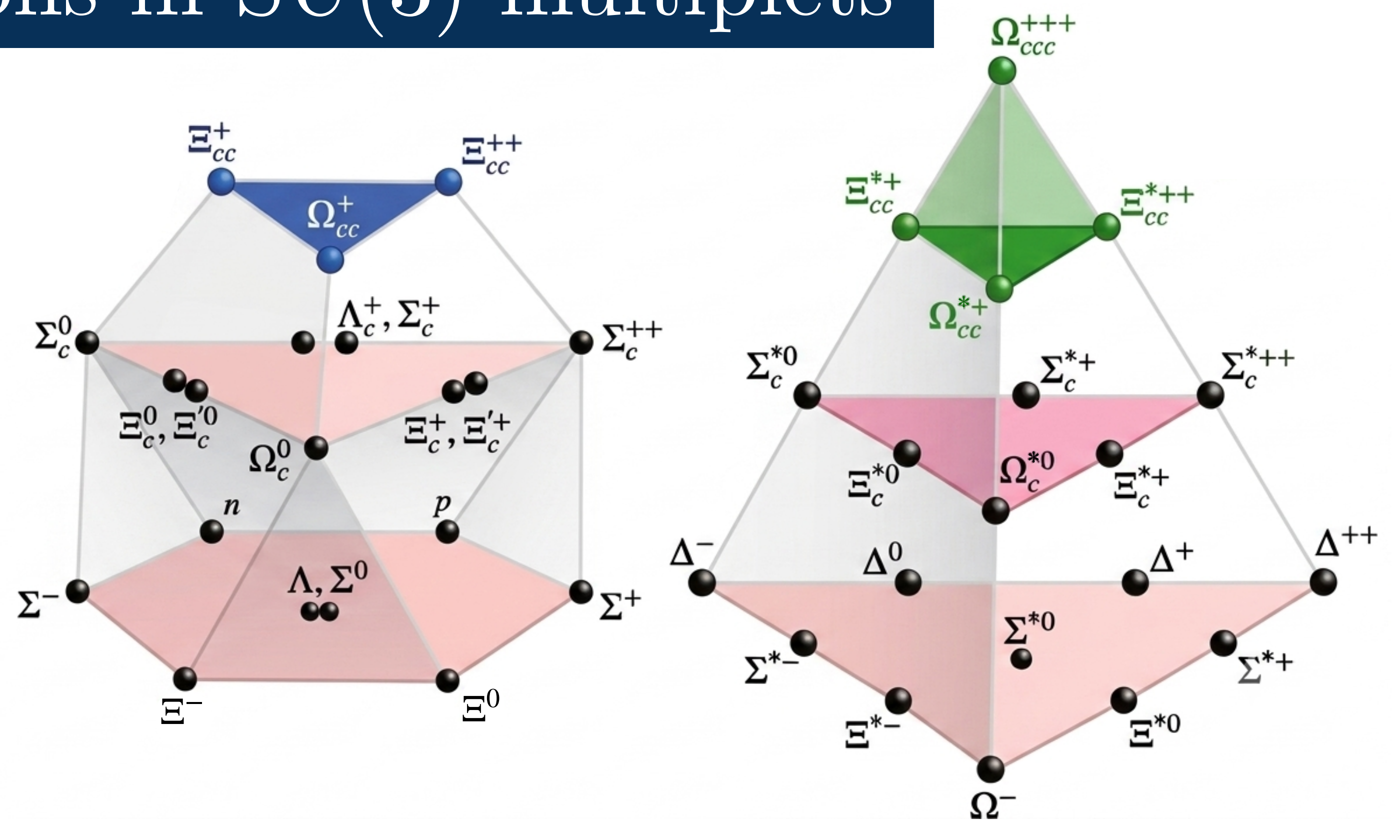
Physical and continuum limit:

$$m_q \to m_{q,\mathrm{ph}} \quad L \to \infty \quad a \to 0$$

$$\mathbf{M}(\{m_q\}, L, a)\sqrt{\mathbf{t_0}(\{m_q\}, a)} \longrightarrow M\sqrt{t_{0,\mathrm{ph}}} \qquad \mathbf{t_0}(\{m_q\}, a) \longrightarrow t_{0,\mathrm{ph}}$$

Charmed Baryons in SU(3) multiplets

20_M



20_S

Multiplet	J^P	States	Quark content
anti-triplet $\bar{\mathbf{3}}$	$\frac{1}{2}^+$	$\Lambda_c,\ \Xi_c$	$udc,\ usc/dsc$
sextet $\mathbf{6}$	$\frac{1}{2}^+$	$\Sigma_c,\ \Xi_c',\ \Omega_c$	$uuc,\ usc,\ ssc$
sextet $\mathbf{6}$	$\frac{3}{2}^+$	$\Sigma_c^*,\ \Xi_c^*,\ \Omega_c^*$	$uuc,\ usc,\ ssc$
triplet $\mathbf{3}$	$\frac{1}{2}^+$	$\Xi_{cc},\ \Omega_{cc}$	$ucc,\ scc$
triplet $\mathbf{3}$	$\frac{3}{2}^+$	$\Xi_{cc}^*,\ \Omega_{cc}^*$	$ucc,\ scc$

Extrapolation to the physical point

full parametrization of light/strange/ charm quark mass dependence

Defining:

$$\overline{M}^2 = \tfrac{1}{3}\left(2M_K^2 + M_\pi^2\right) \propto \; m_s + 2\, m_\ell \;, \qquad \delta M^2 = 2\left(M_K^2 - M_\pi^2\right) \;\propto\; m_s - m_\ell$$

for the spin-$\frac{1}{2}$ sextet ($f_{\mathcal{B}} \equiv m_{\mathcal{B}}\sqrt{t_0}$):

Gell-Mann-Okubo relations

$$\begin{aligned}
f_{\Sigma_c} &= b_6 + b_{c6}\, M_{\overline{D}}\sqrt{t_0} + \bar{b}_6\, \overline{M}^2 t_0 - 2\;\delta b_6\, \delta M^2 t_0\\
f_{\Xi'_c} &= b_6 + b_{c6}\, M_{\overline{D}}\sqrt{t_0} + \bar{b}_6\, \overline{M}^2 t_0 + 1\;\delta b_6\, \delta M^2 t_0\\
f_{\Omega_c} &= b_6 + b_{c6}\, M_{\overline{D}}\sqrt{t_0} + \bar{b}_6\, \overline{M}^2 t_0 + 4\;\delta b_6\, \delta M^2 t_0
\end{aligned}$$

group-theory coefficients of δM^2 fixed by SU(3) analogous expressions for $\bar{\mathbf{3}}$, $\mathbf{6}^*$, $\mathbf{3}$ and $\mathbf{3}^*$

$$\begin{aligned}
f_{\Lambda_c}(M_\pi, M_K, M_{\overline{D}}) &= b_{\bar{3}} + b_{c\bar{3}} M_{\overline{D}} + \bar{b}_{\bar{3}}\overline{M}^2 - 2\delta b_{\bar{3}}\delta M^2\\
f_{\Xi_c}(M_\pi, M_K, M_{\overline{D}}) &= b_{\bar{3}} + b_{c\bar{3}} M_{\overline{D}} + \bar{b}_{\bar{3}}\overline{M}^2 + \delta b_{\bar{3}}\delta M^2\\
f_{\Xi_{cc}}(M_\pi, M_K, M_{\overline{D}}) &= b_3 + b_{c3} M_{\overline{D}} + \bar{b}_3\overline{M}^2 - \delta b_3\delta M^2\\
f_{\Omega_{cc}}(M_\pi, M_K, M_{\overline{D}}) &= b_3 + b_{c3} M_{\overline{D}} + \bar{b}_3\overline{M}^2 + 2\delta b_3\delta M^2
\end{aligned}$$

$b_c M_{\bar{D}}\sqrt{t_0}$ - linear charm mass effects constrained by two κ_c values

Exploring more sophisticated fit forms!

Extrapolation to the physical point

Full fit form (n labels the ensemble):

$$\mathbf{m}_{\mathcal{B}}^{(n)}\sqrt{\mathbf{t}_0^{(n)}} = f_{\mathcal{B}}\left(\mathbf{M}_{\pi}^{(n)}, \mathbf{M}_{K}^{(n)}, \mathbf{M}_{\overline{D}}^{(n)}\right) + \frac{1}{\mathbf{t}_0^{*(n)}}\left[c_a + c_{ac}\,\mathbf{M}_{\overline{D}}\sqrt{\mathbf{t}_0} + \bar{c}_a\,\overline{\mathbf{M}}^2\mathbf{t}_0 + \delta c_a^{\mathcal{B}}\,\boldsymbol{\delta}\mathbf{M}^2\mathbf{t}_0\right] \quad \mathrm{O}(a^2)$$

$$+ \left[\mathbf{t}_0^{*(n)}\right]^{-3/2}\bar{c}_{a3} \quad \mathrm{O}(a^3)$$

$a^2 \propto 1/\mathbf{t}_0^*$: the symmetric-point flow scale relates different β values

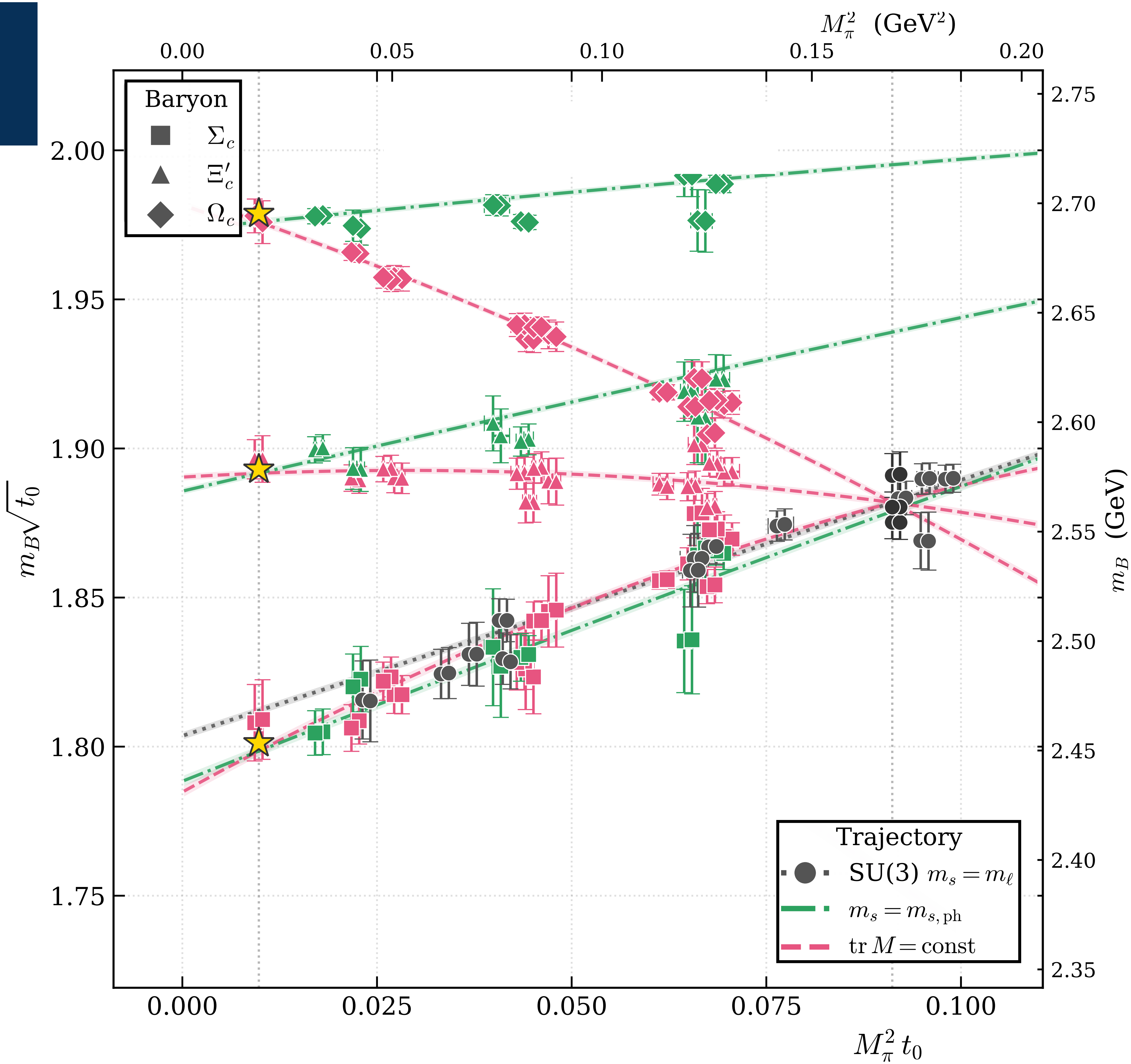
$c_{ac}\,\mathbf{M}_{\overline{D}}\sqrt{\mathbf{t}_0}$: **charm-mass-dependent cutoff effects** $a^2\Lambda\, m_c$ — expected to dominate

$\delta c_a^{\mathcal{B}}$ per baryon: SU(3)-breaking discretization effects

Good model as a first assumption - works fine, but additional models inspired by ChPT as well as lattice spacing dependence are being explored!

Pion Mass Dependence

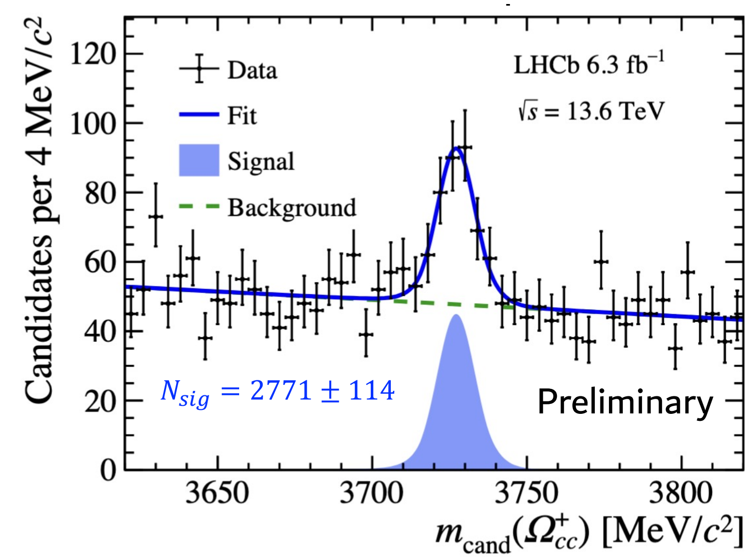
- masses rescaled with $\sqrt{t_0}$ and perform a combined chiral and continuum fit.
- Curves show the continuum part subject to group-theoretical constraints.
- Data points are projected based on the fit, and stars are physical values from PDG (in agreement with the fit).
- All three trajectories are used.

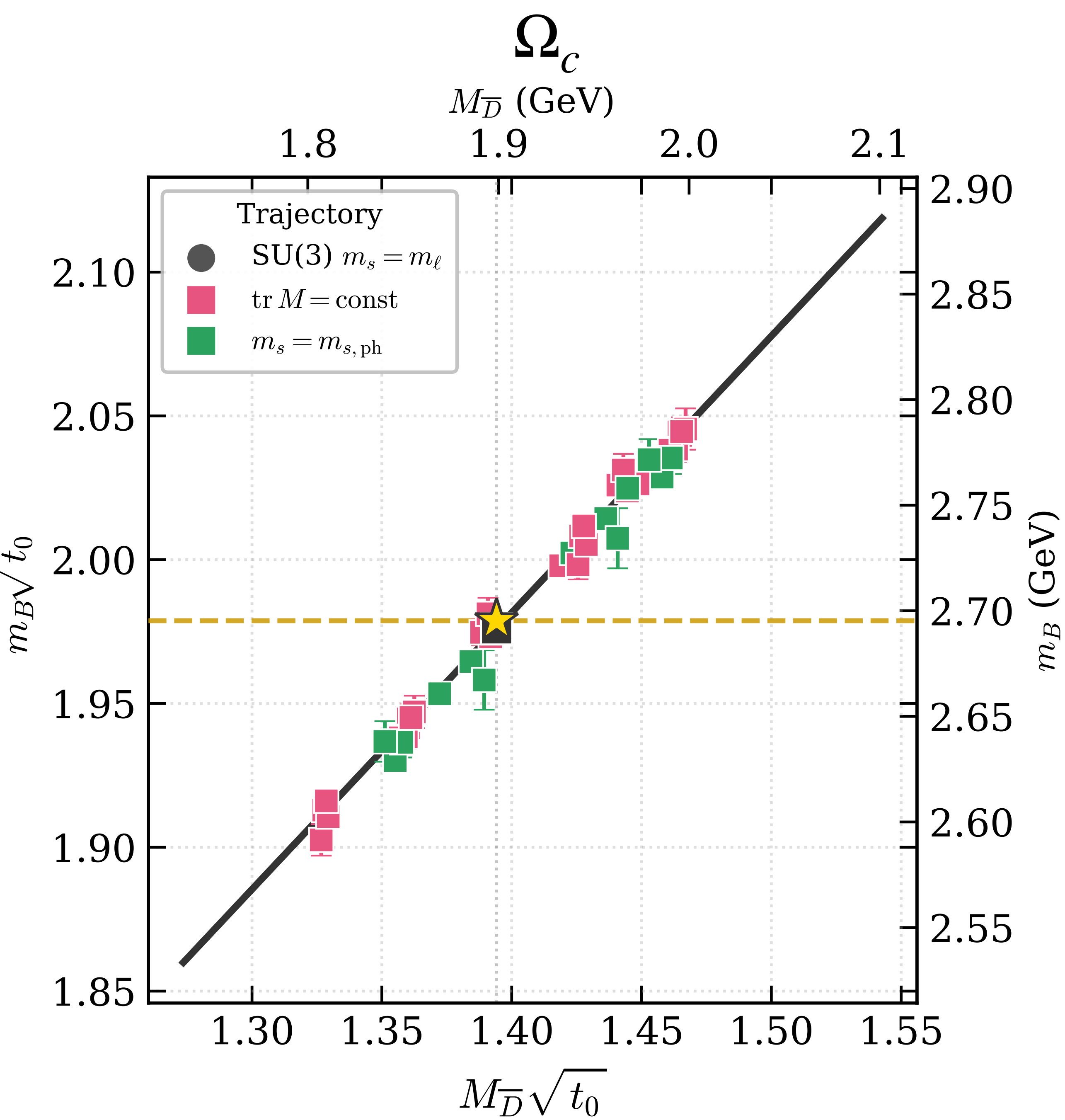


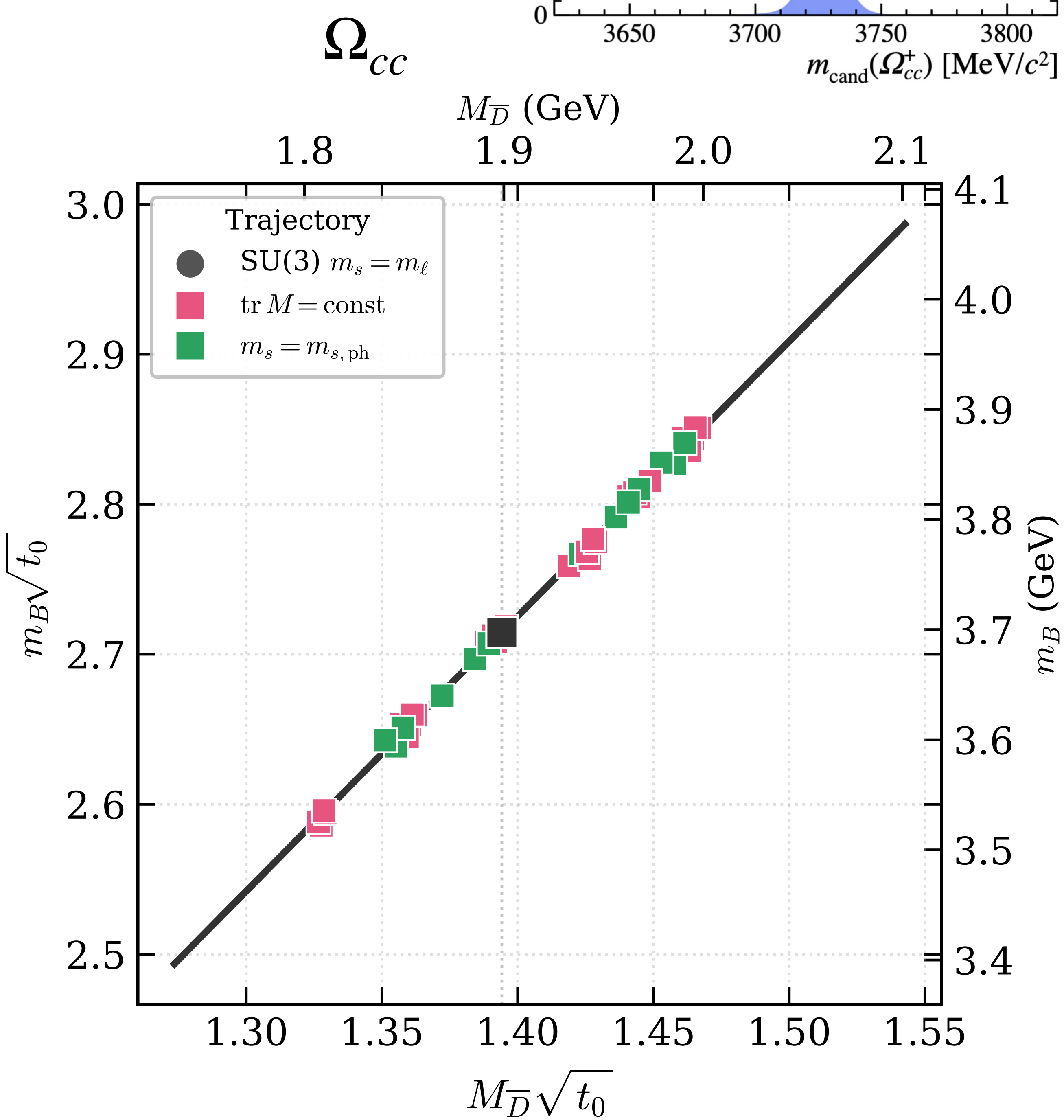
Charm quark mass interpolation

$$M_{\overline{D}} = \frac{2M_D + M_{D_s}}{3} = 1899.4\,\text{MeV}$$

Discovered last month!

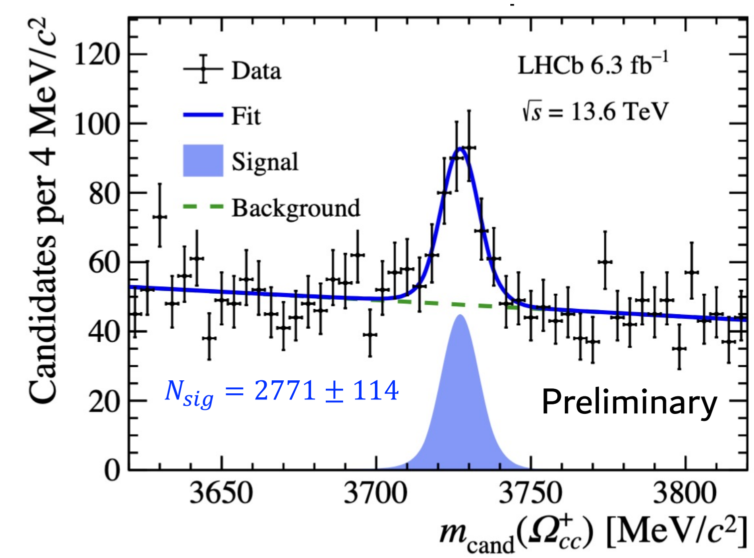


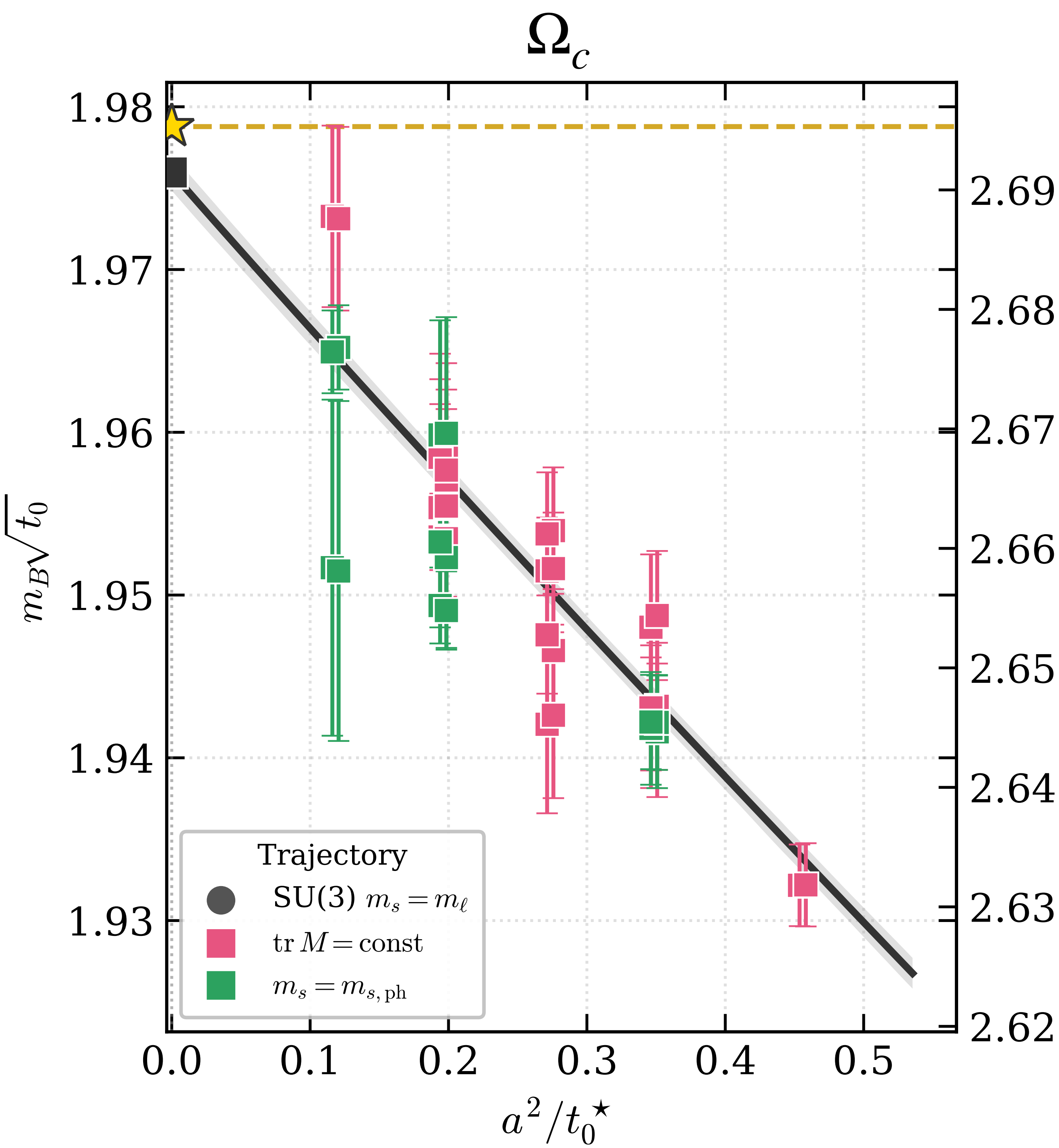


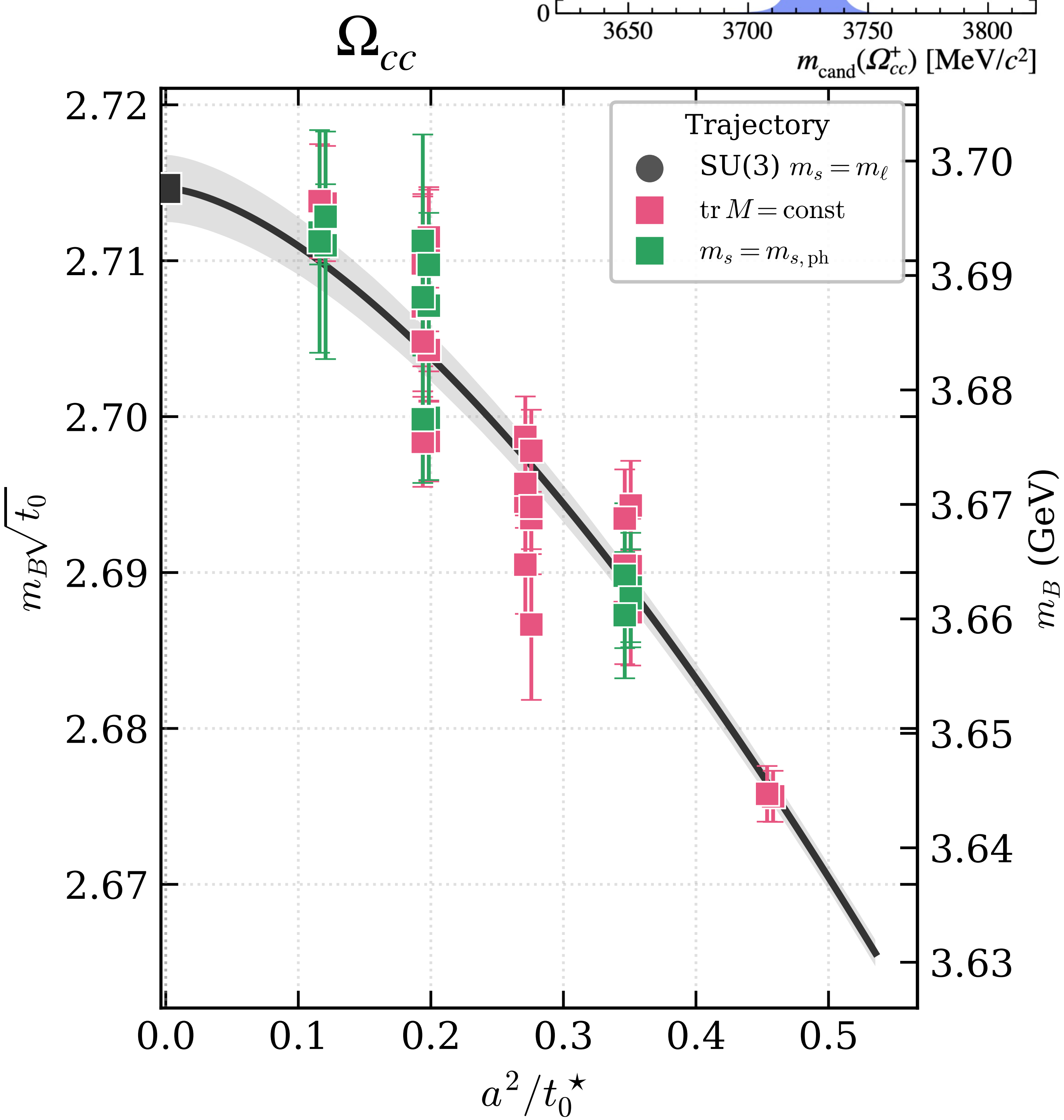


Continuum Extrapolation

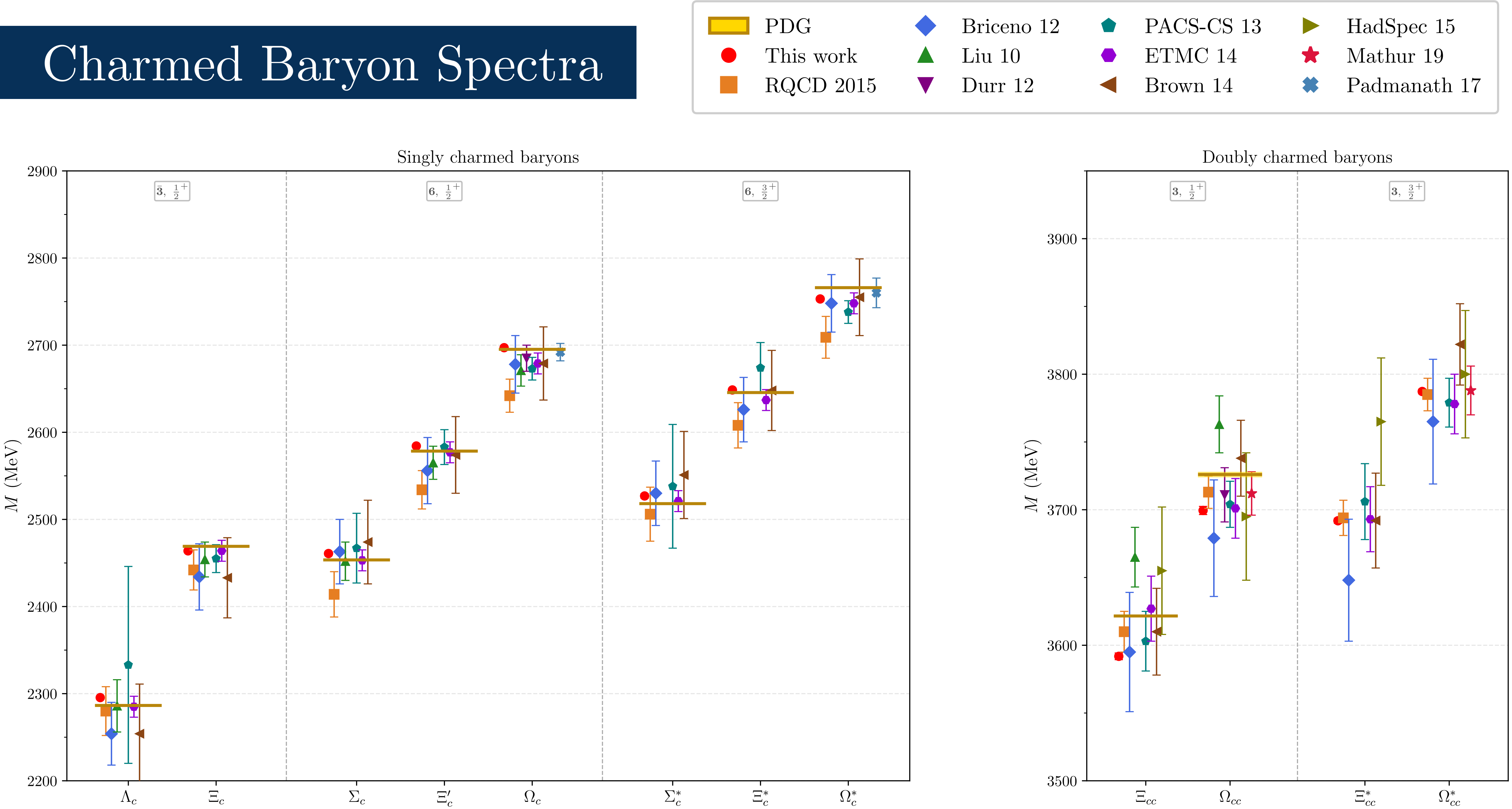
Discovered last month!





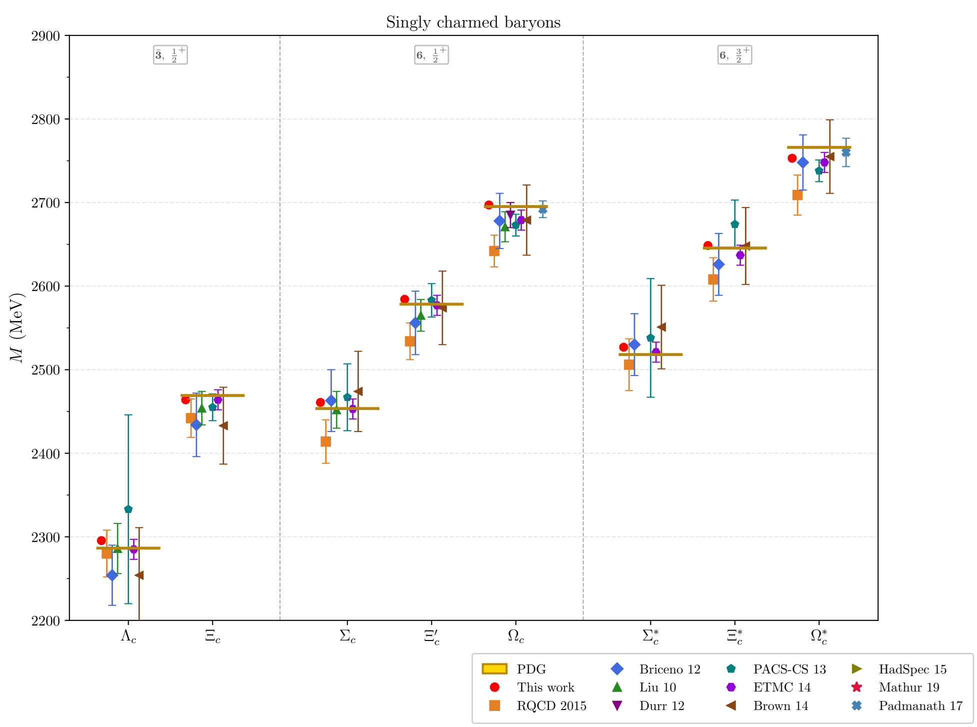


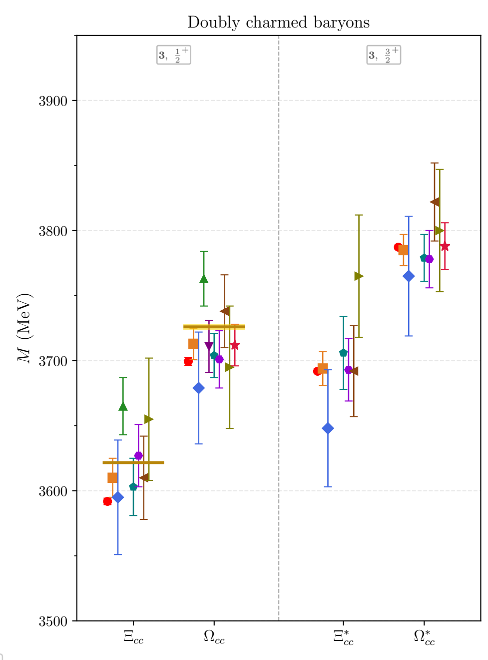
Charmed Baryon Spectra

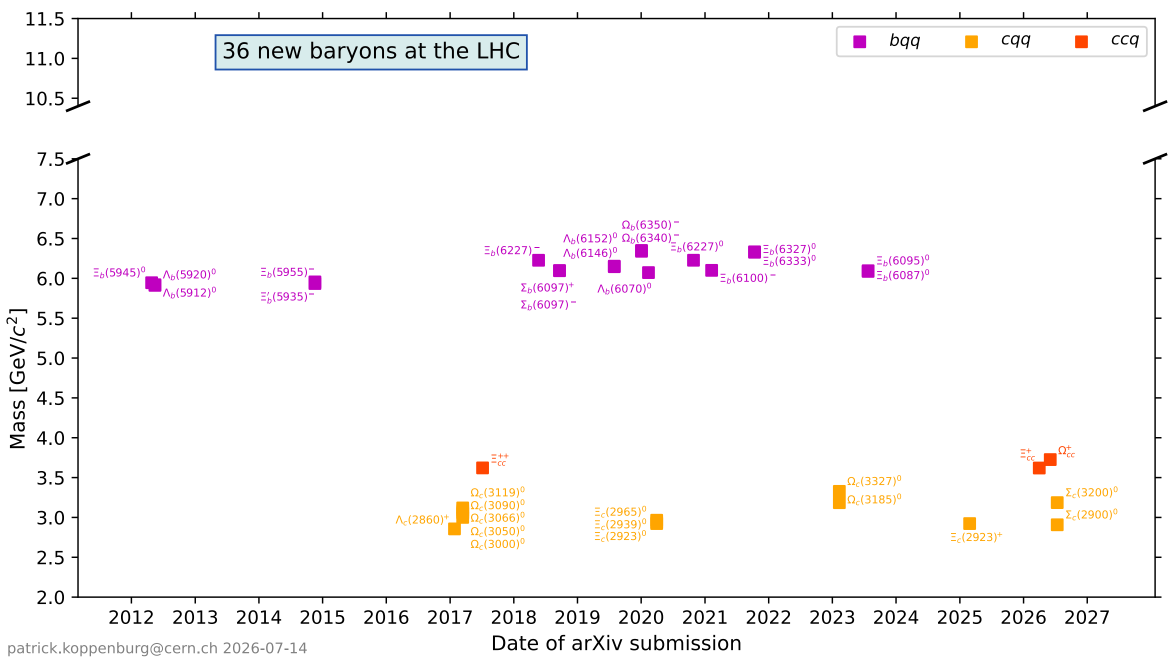


Summary

- Precise determination of the ground-state singly and doubly-charmed baryon spectra with 37 ensembles along 3 mass trajectories.
- A full systematic budget is in progress.
- Model variations with finite-volume terms, etc., are in progress.
- Extend to the bottom and mixed charm-bottom sectors.

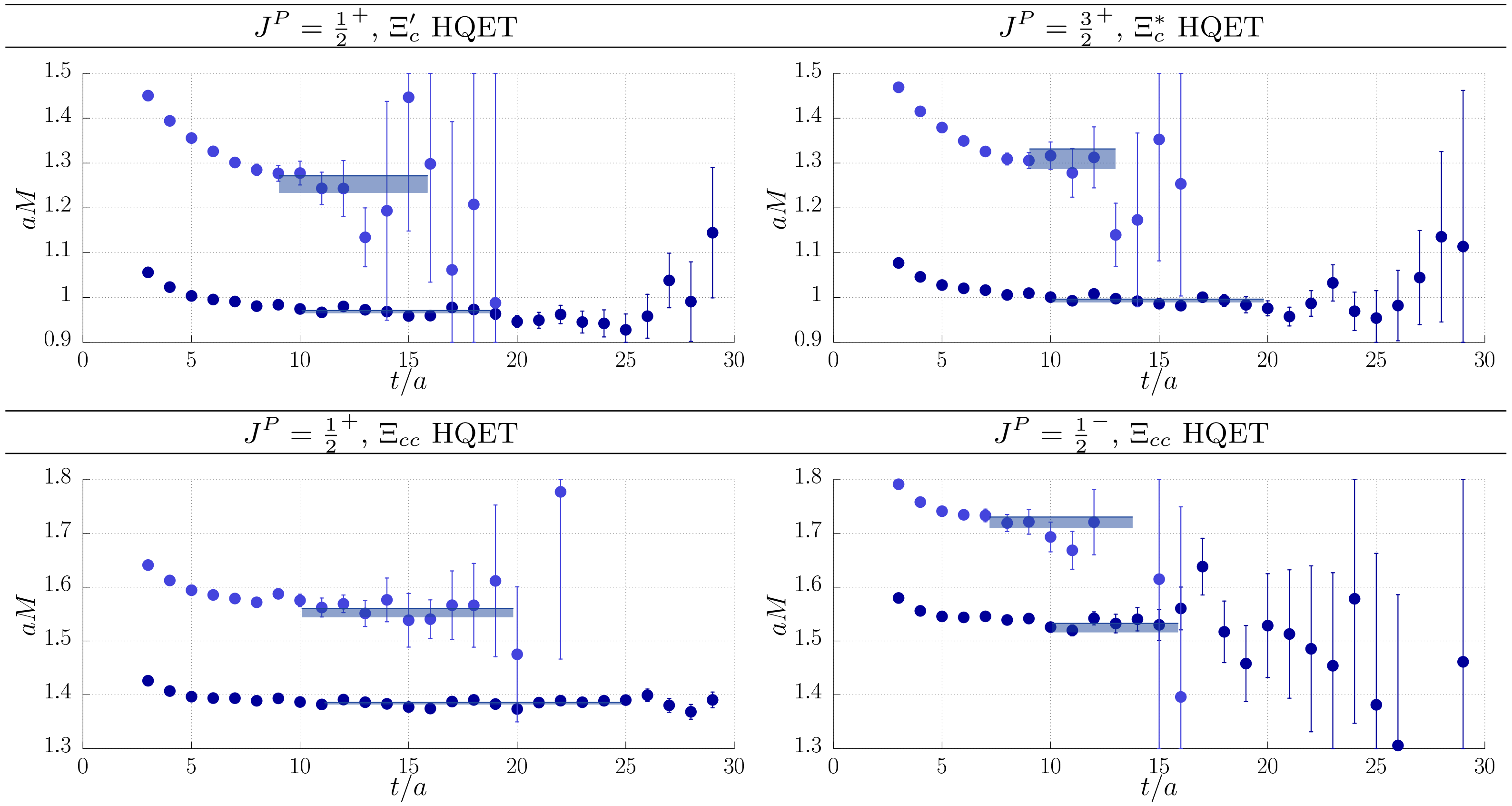




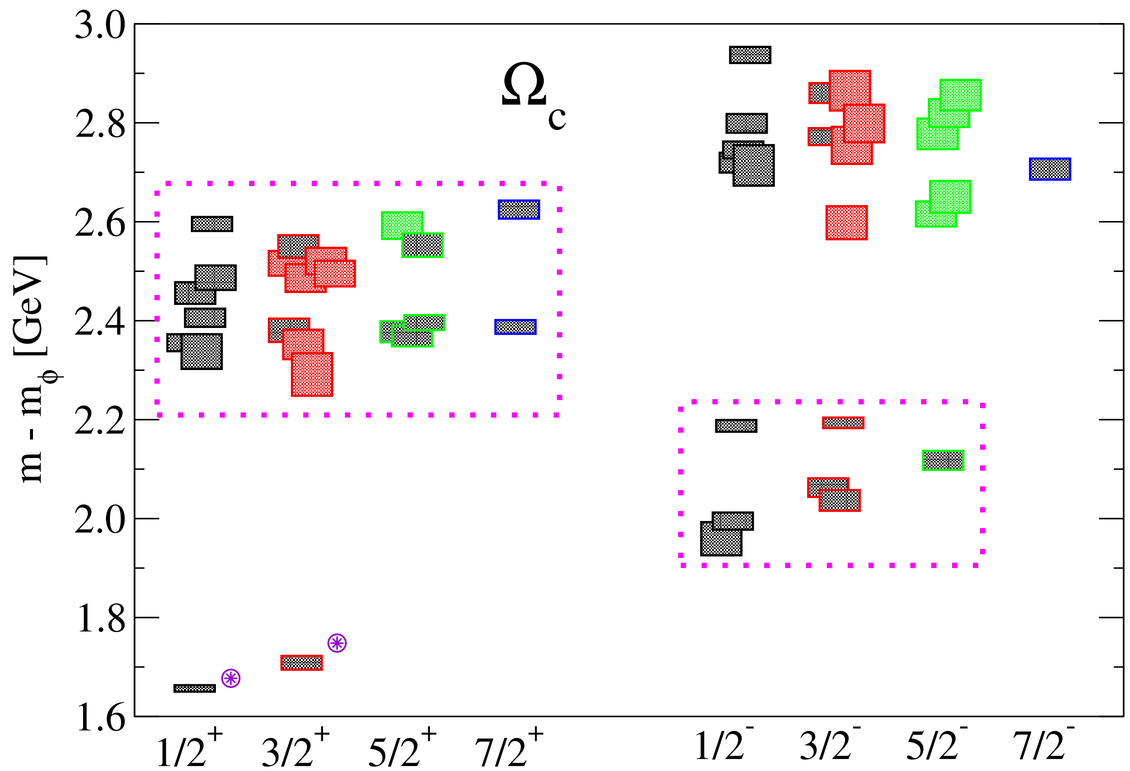


Backup

GEVP



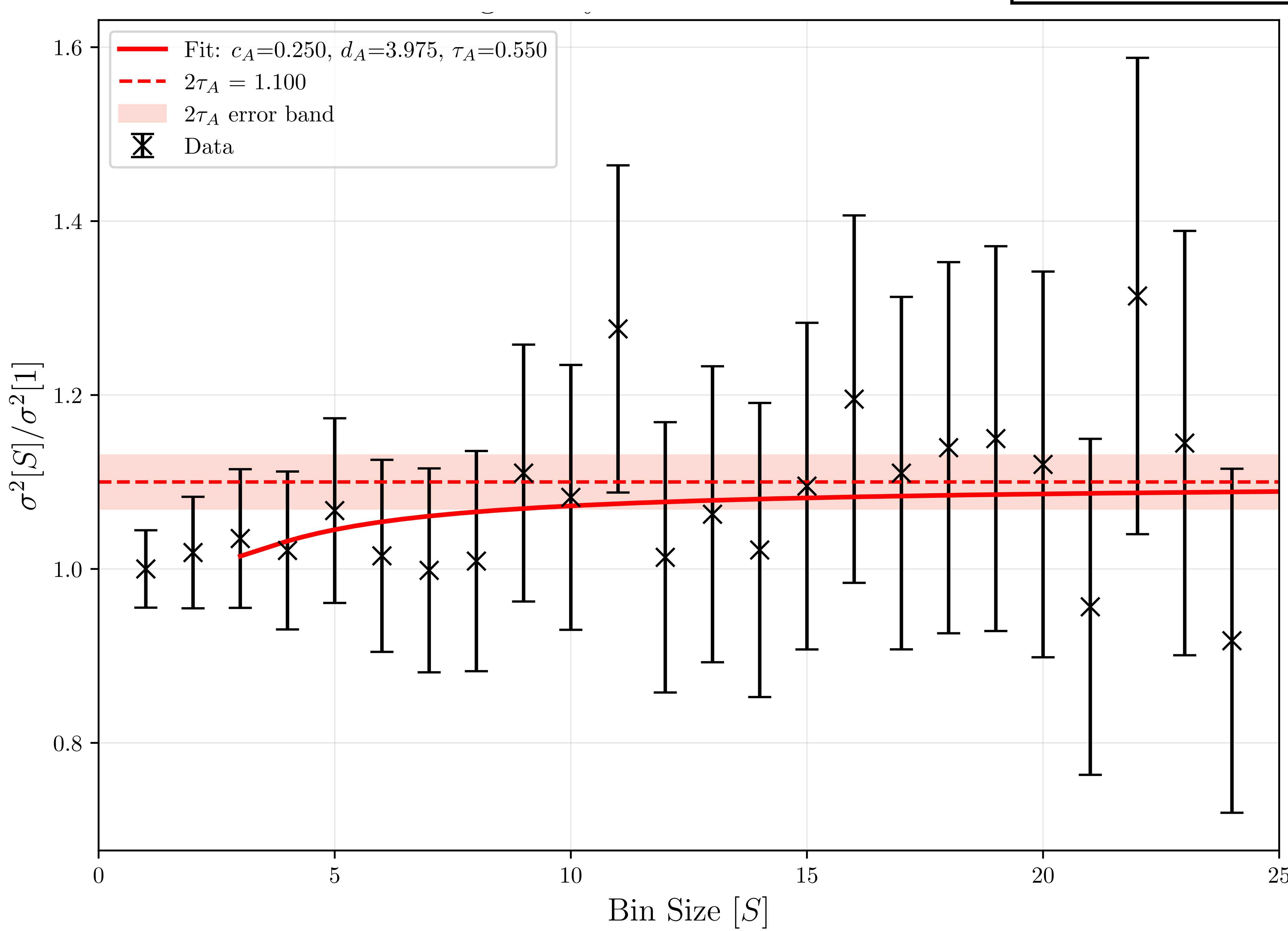
$J^P = \frac{1}{2}^+$, Ξ_c' HQET
$J^P = \frac{3}{2}^+$, Ξ_c^* HQET
$J^P = \frac{1}{2}^+$, Ξ_{cc} HQET
$J^P = \frac{1}{2}^-$, Ξ_{cc} HQET
aM
t/a



Ω_c
m - m$_\phi$ [GeV]
1/2$^+$
3/2$^+$
5/2$^+$
7/2$^+$
1/2$^-$
3/2$^-$
5/2$^-$
7/2$^-$

Binsize Analysis

$$\frac{\sigma_A^2[S]}{\sigma_A^2[1]} \approx 2\tau_{A,\mathrm{int}}\left(1 - \frac{c_A}{S} + \frac{d_A}{S}\, e^{-S/\tau_{A,\mathrm{int}}}\right), \qquad c_A > d_A \geq 0$$



Extrapolation to the physical point

Total least-squares function:

$$\chi^2 = \sum_{n,i,j} \left(x_i^n - f_i^n\right) \left[C_{ij}^n\right]^{-1} \left(x_j^n - f_j^n\right) + \sum_k \frac{\left(p_k - f_k\right)^2}{\Delta p_k^2}$$

$\smile_{ij}^{n}$: per-ensemble covariance of *all* observables $\{\mathbf{m}_{\mathcal{B}}, \mathbf{M}_{\pi}, \mathbf{M}_{K}, \mathbf{M}_{\overline{D}}, \sqrt{\mathbf{t}_0}\}$ from **binned jackknife**

x-**errors**: every input $(\mathbf{M}_{\pi}, \mathbf{M}_{K}, \mathbf{M}_{\overline{D}}, \mathbf{t}_0, \ldots)$ promoted to a fit parameter

:

Error propagation: **500 bootstrap samples**

More Models!

Finite Size Effects

NLO in ChPT

$$M_\pi^2(L) = M_\pi^2\left[1 + \frac{M_\pi^2}{(4\pi F_0)^2} h(LM_\pi) - \frac{1}{3}\frac{M_{\eta_8}^2}{(4\pi F_0)^2} h(LM_{\eta_8})\right],$$

$$M_K^2(L) = M_K^2\left[1 + \frac{2}{3}\frac{M_{\eta_8}^2}{(4\pi F_0)^2} h(LM_{\eta_8})\right],$$

$$M_{\eta_8}^2 = \frac{1}{3}\left(4M_K^2 - M_\pi^2\right),$$

Transitions!

$$f_{\Xi_{cc}} \mapsto f_{\Xi_{cc}} + \sqrt{t_0}m_3^3\frac{g^2}{2(4\pi F_0)^2}\left[3H\left(\frac{M_\pi}{m_3}\right) + 2H\left(\frac{M_K}{m_3}\right) + \frac{1}{3}H\left(\frac{M_\eta}{m_3}\right)\right],$$

$$f_{\Omega_{cc}} \mapsto f_{\Omega_{cc}} + \sqrt{t_0}m_3^3\frac{g^2}{2(4\pi F_0)^2}\left[4H\left(\frac{M_K}{m_3}\right) + \frac{4}{3}H\left(\frac{M_\eta}{m_3}\right)\right],$$