Measurement of the form factor shape for the semileptonic decay $\Lambda_b \rightarrow \Lambda_c \mu \nu$

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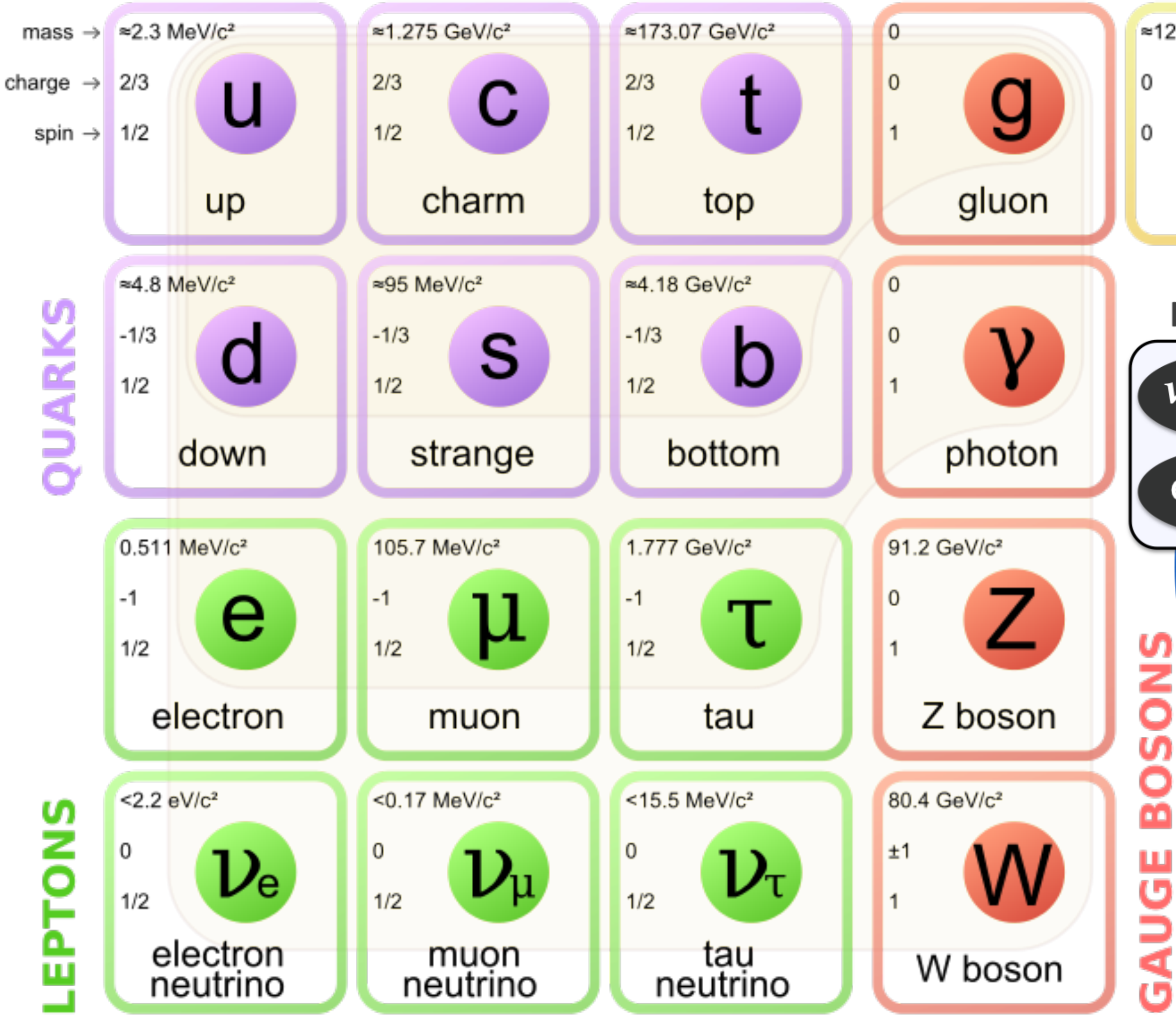
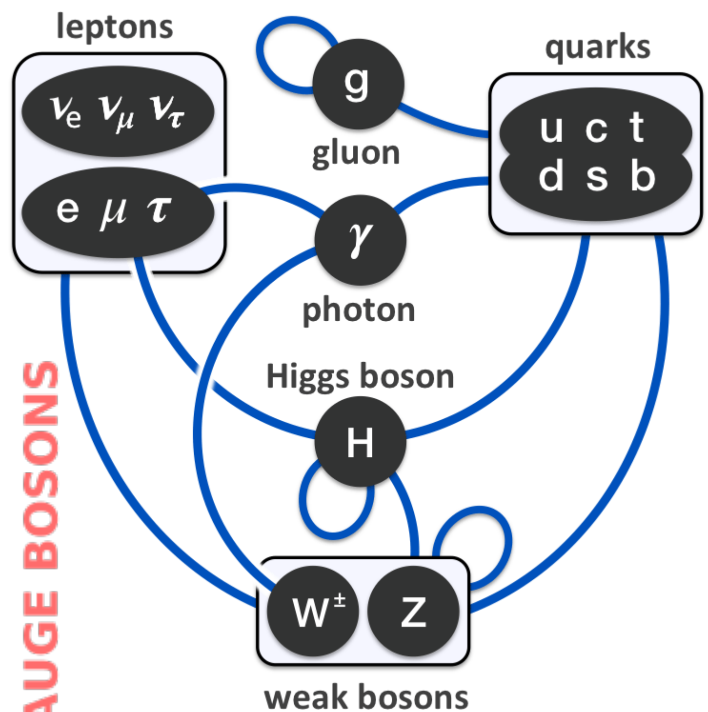
The Standard Model



Based on the gauge group SU(3)×SU(2)×U(1)

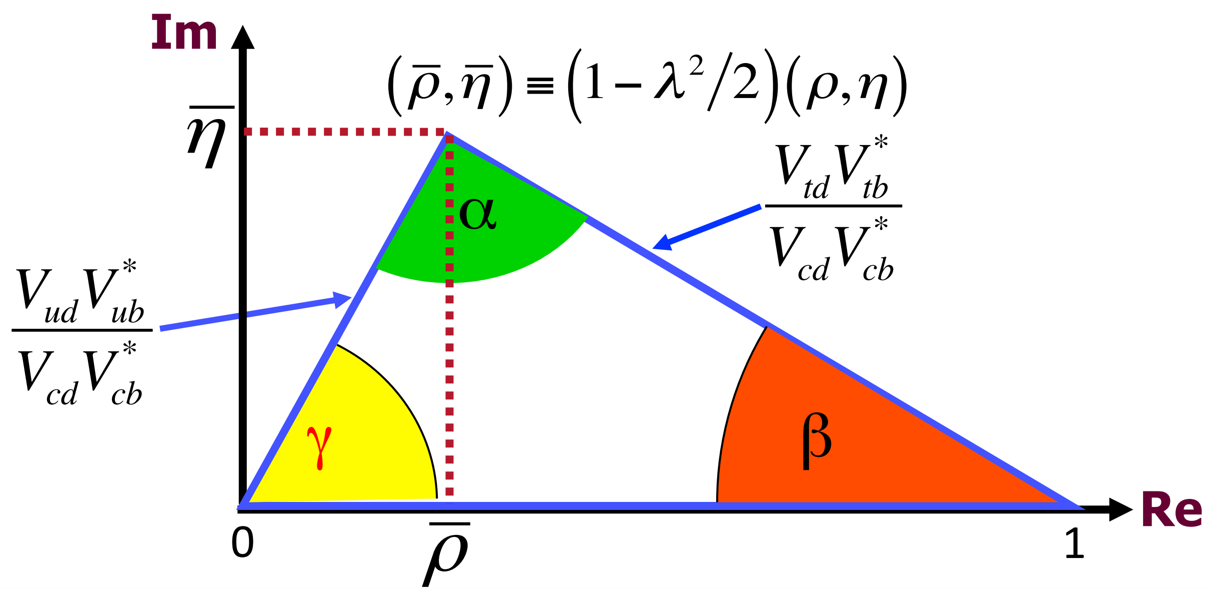


The CKM matrix

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

From unitarity ($V_{CKM} V^{\dagger}_{CKM}=1$) :
CKM has ***four*** free parameters:
- 3 real: λ (≈ 0.22) , A (≈ 1), ρ
- 1 imaginary: $i\eta$

$$V_{ud} \cdot V_{ub}^* + V_{cd} \cdot V_{cb}^* + V_{td} \cdot V_{tb}^* = 0$$



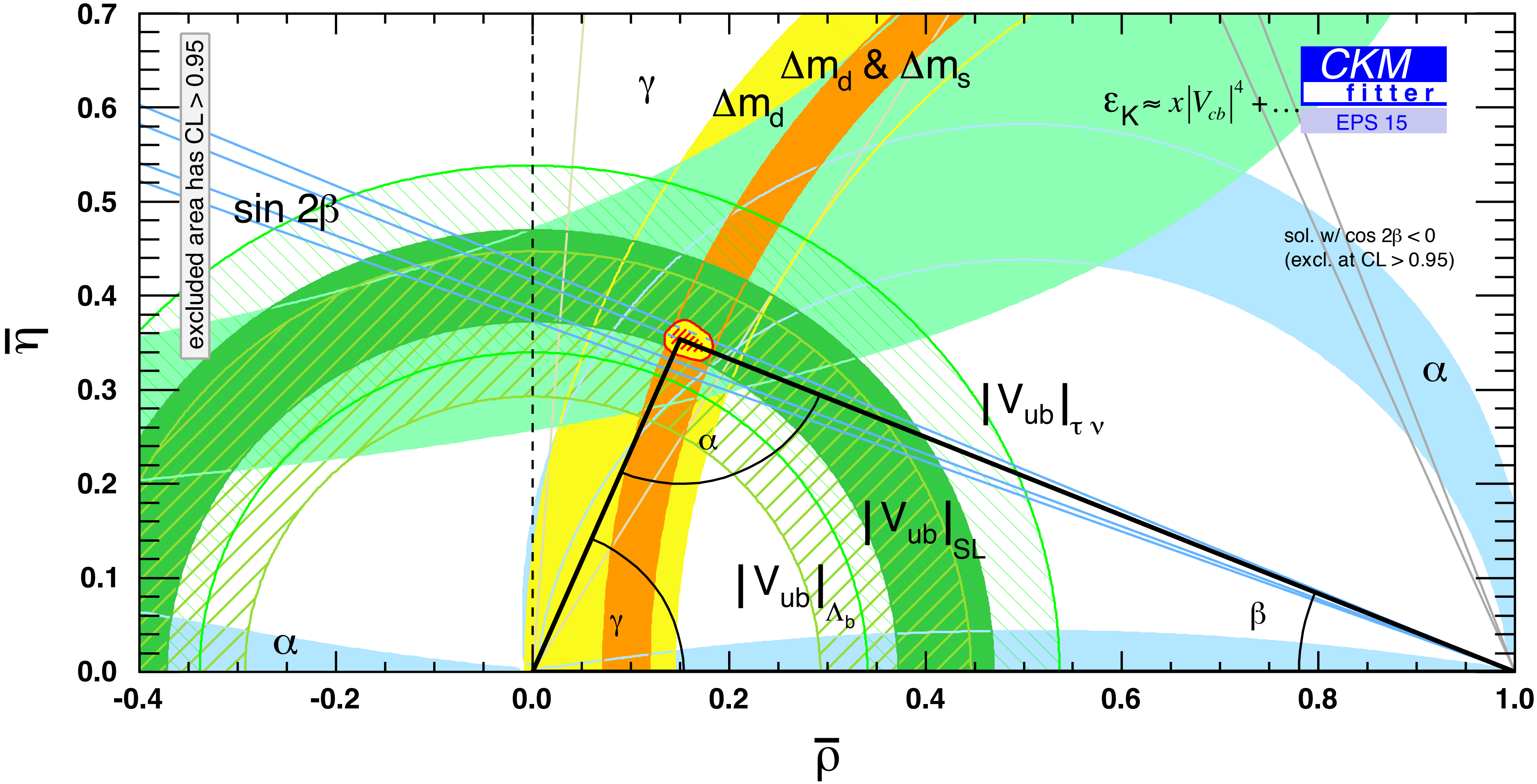
$$\alpha \equiv \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

$$\beta \equiv \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

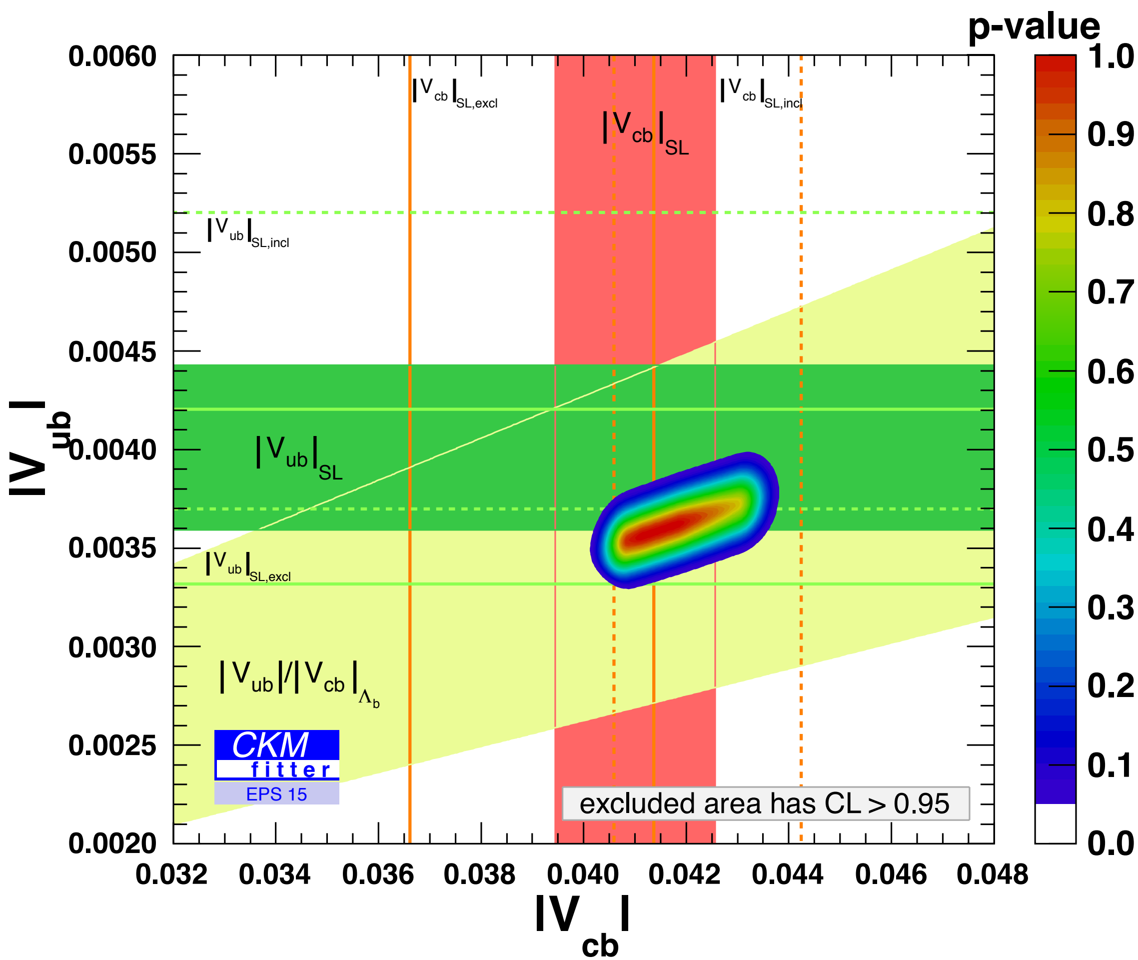
$$\gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

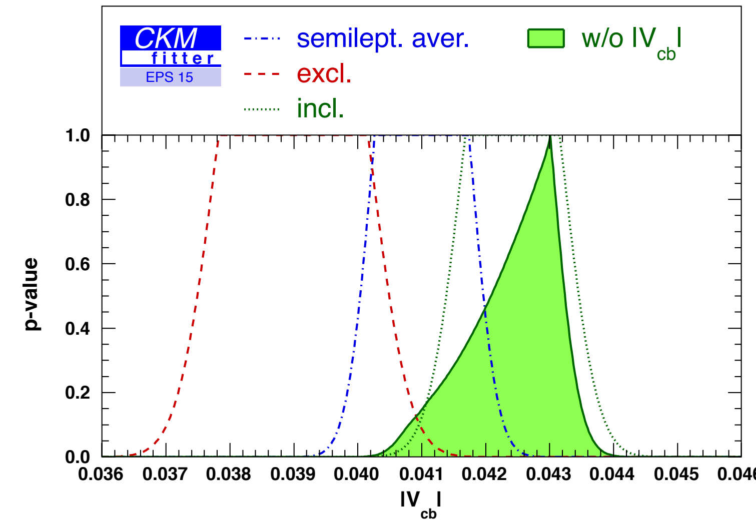
Unitarity triangle

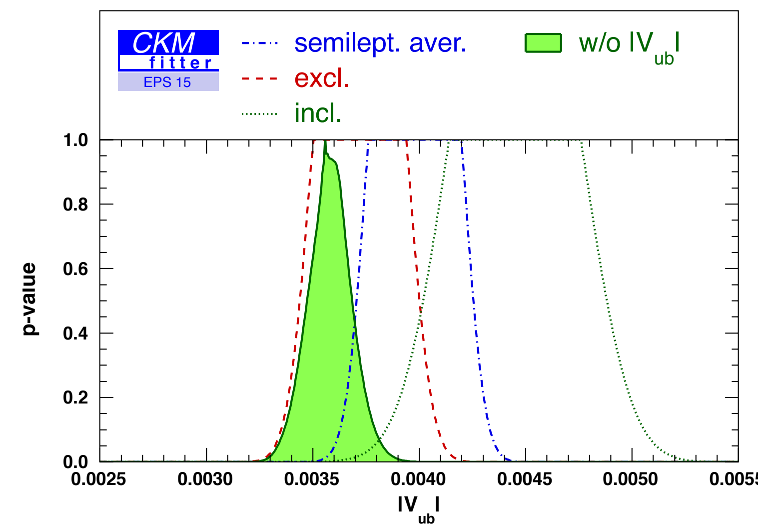
V_{cb} plays an important role in the prediction of FCNC: $\propto |V_{tb}V_{ts}|^2 \cong |V_{cb}|^2 [1 + O(\lambda^2)]$



$|V_{xb}|$ current status







The Large Hadron Collider

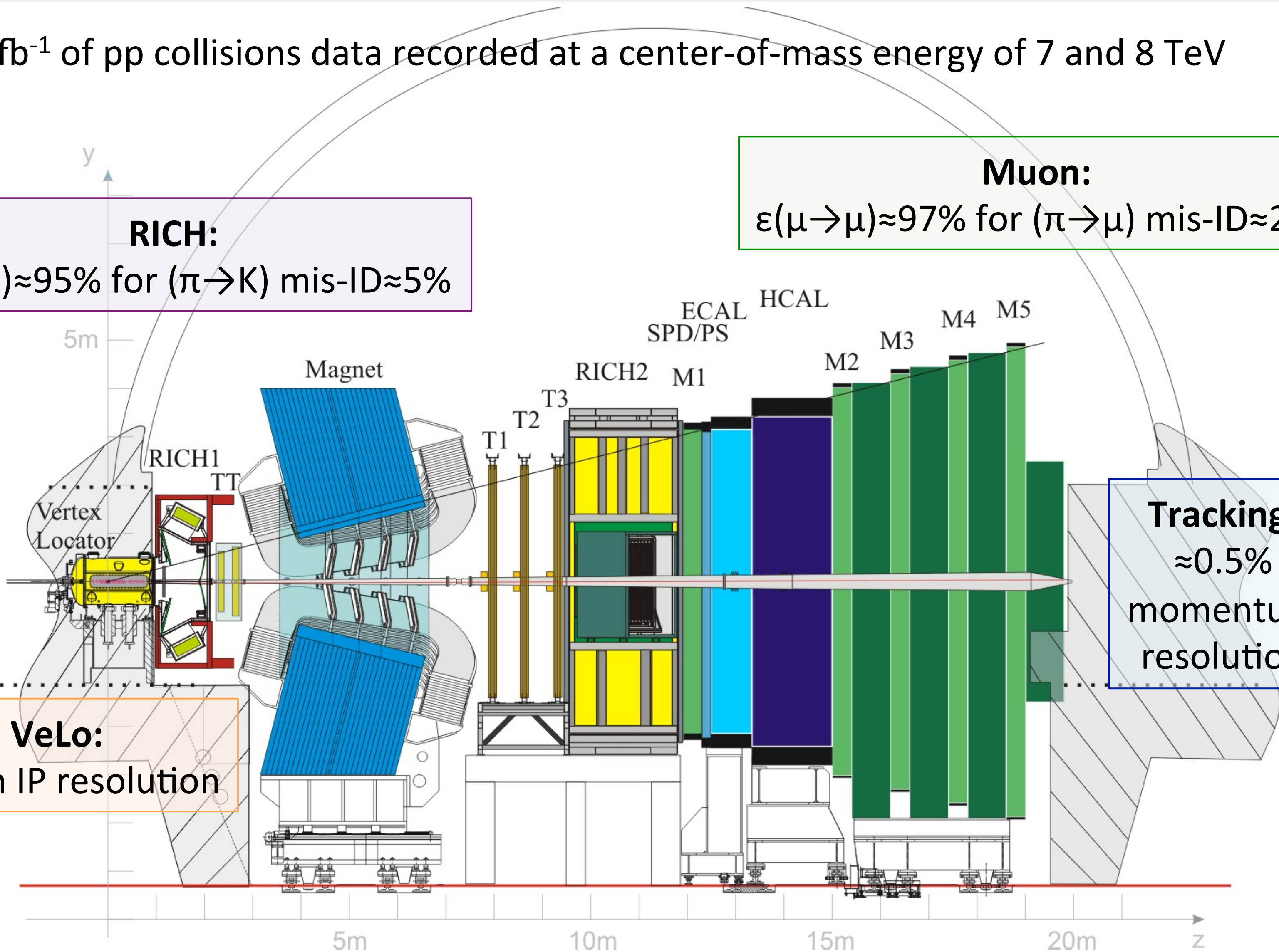
The LHC is a proton-proton collider located at CERN, with a circumference of 27km, a design center-of-mass energy of 14TeV. The high luminosity of the LHC is delivered through intense bunches, separated by 50ns intervals between each crossing.

The LHCb detector

3fb^{-1} of pp collisions data recorded at a center-of-mass energy of 7 and 8 TeV

RICH:
ε(K→K)≈95% for (π→K) mis-ID≈5%

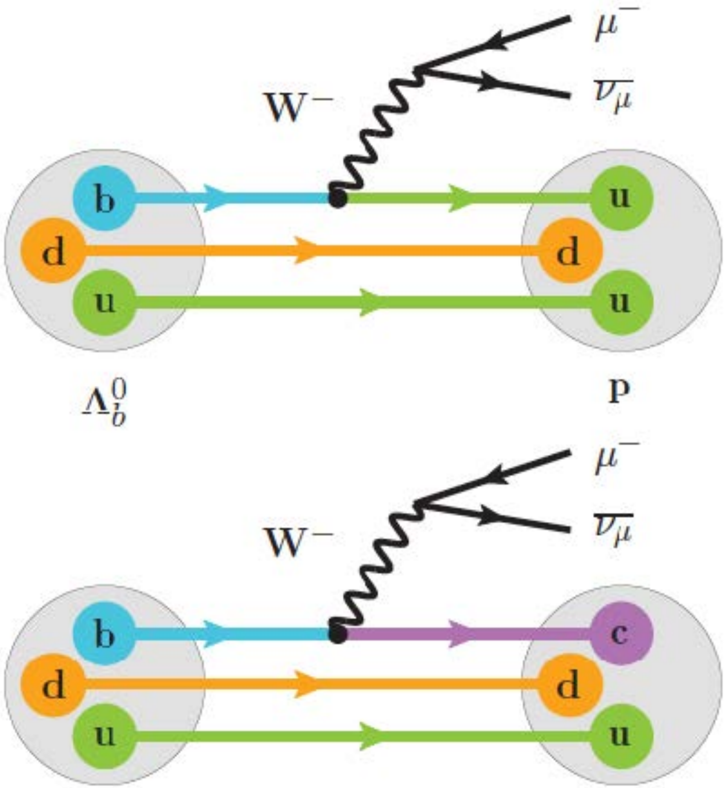
Muon:
ε(μ→μ)≈97% for (π→μ) mis-ID≈2%



Tracking:
≈0.5% momentum resolution

VeLo:
≈20μm IP resolution

Heavy baryon decays in HQET



- Λ_b system is an ideal laboratory to apply the "heavy quark effective theory" as light di-quark system accompanying the b-quark has spin zero and thus not affected by the chromomagnetic correction.

$$w = v_{\Lambda_b} \bullet v_{\Lambda_c} = \frac{m_{\Lambda_b}^2 + m_{\Lambda_c}^2 - q^2}{2 m_{\Lambda_b} m_{\Lambda_c}}$$

Heavy baryon decays in HQET

- The form factors can be parameterized by a universal "Isgur-Wise" (IW) function ξ(w):

$$\frac{d\Gamma(\Lambda_b \to \Lambda_c^+ \mu^- \overline{\nu}_\mu)}{dw} = \frac{G_F^2 m_{\Lambda_b}^5 |V_{cb}|^2}{24\pi^3} r_\Lambda^3 \sqrt{w^2 - 1}\left[6w + 6wr_\Lambda^2 - 4r_\Lambda - 8r_\Lambda w^2\right]\xi^2(w)$$

$$\xi(w) = \xi(1) \times \left[1 - \rho^2(w-1) + 0.5\sigma^2(w-1)^2\right]$$

slope

curvature

IW function

IW function old lattice QCD calculation:

$\rho^2 = 1.1 \pm 1.0$ UKQCD hep-lat/9709028

Theoretical input

- Sum rules that constrain parameterization of IW function, most recent constraint:

$$\sigma^2 \geq \frac{5}{4}\rho^2$$

$$\sigma^2 \geq \frac{1}{5}\left[4\rho^2 + 3(\rho^2)^2\right]$$

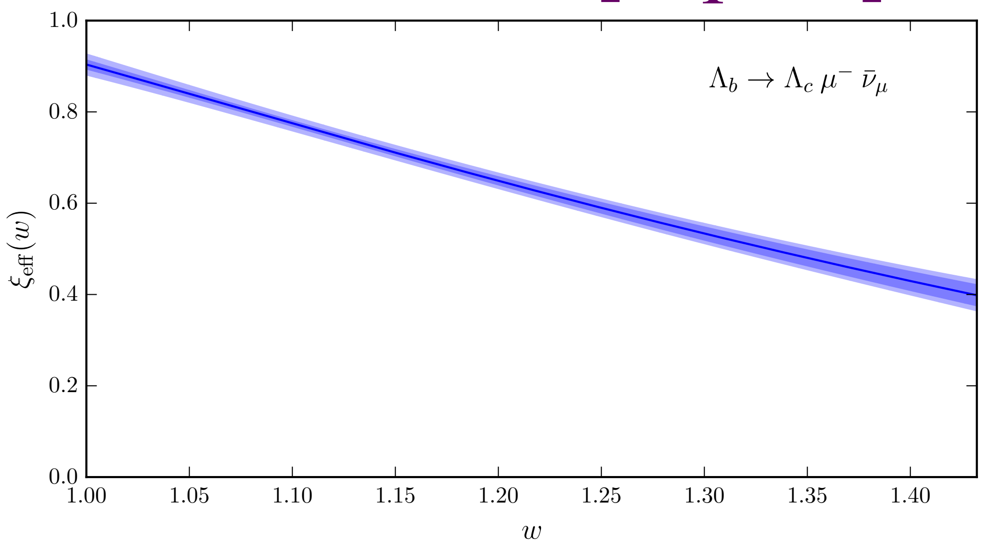
hep-ph/0307197

- Input from lattice QCD: 1503.01421 [hep-lat]

Effective IW function:

$$\xi_{eff}(1) = 0.904 \pm 0.011_{stat} \pm 0.022_{syst}$$

$$\frac{d\xi_{eff}}{dw}(1) = -1.26 \pm 0.10_{stat} \pm 0.16_{syst}$$



Experimental study of $\Lambda_b \to \Lambda_c \mu \nu$

Analysis steps:

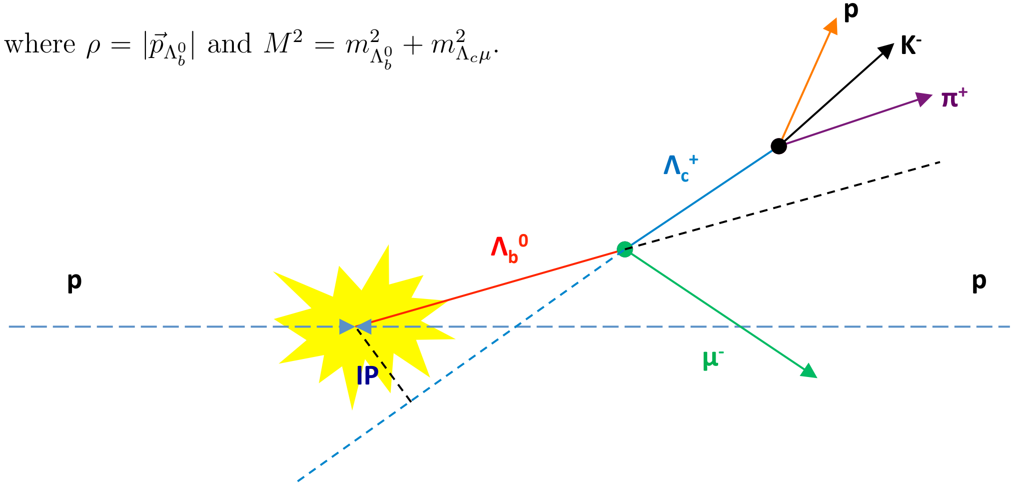
1. We start with the inclusive $\Lambda_b \to \Lambda_c \mu \nu X$ with $\Lambda_c \to pK\pi$.
2. We study $\Lambda_c \pi^+ \pi^- \mu \nu$ final states to infer contributions from excited states.
3. We correct the measured exclusive *w* spectrum for HLT2 efficiency using TISTOS method.
4. We unfold the data using RooUnfold package and SVD (Singular Value Decomposition) method to obtain dN/dw_{true}.
5. We correct the unfolded data for acceptance and selection criteria using MC simulation.
6. We fit to functional forms “theoretically motivated”.

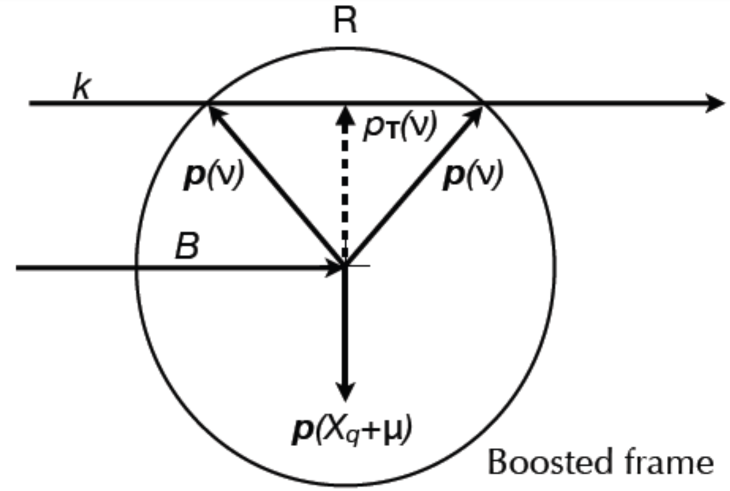
Neutrino reconstruction

Requiring $(p_B - p_{X\mu})^2 = p_\nu^2 = 0$, in four-vector notation, leads to the kinematic constraint for a semileptonic decay:

$$\underbrace{\left[\left(\frac{\hat{p}_{\Lambda_b^0}\cdot\vec{p}_{\Lambda_c\mu}}{E_{\Lambda_c\mu}}\right)^2 - 1\right]}_{a}\rho^2 + \underbrace{\left[M^2\frac{\hat{p}_{\Lambda_b^0}\cdot\vec{p}_{\Lambda_c\mu}}{E^2_{\Lambda_c\mu}}\right]}_{b}\rho + \underbrace{\left[\left(\frac{M^2}{2E_{\Lambda_c\mu}}\right)^2 - m^2_{\Lambda_b^0}\right]}_{c} = 0$$

where $\rho = |\vec{p}_{\Lambda_b^0}|$ and $M^2 = m^2_{\Lambda_b^0} + m^2_{\Lambda_c\mu}$.

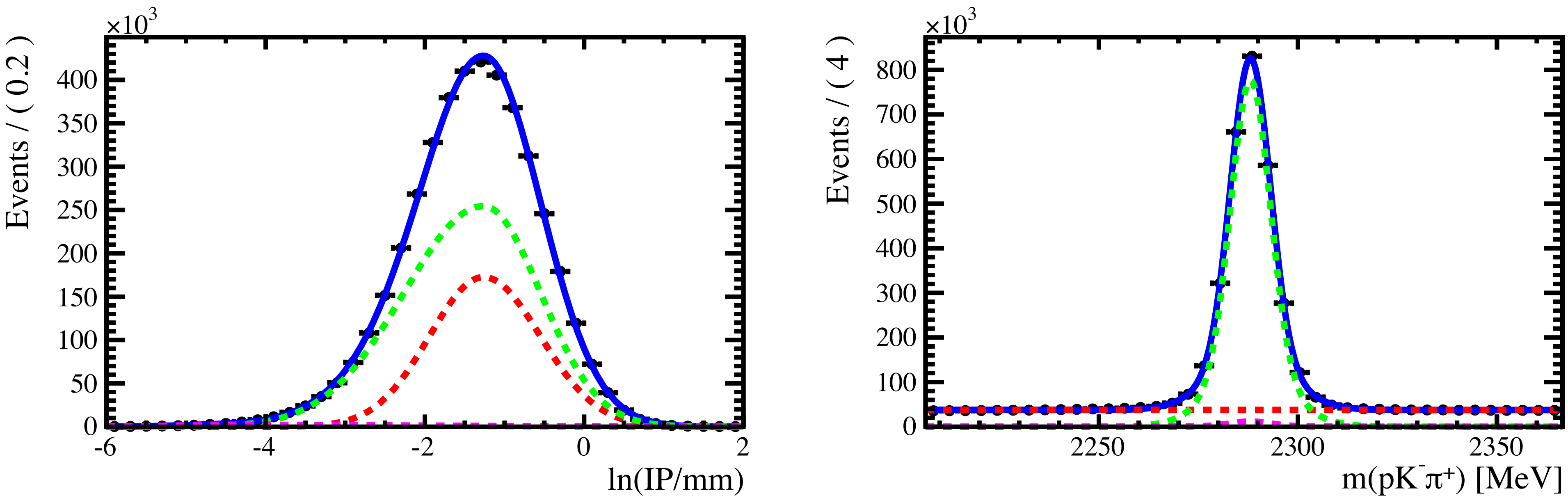




$$w = v_{\Lambda_b}\cdot v_{\Lambda_c} = \frac{m^2_{\Lambda_b} + m^2_{\Lambda c} - q^2}{2m_{\Lambda_b}m_{\Lambda_c}}$$

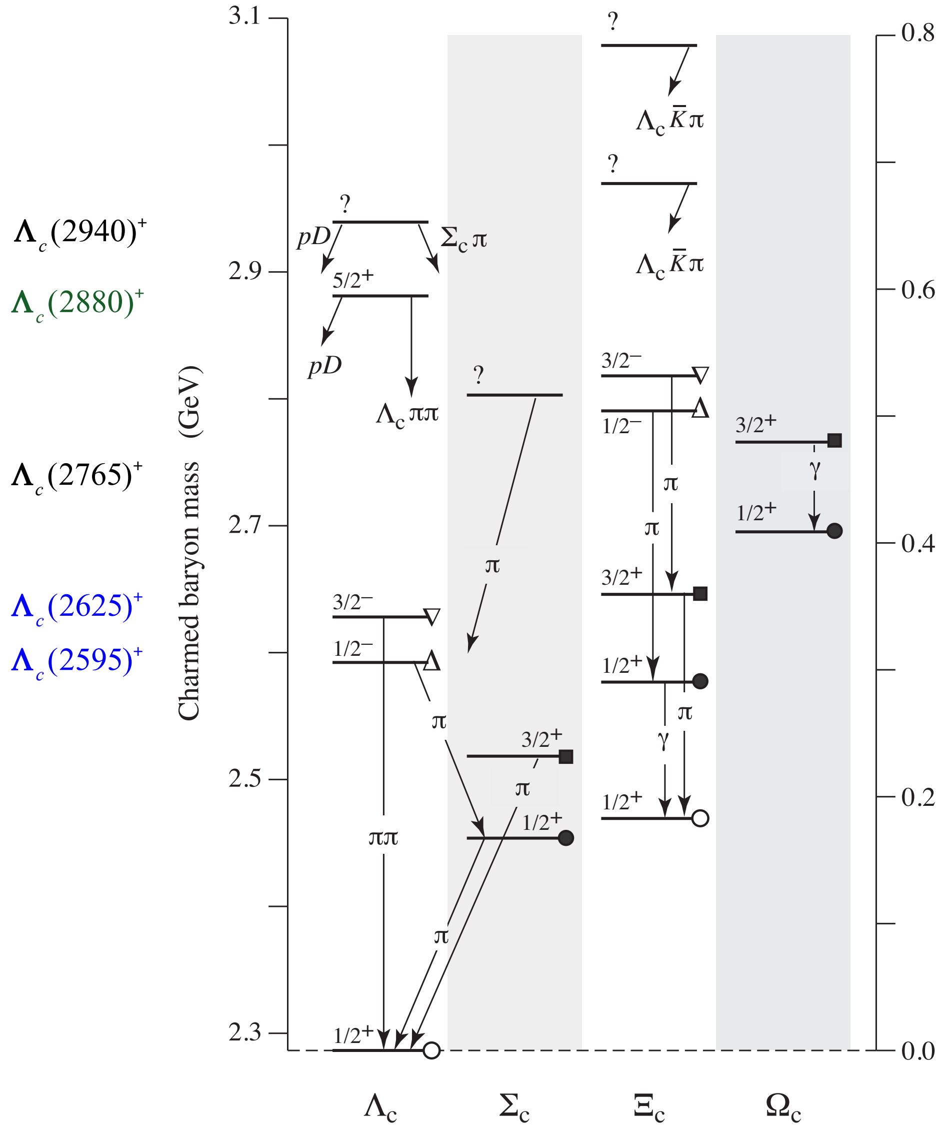
- In this analysis, the Λ_b direction is inferred from the line of flight, connecting the closest primary vertex to the $\Lambda_c\mu$ secondary vertex.
- $|p_{\Lambda b}|$ in semileptonic decays can be determined with a two-fold ambiguity from the Λ_b direction (we keep the lowest solution).
- Once we know the Λ_b momentum, we can reconstruct the neutrino four-vector and other relevant kinematic quantities.

The $\Lambda_b \to \Lambda_c \mu \nu X$ final state



- ❑ Simultaneous fit of the logarithm of the IP distributions and invariant mass distributions for RS $\Lambda_c(pK\pi)$ events. The prompt background is **1.5%** of the total number of Λ_c reconstructed and can be safely neglected.
- ❑ 2.7 millions $\Lambda_b \to \Lambda_c \mu \nu X$ candidates

$\Lambda_b \to \Lambda_c \pi^+ \pi^- \mu \nu$



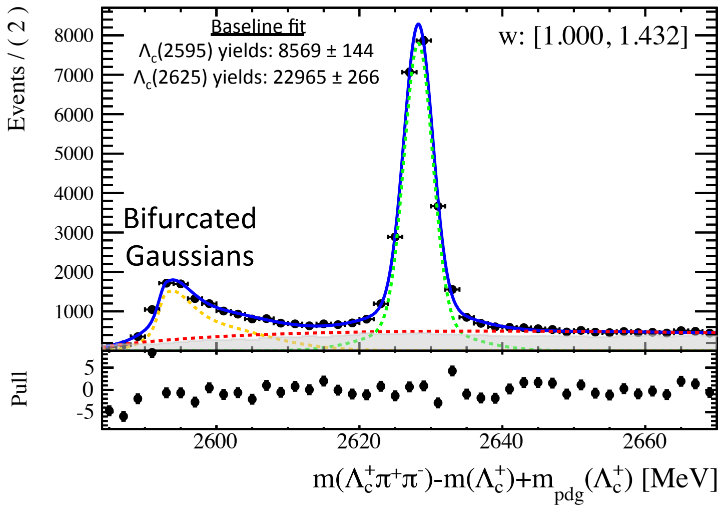
- Only first column is expected to appear in the final state of the Λ_b semileptonic decay (due to the isospin conservation).

The effect of isospin breaking in a Cabibbo favored Λ_b semileptonic decay has not been measured.

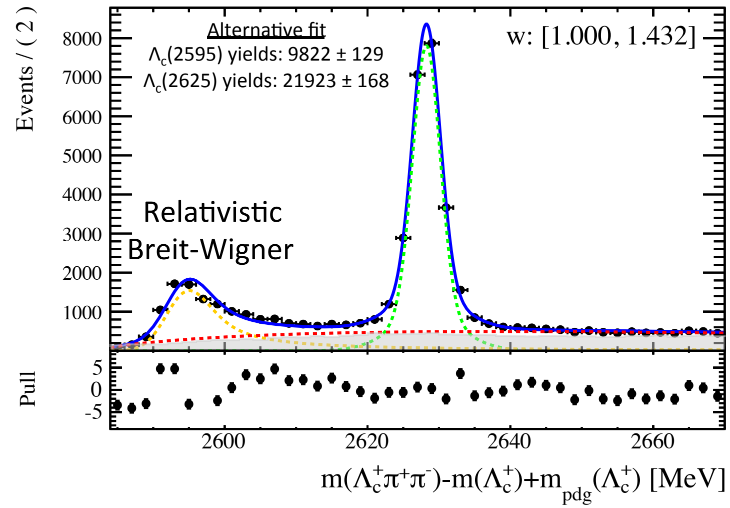
- Many states are uncertain.
- Only the $\Lambda_c\pi^+\pi^-$ final states have been observed.

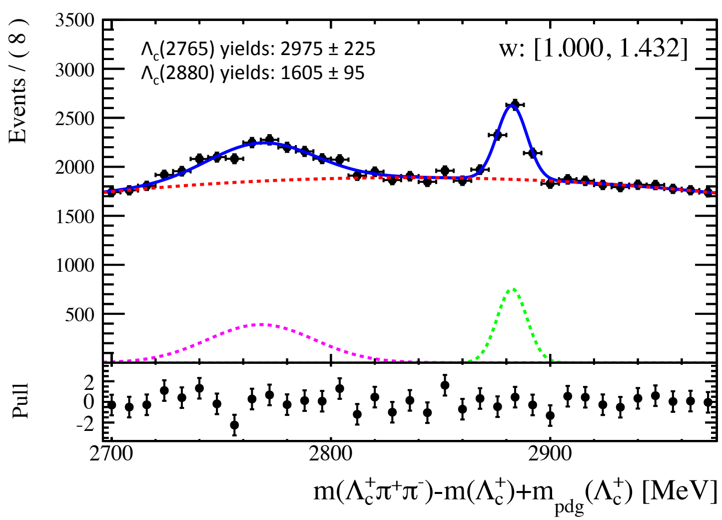
Lots to be studied here!

The $\Lambda_c \pi^+ \pi^- \mu \nu$ final states



Exponential threshold function for background based on the pion like-sign events





Relativistic Breit-Wigner:

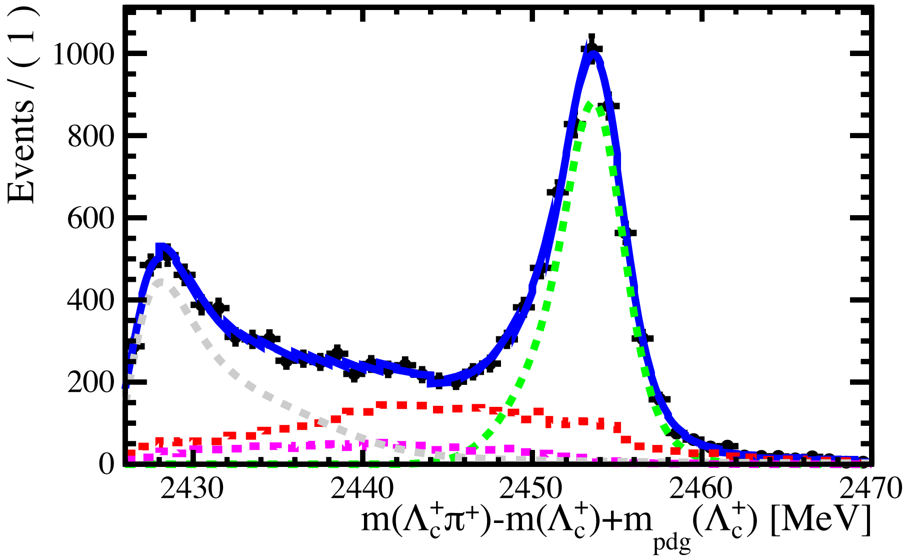
$$BW(m) = \frac{m \times \Gamma(m)}{\left(m^2 - m_R^2\right) + \left(m_R \times \Gamma(m)\right)^2}$$

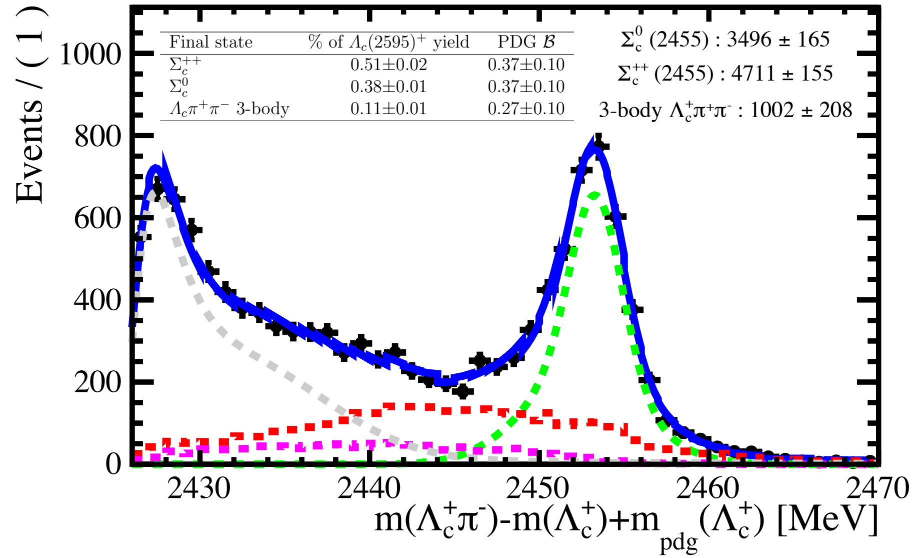
m_R : $\Lambda_c(2595)$ resonance mass
$\Gamma(m)$: mass-dependent width

Resonance	Measured mass (MeV)	Measured sigma (MeV)	PDG mass (MeV)	PDG width (MeV)
$\Lambda_c(2765)$	2769 ± 2.0	24.8 ± 2.4	2766.6 ± 2.4	≈50
$\Lambda_c(2880)$	2883 ± 0.5	6.5 ± 0.5	2881.5 ± 0.35	5.8 ± 1.1

The $\Sigma_c \pi \mu \nu$ final states

$2587\text{MeV} \leq M(\Lambda_c^+ \pi^+ \pi^-) \leq 2612\text{MeV}$



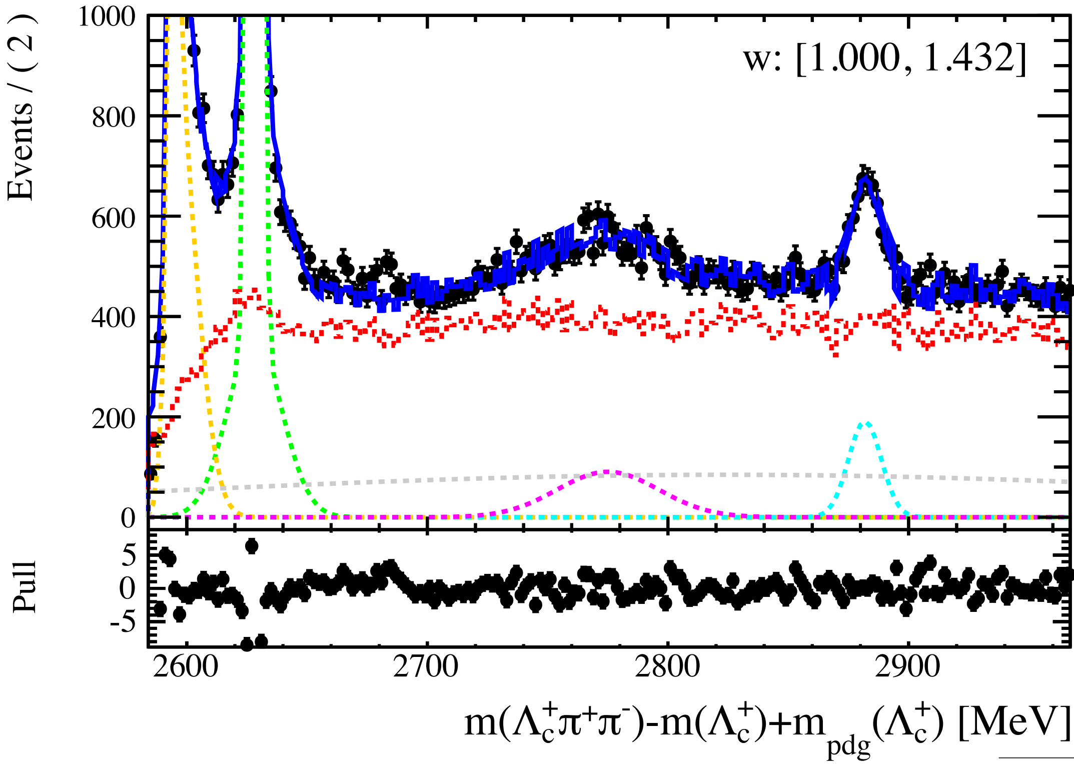


Resonances	Yields
baseline	
$\Lambda_c(2595)^+$	8569 ± 144
$\Lambda_c(2625)^+$	22965 ± 266
check	
$\Lambda_c(2595)^+$	9822 ± 129
$\Lambda_c(2625)^+$	21923 ± 168
Higher mass resonances	
$\Lambda_c(2765)^+$	2975 ± 225
$\Lambda_c(2880)^+$	1605 ± 95

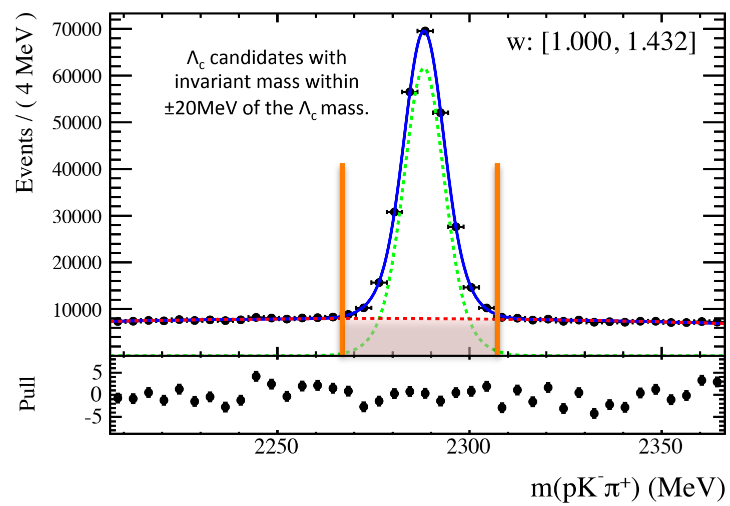
Final state	$\Lambda_c(2595)^+$	$\Lambda_c(2625)^+$	$\Lambda_c(2765)^+$	$\Lambda_c(2880)^+$	Excited	All
$\Sigma_c(2455)^{++}\pi^-$	4711±155	1476±111	3331±102	443±43	11754±246	11827±306
$\Sigma_c(2455)^0\pi^+$	3496±165	1280±111	2103±81	214±30	8447±215	8675±232
$\Lambda_c\pi^+\pi^-$ 3-body	1002±208	21843±498			21992±362	22251±433
$\Sigma_c(2520)^{++}\pi^-$			1378±89	330±39	1623±103	1920±133
$\Sigma_c(2520)^0\pi^+$			1503±90	307±39	1485±103	1828±130

We measure 36114 ± 389 yields coming from all Λ_c^* excited states. The Σ_c and 3-body yields are added to 46501 ± 608, resulting an excess of **10387 ± 722** NR yields.

The $\Lambda_c\pi^+\pi^-\mu\nu$ final states



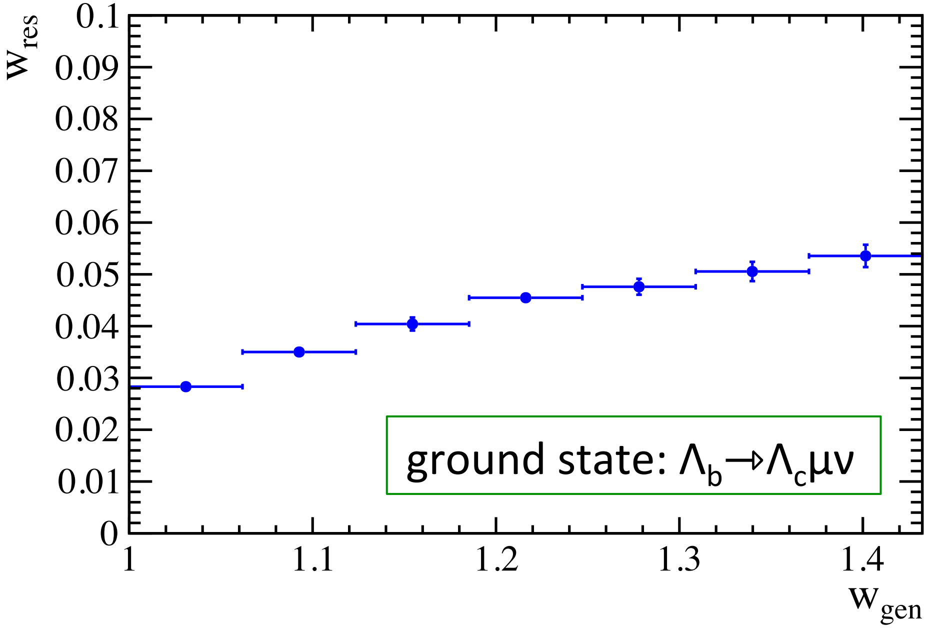
Λ_c sideband background from RS events. The WS contribution is subtracted from the RS one since its already included in the fit.

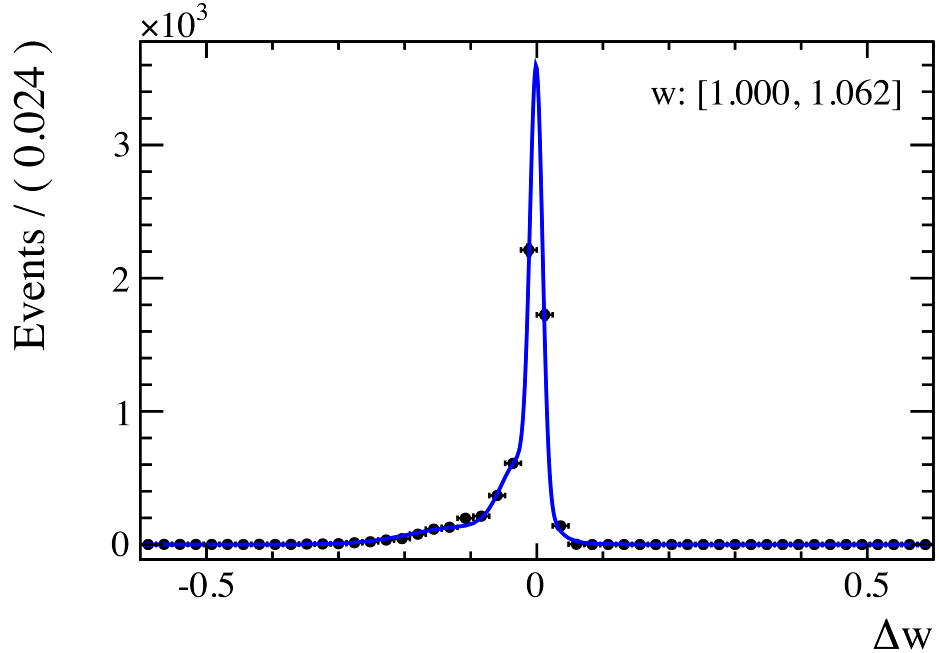


After subtracting Λ_c^+ sideband background from "background" excess, we measure **11690 ± 502** $\Lambda_b \to \Lambda_c\pi^+\pi^-\mu\nu$ NR yields.

w	$\Lambda_c(2595)^+$	$\Lambda_c(2625)^+$	$\Lambda_c(2765)^+$	$\Lambda_c(2880)^+$	bkg excess	Λ_c^+ sideband
1.000-1.031	16±6	89±13	0±3	0±8	1395±66	999±54
1.031-1.062	143±18	337±23	10±36	26±20	1990±105	1651±67
1.062-1.092	309±28	830±34	114±41	61±23	2103±121	1761±78
1.093-1.123	443±31	1456±52	146±47	112±27	2831±137	1737±76
1.124-1.154	563±43	2073±74	142±49	135±27	2581±143	1836±78
1.154-1.185	817±42	2479±68	177±50	156±28	3050±145	1580±77
1.185-1.216	883±43	3021±73	448±53	198±29	2364±146	1575±75
1.216-1.247	1095±47	3044±75	260±50	185±28	2220±142	1250±66
1.247-1.278	998±45	3085±74	204±48	157±27	2206±136	849±64
1.278-1.309	936±44	2559±70	292±45	104±25	1903±127	532±56
1.309-1.340	818±45	2314±73	172±41	171±24	1345±113	601±54
1.340-1.371	635±38	1569±57	155±35	85±20	989±93	340±49
1.371-1.402	371±30	930±44	31±28	89±17	939±73	87±41
1.402-1.432	128±15	303±22	0±7	0±3	690±47	117±32

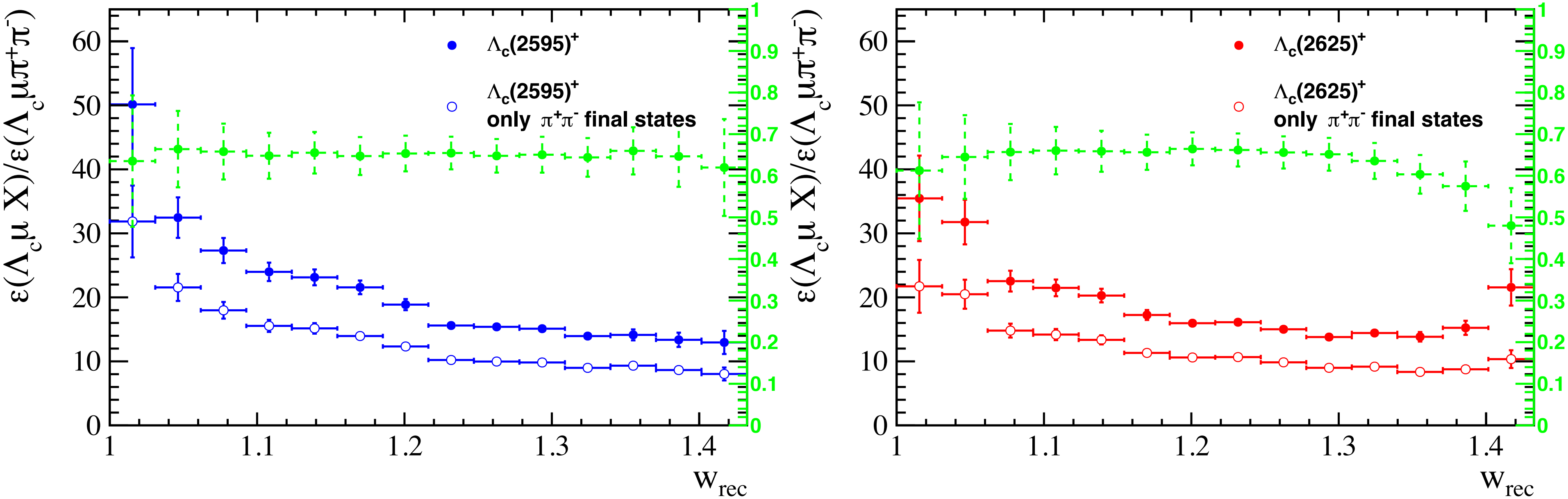
w resolution





- w_{res} is defined from $\Delta w = w_{gen} - w_{rec}$ and calculated in different w_{gen} bins.
- The PDF used in the fits of each w bin is a triple gaussian distribution.
- The w_{res} is studied in terms of several kinematic variables, such as the flight distance of Λ_b.

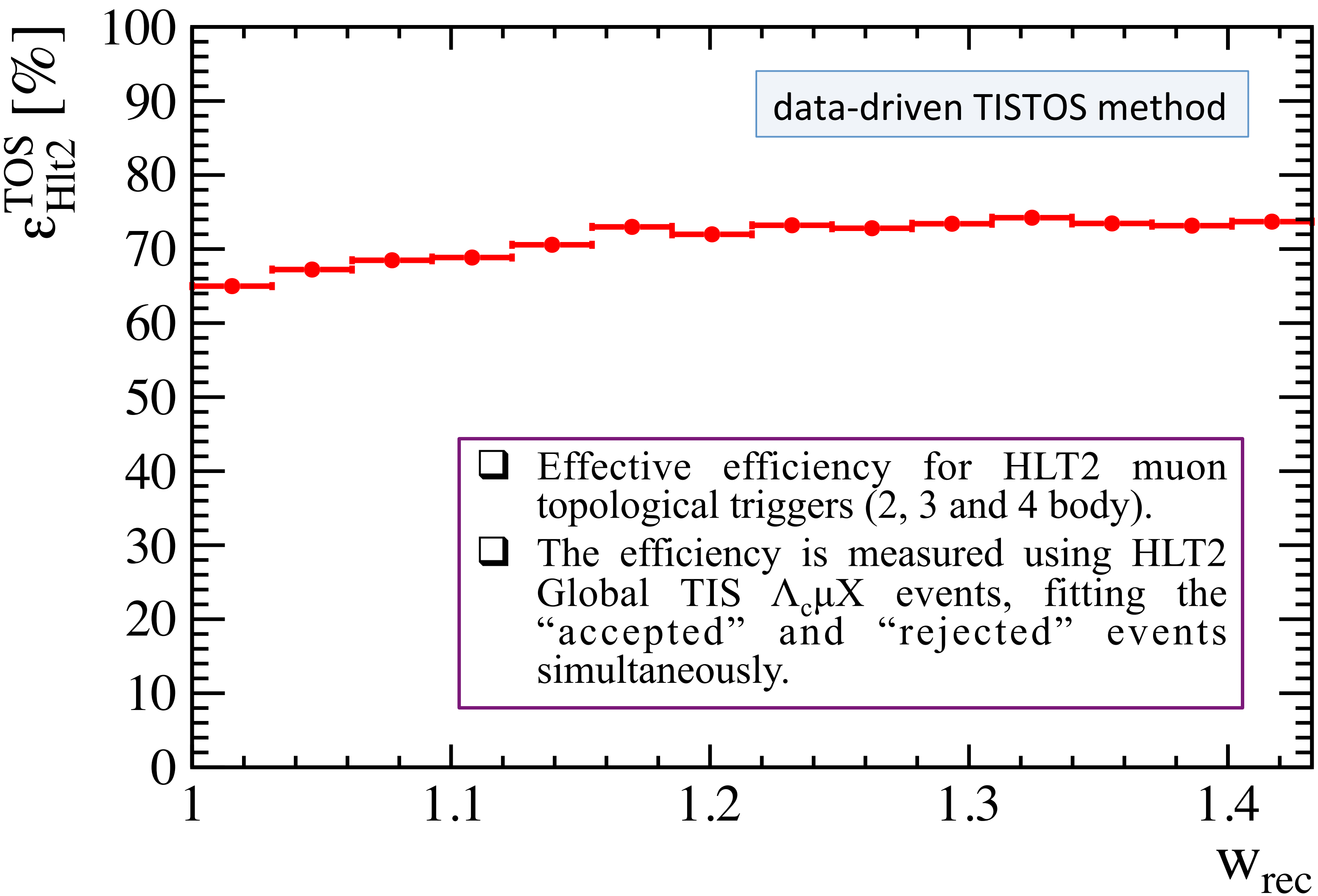
Efficiency ratios for excited states



- Need to scale up the contributions from the excited states. Scale factors obtained by estimating reconstruction efficiency in MC with PID correction (π, K, p, μ) in bins of η, p_T derived from calibration samples (PIDCalib).
- Uncertainty associated with excited states decaying into neutrals by changing the fraction of neutral to charged di-pion final states (R_{MC} = 0.67):

$$R_{meas} = \frac{N(\Sigma_c^{++}) + N(\Sigma_c^0)}{N(\Sigma_c^{++}) + N(\Sigma_c^0) + N(\Sigma_c^+)\left[\varepsilon(\Lambda_c^+\pi^+\pi^-\mu^-)/\varepsilon(\Lambda_c^+\pi^0\mu^-)\right]} = 0.63 \pm 0.14$$

HLT2 trigger correction



Unfolding w_{true}

$$(A_{ij})\frac{dN}{dw_{true,j}} = \frac{dN}{dw_{meas,i}}$$

We need to solve the problem: $\hat{\mathbf{A}}\mathbf{x} = \mathbf{b}$

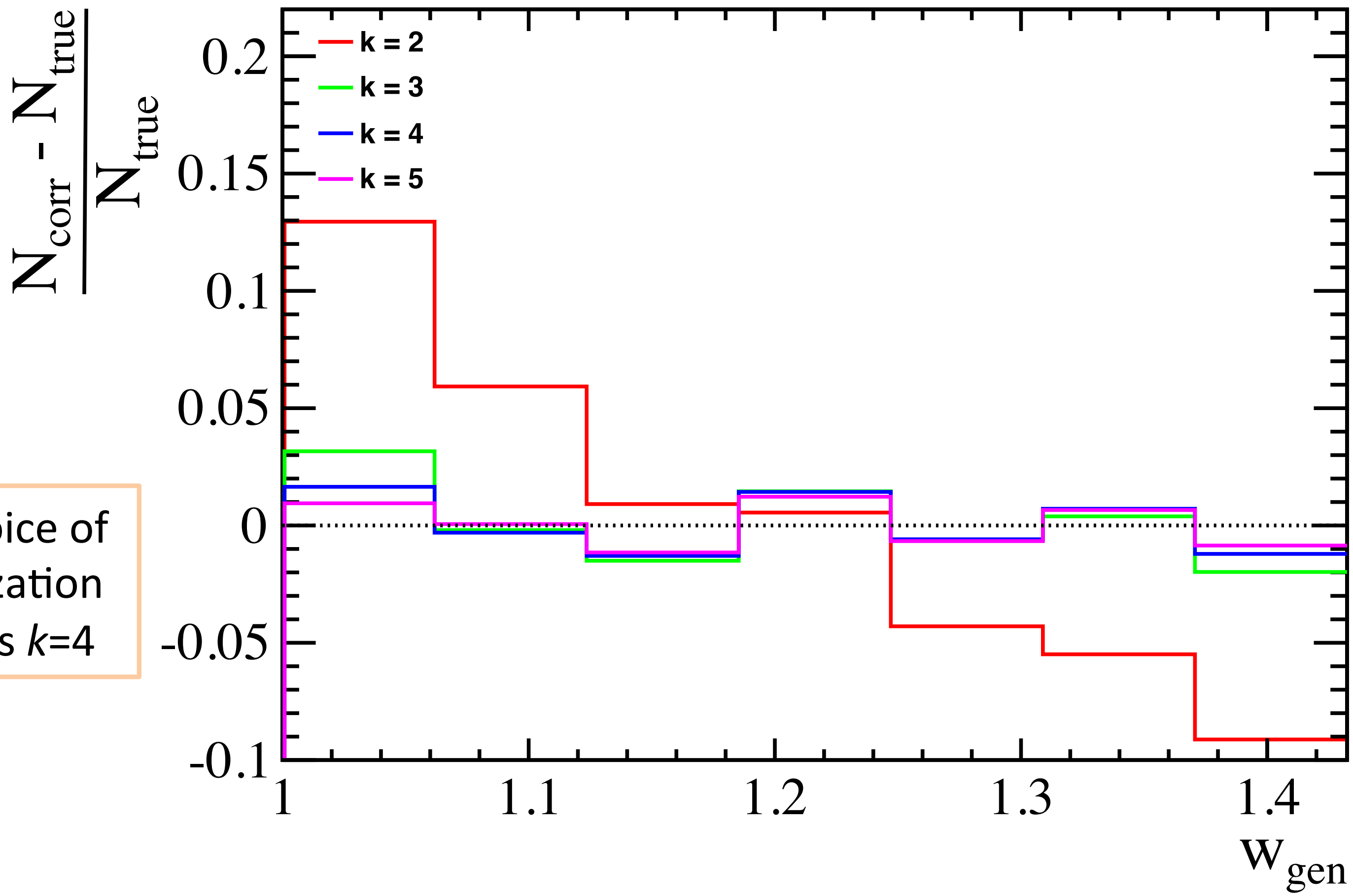
between the true (x) and measured (b) distributions with Â being the *response matrix* of the detector.

- Singular Value Decomposition (SVD): $\hat{A}=USV^T$ with U and V orthogonal matrices and S a diagonal matrix with elements called *singular values*.

- Regularization: For SVD, the unfolding is something like a Fourier expansion. Choosing the regularization parameter *k* effectively, determines up to which frequencies the terms in the expansion are kept.

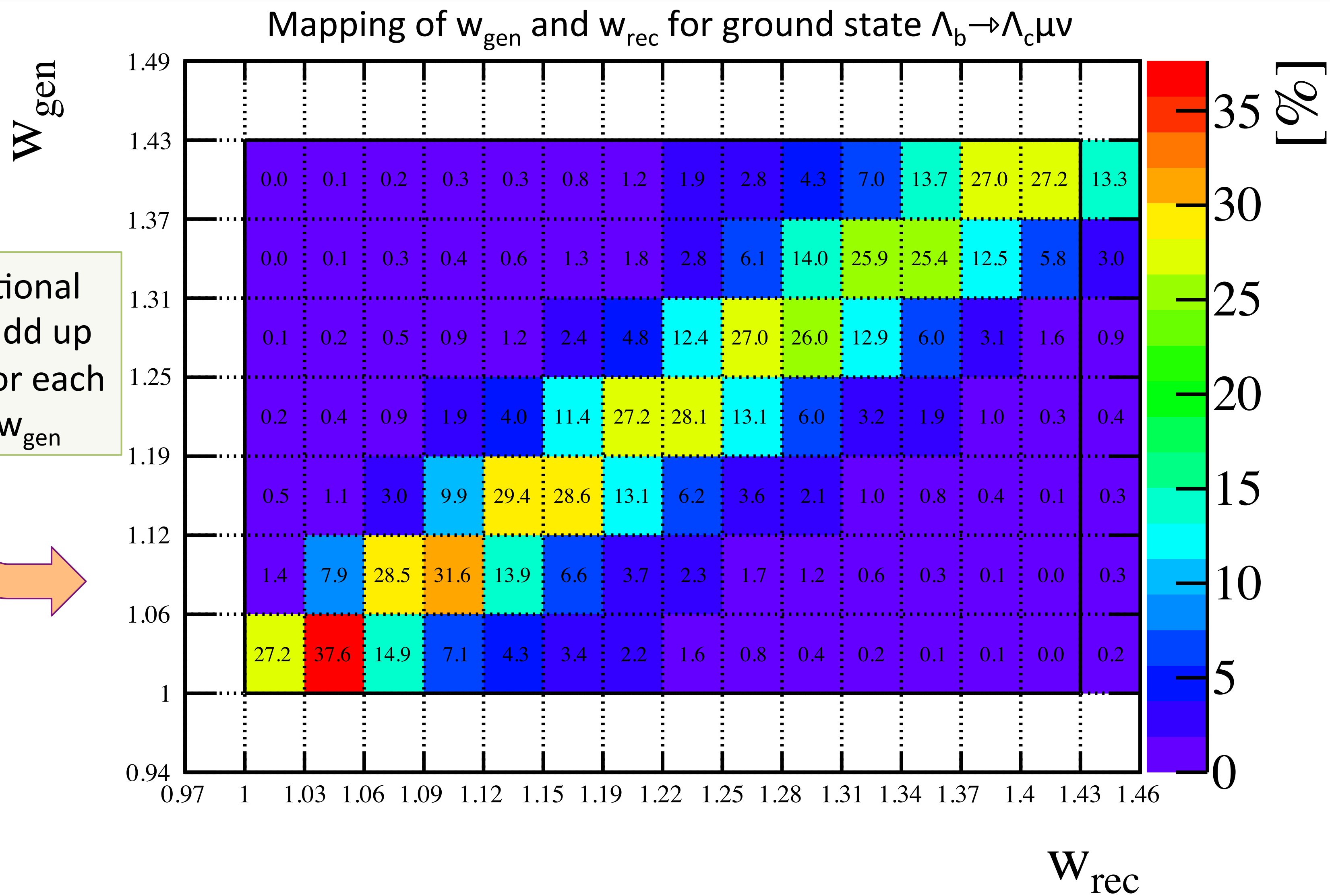
Choice of regularization parameter

- This needs to be tuned for any given distribution, number of bins, and approximate sample size — with k between 2 and the number of bins.



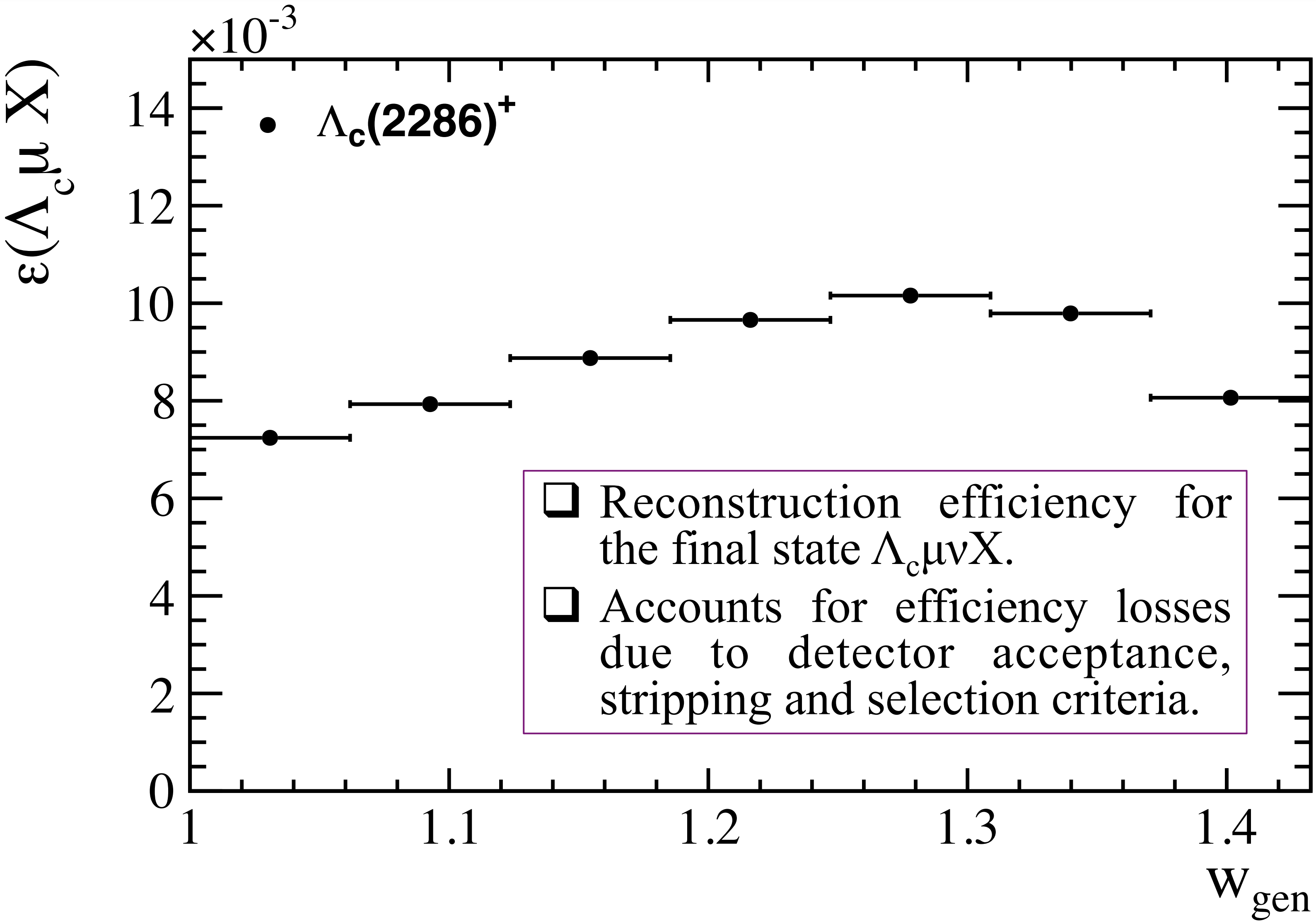
The best choice of the regularization parameter is k=4

The response matrix



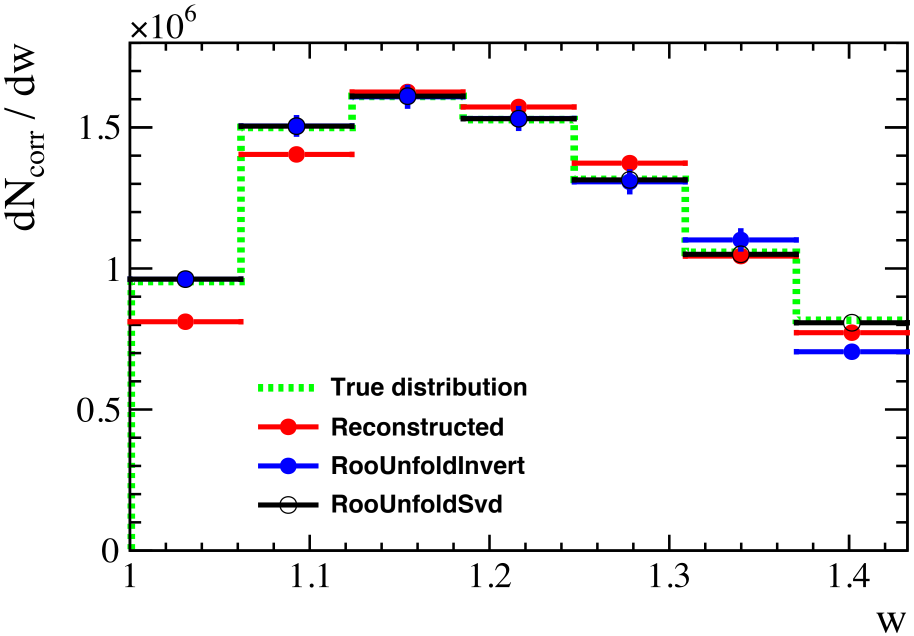
The fractional weights add up to 100% for each row of w_{gen}

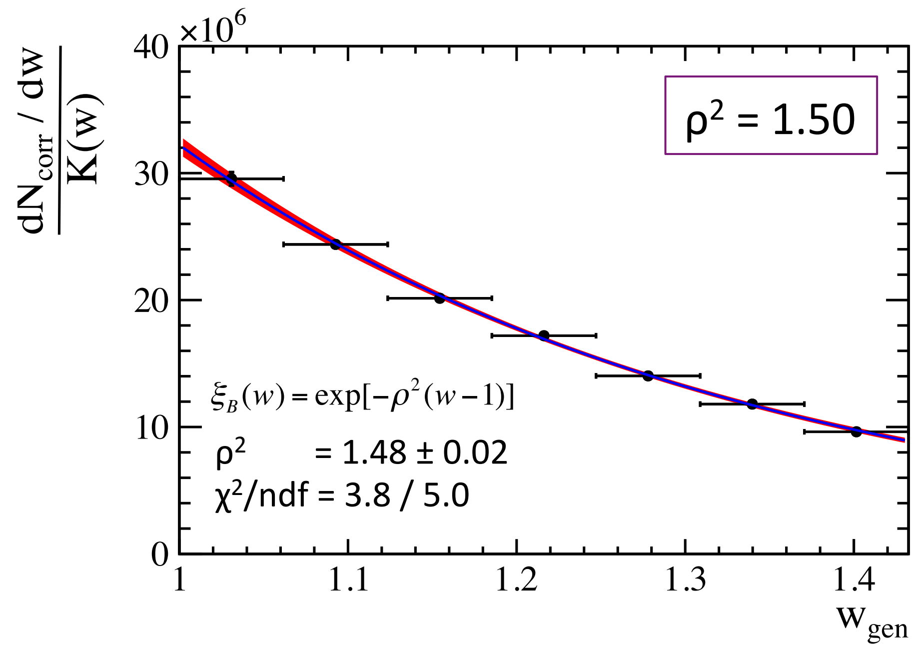
Efficiency correction after unfolding



- Reconstruction efficiency for the final state $\Lambda_c \mu \nu X$.
- Accounts for efficiency losses due to detector acceptance, stripping and selection criteria.

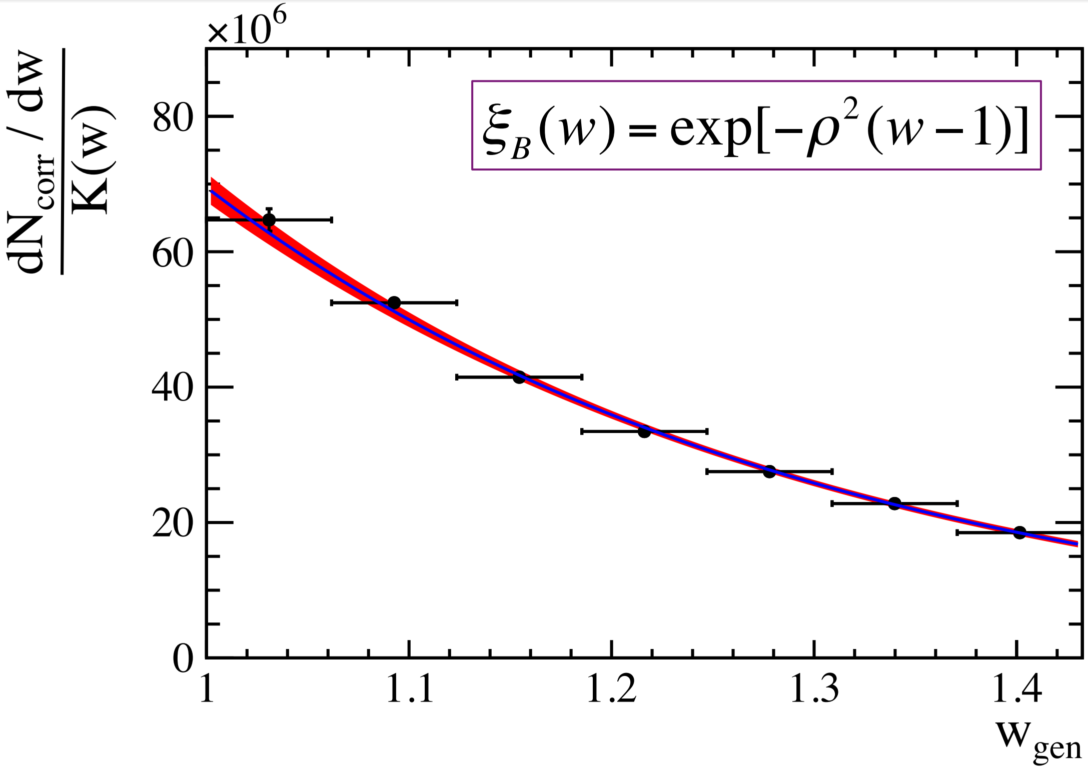
MC validation

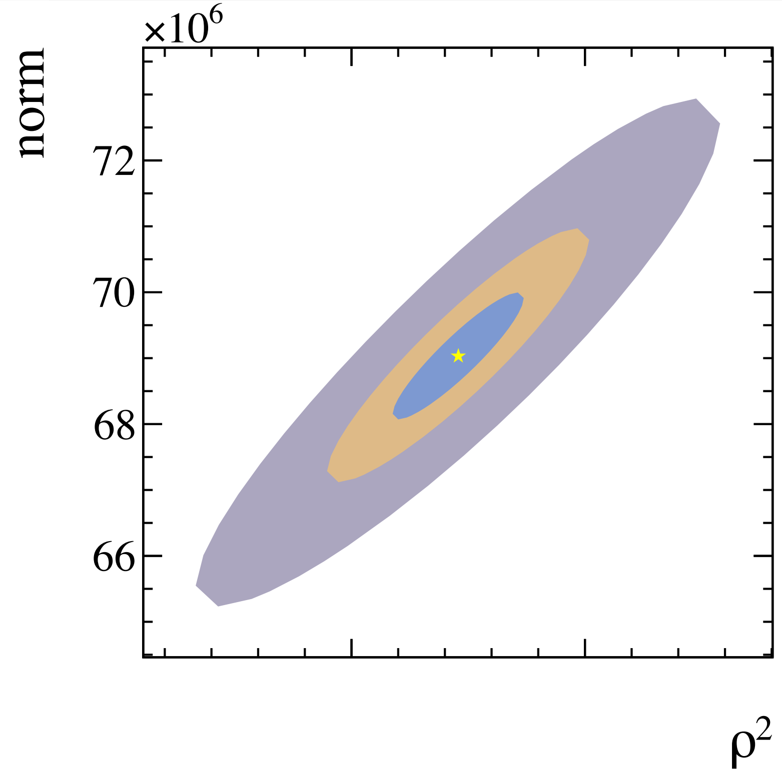




- **RooUnfoldSvd:** We use the SVD regularization method for the unfolding (arXiv:hep-ph/9509307) and k=4 (regularization parameter).
- **RooUnfoldInvert:** This is not accurate for small matrices and produces inaccurate unfolded distributions.
- We get back the original generated distribution by unfolding. We repeated the procedure for different form factor (ρ^2 = 1.50) and it works.

Fit to functional forms





Include contributions from Λ_c^*

Shape	ρ^2	σ^2	χ^2/dof
Exponential			5.3/5
Dipole			5.3/5
Taylor series			4.5/4

Include contributions from Λ_c^* and $\Lambda_b \to \Lambda_c \pi^+ \pi^- \mu\nu$ NR

Shape	ρ^2	σ^2	χ^2/dof
Exponential			6.7/5
Dipole			6.4/5
Taylor series			5.8/4

Systematic uncertainties

Item	$\sigma(\rho^2)$
MC statistics	0.02
MC modeling	0.02
Form factor change in MC	0.03
Λ_b kinematic dependencies	0.02
Additional components of SL spectrum	0.02
HLT2 trigger efficiency	0.02
w binning	0.03
SVD unfolding regularization	0.03
Phase space averaging	0.03
Signal PDF for $\Lambda_c(2595)$	0.02
Signal fit for Λ_c	0.02
Sum	**0.08**

MC modeling includes the calculation of the efficiency for the two additional excited states $\Lambda_c(2765)$ and $\Lambda_c(2880)$ and the fraction of neutral to charged di-pion final states.

Input from lattice

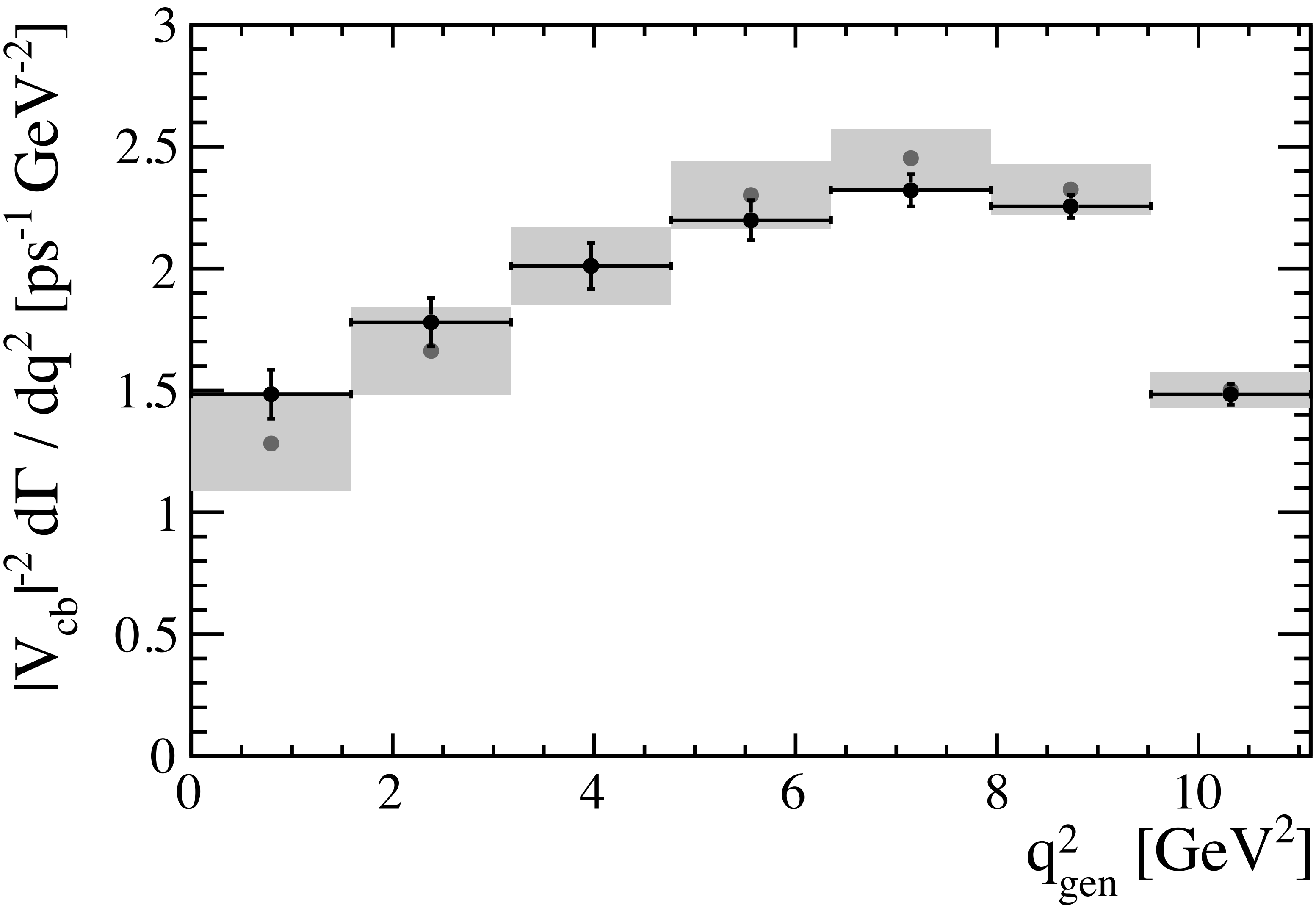
- Recent lattice predictions (arXiv:1503.01421v2) of the form factors of $\Lambda_b \to \Lambda_c \mu \nu$ are expressed in terms of q^2:

$$s_\pm = (m_{\Lambda_b} \pm m_X)^2 - q^2.$$

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2 |V_{qb}^L|^2 \sqrt{s_+ s_-}}{768\pi^3 m_{\Lambda_b}^3} \left(1 - \frac{m_\ell^2}{q^2}\right)^2$$
$$\times \left\{ 4\left(m_\ell^2 + 2q^2\right)\left(s_+\left[(1-\epsilon_q^R) g_\perp\right]^2 + s_-\left[(1+\epsilon_q^R) f_\perp\right]^2\right) \right.$$
$$+2\frac{m_\ell^2 + 2q^2}{q^2}\left(s_+\left[(m_{\Lambda_b} - m_X)(1-\epsilon_q^R) g_+\right]^2 + s_-\left[(m_{\Lambda_b} + m_X)(1+\epsilon_q^R) f_+\right]^2\right)$$
$$\left. + \frac{6m_\ell^2}{q^2}\left(s_+\left[(m_{\Lambda_b} - m_X)(1+\epsilon_q^R) f_0\right]^2 + s_-\left[(m_{\Lambda_b} + m_X)(1-\epsilon_q^R) g_0\right]^2\right) \right\},$$

- As lattice calculations offer the prospect of extraction of the CKM parameter V_{cb} with increasing accuracy, it is important to check the form factor shape predicted by them.

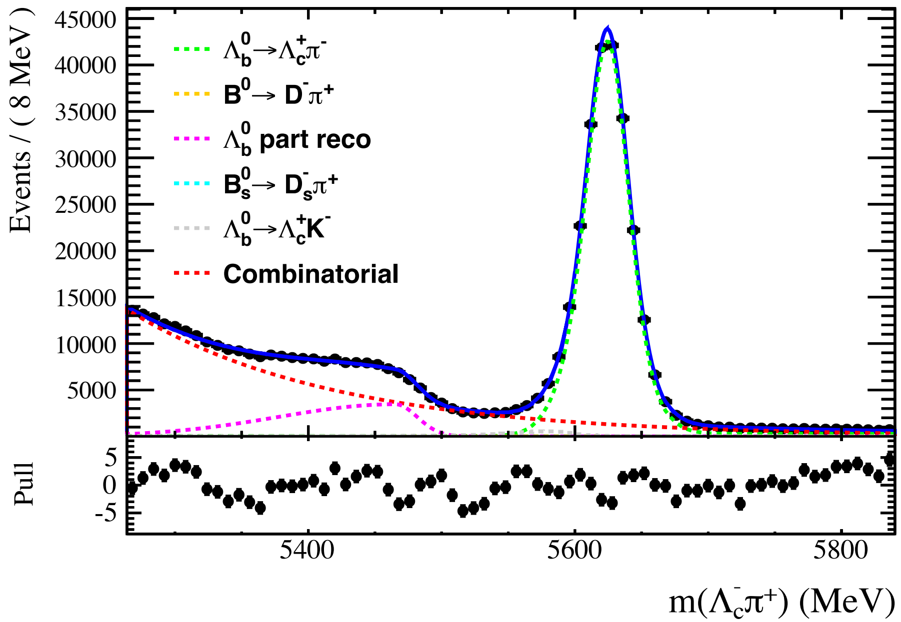
Results using the nominal model

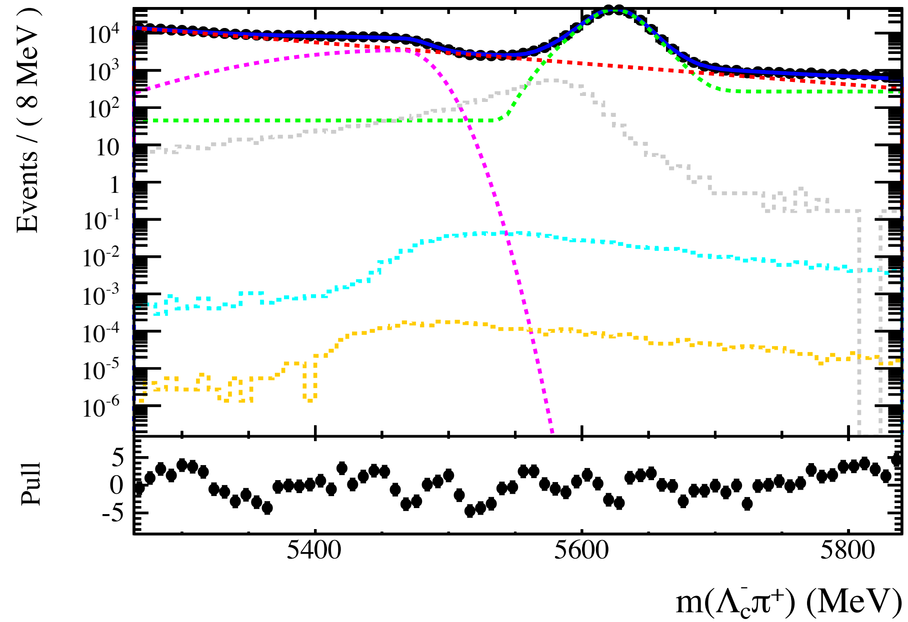


Measurement of $|V_{cb}|$

- Absolute normalization and measurement of V_{cb}. Normalization modes: $\Lambda_b \to \Lambda_c \pi$ and $B \to D^* \mu\nu$.

$$B(\Lambda_b \to \Lambda_c \mu\nu) = \frac{\Gamma(\Lambda_b \to \Lambda_c \mu\nu)}{\Gamma(\Lambda_b)} = \tau_{\Lambda_b} \cdot \Gamma(\Lambda_b \to \Lambda_c \mu\nu) = |V_{cb}|^2 \tau_{\Lambda_b} \int_1^{w_{max}} \frac{d\Gamma'}{dw} \cdot dw$$





Conclusions

- We studied the Isgur–Wise function with different functional forms and the results are consistent with the sum rule bounds. From sum rules, the bound on the curvature is $\rho^2 > 1.5$.

- This FF shape measurement represents a considerable improvement with respect to the DELPHI collaboration result (hep-ex/0403040): $\rho^2 = 2.03 \pm 0.46(stat)^{+0.72}_{-1.00}(sys)$

$$\rho^2 = \qquad \pm 0.03(stat) \pm 0.08(sys)$$

- The q^2 spectrum is compared with Meinel's *et al.* prediction from lattice QCD.

Back-up slides follow

THE END

Decays of the excited states ($\Lambda_b \to \Lambda_c^* \mu \nu$)

Included in the MC cocktail

$\Lambda_c(2595)^+$ decay	Branching fraction
$\Sigma_c^{++}(\Lambda_c^+\pi^+)\pi^-$	0.24
$\Sigma_c^{0}(\Lambda_c^+\pi^-)\pi^+$	0.24
$\Lambda_c^+\pi^+\pi^-$	0.18
$\Sigma_c^{+}(\Lambda_c^+\pi^0)\pi^0$	0.24
$\Lambda_c^+\pi^0\pi^0$	0.09
$\Lambda_c\gamma$	0.01

$\Lambda_c(2625)^+$ decay	Branching fraction
$\Lambda_c^+\pi^+\pi^-$	0.66
$\Lambda_c^+\pi^0$	0.33
$\Lambda_c^+\gamma$	0.01

Definition of the form factors

- The form factors are extracted at different lattice spacings and quark masses from non-perturbative Euclidean correlation functions.

- Global fits of the helicity form factors are performed based on the simplified z-expansion (arXiv:0807.2722).

- The pole mass in each dataset is evaluated as the sum of the B_c mass and the mass splitting between the meson with the relevant quantum numbers and B_c.

$$f(q^2) = \frac{1}{1 - q^2/(m^f_{\rm pole})^2}\left[a_0^f + a_1^f\, z(q^2)\right],$$

$$f_{\rm HO}(q^2) = \frac{1}{1 - q^2/(m^f_{\rm pole})^2}\left[a_0^f + a_1^f\, z(q^2) + a_2^f\, z^2(q^2)\right].$$